THE PROPERTIES OF Lyα NEBULAE: GAS KINEMATICS FROM NONRESONANT LINES*

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ABSTRACT

With the Very Large Telescope/X-shooter, we obtain optical and near-infrared spectra of six Lyα blobs at $z \sim 2.3$. For a total sample of eight Lyα blobs (including two that we have previously studied), the majority (6/8) have broadened Lyα profiles with shapes ranging from a single peak to symmetric or asymmetric double-peaked. The remaining two systems, in which the Lyα profile is not significantly broader than the [O III] or Hα emission lines, have the most spatially compact Lyα emission, the smallest offset between the Lyα and the [O III] or Hα line velocities, and the only detected C IV and He II lines in the sample, implying that a hard ionizing source, possibly an active galactic nucleus (AGN), is responsible for their lower optical depth. Using three measures—the velocity offset between the Lyα line and the nonresonant [O III] or Hα line ($\Delta v_{Ly\alpha}$), the offset of stacked interstellar metal absorption lines, and a new indicator, the spectrally resolved [O III] line profile—we study the kinematics of gas along the line of sight to galaxies within each blob center. These three indicators generally agree in velocity and direction and are consistent with a simple picture in which the gas is stationary or slowly outflowing at a few hundred km s$^{-1}$ from the embedded galaxies. The absence of stronger outflows is not a projection effect: the covering fraction for our sample is limited to <1/8 (13%). The outflow velocities exclude models in which star formation or AGNs produce “super-” or “hyper-winds of up to $\sim 1000$ km s$^{-1}$. The $\Delta v_{Ly\alpha}$ offsets here are smaller than typical of Lyman break galaxies but similar to those of compact Lyα emitters (LAEs). The latter suggests a connection between blob galaxies and LAEs and that outflow speed cannot be a dominant factor in driving extended Lyα emission. For one Lyα blob (CDFS-LAB14), whose Lyα profile and metal absorption line offsets suggest no significant bulk motion, we use a simple radiative transfer model to make the first column density measurement of gas in an embedded galaxy, finding it consistent with a damped Lyα absorption system. Overall, the absence of clear inflow signatures suggests that the channeling of gravitational cooling radiation into Lyα is not significant over the radii probed here. However, one peculiar system (CDFS-LAB10) has a blueshifted Lyα component that is not obviously associated with any galaxy, suggesting either displaced gas arising from tidal interactions among blob galaxies or gas flowing into the blob center. The former is expected in these overdense regions where Hubble Space Telescope images resolve many galaxies. The latter might signify the predicted but elusive cold gas accretion along filaments.

Key words: galaxies: formation – galaxies: high-redshift – intergalactic medium

Online-only material: color figures

1. INTRODUCTION

Giant Lyα nebulae, or “blobs,” are extended sources at $z \sim 2–6$ with typical Lyα sizes of $\gtrsim 50$ kpc and line luminosities of $L_{Ly\alpha} \gtrsim 10^{43}$ erg s$^{-1}$ (e.g., Keel et al. 1999; Steidel et al. 2000; Francis et al. 2001; Matsuda et al. 2004, 2011; Dey et al. 2005; Saito et al. 2006; Smith & Jarvis 2007; Hennawi et al. 2009; Ouchi et al. 2009; Prescott et al. 2009, 2012b; Yang et al. 2009, 2010; Erb et al. 2011). The low number counts, strong clustering, multiple embedded sources, and location in overdense environments of the largest Lyα blobs indicate that they lie in massive ($M_{halo} \sim 10^{13} M_\odot$) dark matter halos, which will evolve into those typical of rich galaxy groups or clusters today (Yang et al. 2009, 2010; Prescott et al. 2008, 2012a). Therefore, Lyα blobs are unique tracers of the formation of the most massive galaxies and their early interaction with the surrounding intergalactic medium (IGM).

This interaction is probably tied on some scale to the source of the blobs’ extended Lyα emission, but that mechanism is poorly understood. Emission from Lyα blobs could arise from several phenomena, which may even operate together, including shock heating by galactic superwinds (Taniguchi & Shioya 2000) or gas photoionized by active galactic nuclei (AGNs; Haiman & Rees 2001; Geach et al. 2009). Another possibility is smooth gas accretion, which is likely to play an important role in the formation of galaxies (e.g., Keres et al. 2005, 2009) and which should channel some of its gravitational cooling radiation into atomic emission lines such as Lyα (Haiman et al. 2000; Fardal et al. 2001; Dijkstra & Loeb 2009; Goerdt et al. 2010). Another scenario is the resonant scattering of Lyα photons produced by star formation or AGNs (Steidel et al. 2010; Hayes et al. 2011) in the embedded galaxies.

To resolve the debate about the nature of Lyα blobs requires—at the very least—that we discriminate between outflowing and inflowing models. Because Lyα is a resonant line and typically optically thick in the surrounding IGM, studies even of the same Lyα blob’s kinematics can disagree. On one hand, Wilman et al. (2005) argue that their integral field unit (IFU) spectra of an Lyα blob are consistent with a simple model where the Lyα emission is absorbed by a foreground slab of neutral gas swept out by a galactic-scale outflow. On the other

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hand, Dijkstra et al. (2006b) explain the same data as arising from the infall of the surrounding IGM. Worse, Verhamme et al. (2006) claim that the same symmetric Lyα profiles are most consistent with static surrounding gas.

To distinguish among such possibilities requires a comparison of the center of the Lyα line profile with that of a nonresonant line like Hα λ6563 or [O III] λ5007. These rest-frame optical nebular lines are better measures of the Lyα blob’s systemic velocity, i.e., of the precise redshift, because it is not seriously altered by radiative transfer (RT) effects and is more concentrated about the galaxies in the Lyα blob’s core. We illustrate this line offset technique in Figure 1. While gas accretion models predict different line profile shapes depending on various assumptions, e.g., the location of ionizing sources, the detailed geometry, and the velocity field, they all predict that the overall Lyα line profile, originating from the central source or the surrounding gas, will be blueshifted with respect to the center of a nonresonant line such as Hα that is optically thin to the surrounding H I gas (Verhamme et al. 2006; Dijkstra et al. 2006a). This is because the red side of the Lyα profile will see higher optical depth due to the infalling (approaching) gas. In other words, the Hα kinematics represent the true underlying velocity field if the Lyα blob is accreting gas from the IGM. The same is true if the gas is outflowing, except that the Lyα line will be redshifted with respect to Hα. Thus, if we measure the direction of the Lyα–Hα and/or Lyα–[O III] line offset (hereafter defined as $\Delta v_{\text{Lyα}}$), we can distinguish an inflow from an outflow.

The first such analysis for two Lyα blobs shows that Lyα is coincident with or redshifted by $\sim 200$ km s$^{-1}$ from the Hα line center (Yang et al. 2011, see also McLinden et al. 2013). These offsets are much smaller than the $\sim 1000$ km s$^{-1}$ expected from superwind models (Taniguchi & Shioya 2000) and even smaller than those typical of Lyman break galaxies (LBGs), which are widely believed to have galactic outflows (Steidel et al. 2004, 2010). Thus, if $\Delta v_{\text{Lyα}}$ is a proxy for outflow velocities ($v_{\text{exp}}$), our initial results suggest that star-formation- or AGN-produced winds may not be required for powering Lyα blobs, making other interpretations of their emission more likely.

However, we do not yet know whether these results are representative of all Lyα blobs or we have failed to detect strong flows owing to the projected orientations of these two sources. For example, the gas flow may not be isotropic. As in bipolar outflows in M82 (e.g., Bland & Tully 1988), a galactic-scale outflow may occur in the direction of minimum pressure in the surrounding interstellar medium (ISM), often perpendicular to the stellar disks. Or, if gas accretion is taking place in Lyα blobs, numerical simulations suggest that the gas infall may occur preferentially along filamentary streams (Kereš et al. 2005, 2009; Dekel et al. 2009). Thus, if the bulk motion of gas (either infalling or outflowing) happens to be misaligned with our line of sight (LOS), then we may underestimate or even fail to detect the relative velocity shifts. Therefore, it is critical to measure $\Delta v_{\text{Lyα}}$ for a larger sample to average over any geometric effects and obtain better constraints on the

Figure 1. Schematic diagrams of the expected Lyα and nonresonant Hα or [O III] profiles if the gas in the blobs is static, inflowing, or outflowing. The solid (blue) and dashed (red) lines represent the Lyα and nonresonant (optically thin to H I) lines, respectively. Top: static cloud. Because the surrounding gas cloud is optically thick to the Lyα line, Lyα photons in the Doppler wings should escape the cloud through random scatterings in the frequency domain. Therefore, if the surrounding gas is static, the Lyα line should have a double-peaked profile, while the nonresonant line photons will escape without any radiative transfer effects. Middle: spherical infall. If the gas is infalling toward the embedded galaxy, Lyα photons within the cloud on the red side of the double-peaked profile will see higher optical depth due to the LOS infalling gas, and the red peak will be depressed. Bottom: expanding shell. In contrast, if the gas is outflowing, the blue side of the profile will be more diminished. In summary, if there is gas infall (or outflow), the Lyα profiles will be asymmetric and blueshifted (or redshifted) against the nonresonant line owing to radiative transfer in the optically thick medium, but the corresponding nonresonant line profiles should be symmetric. Note that one cannot determine whether the Lyα line is redshifted or blueshifted against the background velocity field unless there is an optically thin reference line, i.e., Hα or [O III]. Both Lyα and nonresonant lines are therefore required to resolve the nature of the Lyα blobs. Middle column: however, the actual geometry of infall and outflow is unknown. For example, gas infall may take place in narrow streams (e.g., Dekel et al. 2009; Gao et al. 2010). Or, an outflow may be bipolar/highly collimated (e.g., M82; Bland & Tully 1988) or “clumpy” (Steidel et al. 2010). A large statistical sample of blob gas kinematics, like that presented in this paper, is required to constrain that geometry.

(A color version of this figure is available in the online journal.)
incidence, direction, speed, and isotropy of bulk gas motions in blobs.

In this paper, in order to overcome these geometry effects, we present new X-shooter optical and near-infrared (NIR) spectroscopy of six more Lyα blobs at $z \approx 2.3$. Note that the survey redshift of this Lyα sample has been carefully selected to allow all important rest-frame optical diagnostic lines (e.g., $[O\text{II}]$ λ3727, $[O\text{III}]$ λ5007, Hβ λ4868, Hα λ6563) to fall in NIR windows and to avoid bright OH sky lines and atmospheric absorption (Yang et al. 2009, 2010). With the resulting large sample of $\Delta v_{\text{Ly} \alpha}$ measurements (a total of eight), we determine the relative frequency of gas infall versus outflow.

Benefiting from X-shooter’s high spectral resolution and wide spectral coverage (3000 Å to 2.5 μm), we constrain the gas kinematics in Lyα blobs using three different tracers: (1) the offset of the Lyα profile with respect to a nonresonant nebular line, (2) the offset of an interstellar metal absorption line in the rest-frame UV with respect to the nebular emission line, and (3) a new indicator, the profile of the spectrally resolved $[O\text{III}]$ emission line.

This paper is organized as follows. In Section 2 we review our sample selection and describe the X-shooter observations and data reduction. In Section 3 we present the results from the X-shooter spectroscopy, confirming the Lyα blobs’ redshift (Section 3.2). We present one-dimensional (1D) and two-dimensional (2D) spectra in Sections 3.2 and 3.3, respectively. We briefly summarize the properties of individual systems in Section 3.4. In Section 3.5 we constrain the gas kinematics using the three different techniques noted above. In Section 3.5.1 we compare the Lyα profiles with the Hα or $[O\text{III}]$ line centers to discriminate between simple infall and outflow scenarios and present the $\Delta v_{\text{Ly} \alpha}$ statistics for the sample. In Section 3.5.2 we describe the interstellar absorption lines detected in three galaxies. In Section 3.5.3 we inspect the $[O\text{III}]$ emission-line profiles in detail to look for possible signatures of warm outflows. In Section 3.6 we constrain the H1 column density of an Lyα blob by comparing its Lyα profile with a simple RT model. In Section 3.7 we focus on an Lyα blob with a blueshifted Lyα component not directly associated with any detected galaxy, a possible marker of gas inflow. Section 5 summarizes our conclusions. Throughout this paper, we adopt the cosmological parameters: $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_k = 0.7$.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Sample

We observe six Lyα blobs from the Yang et al. (2010) sample. These targets were chosen such that they are not X-ray detected ($L(2–32$ keV) $< (0.3–4.2) \times 10^{43}$ erg s$^{-1}$; Lehmer et al. 2005; Luo et al. 2008), and thus are not obvious AGNs, as our primary goal is to cleanly detect gas infall or outflow. These six blobs lie in the Extended Chandra Deep Field South (ECDFS) and were discovered via deep narrowband imaging with the CTIO 4 m MOSAIC II camera and a custom narrowband filter (NB403). This filter has a central wavelength of $\lambda_c \approx 4030$ Å, designed for selecting Lyα-emitting sources at $z \approx 2.3$. In Figure 2 we show the images of these six Lyα blobs (CDFS-LAB06, 07, 10, 11, 12, 13, 14) at various wavelengths ($UBK$, Lyα, $Spitzer$ IRAC 3.6 μm, and Hubble Space Telescope (HST) F606W; Gawiser et al. 2006; Yang et al. 2010; Damen et al. 2011; Rix et al. 2004).

With X-shooter, we are targeting intermediate-luminosity ($L_{\text{Ly} \alpha} \sim 10^{43}$ erg s$^{-1}$) Lyα blobs: the higher Lyα blob ID indicates the lower Lyα luminosity in our sample. Our sample was obtained from a blind survey, so combined with the two brightest Lyα blobs presented in Yang et al. (2011), the full sample (a total of eight) spans a wide and more representative range of Lyα luminosity and size. Furthermore, the transition from compact Lyα emitters (LAEs; isophotal area of a few arcsec$^2$) to extended Lyα blobs (>10 arcsec$^2$) is continuous (Matsuda et al. 2004; Yang et al. 2010); thus, the gas kinematics for our faintest Lyα blobs might share the properties with those of bright LAEs. We refer readers to Yang et al. (2010) for details of the sample selection and to Yang et al. (2011) for the first results of our spectroscopic campaign.

2.2. UV-to-NIR Spectroscopy

We obtained high-resolution optical–NIR (3000 Å to 2.5 μm) spectra of the six Lyα blobs using X-shooter, a single object echelle spectrograph (Vernet et al. 2011), on the Very Large Telescope (VLT) UT2 telescope in service mode between 2010 November 6 and 2011 January 28. In Table 1 we summarize the X-shooter observations. In Figure 2 we show the location of the spectrograph slit on the sky, which was placed on UV-brightest galaxy or galaxies embedded at or near the Lyα blob center. These galaxies or galaxy fragments also lie in the region of brightest Lyα emission. Later, we assume that their redshifts mark the systemic redshift of the Lyα blob.

X-shooter consists of three arms (UVB, VIS, NIR), which cover the spectral ranges of 3000–5500 Å, 5500 Å to 1 μm, and 1 μm–2.5 μm, respectively. This enormous spectral coverage allows us to obtain both Lyα and Hα lines with a single exposure, in contrast to our previous approach (Yang et al. 2011) involving both optical and NIR spectrographs. Furthermore, X-shooter can detect at least one of the nebular lines ([OII], Hβ, [OIII], Hα), which will provide the systemic velocity of the embedded galaxies. Because at the redshift of our targets ($z \approx 2.3$) most of the emission lines of interest (Lyα, C iv, He ii, [OII], [OIII], Hα) are located in the UVB or NIR arms, we focus only on the UVB ($\lambda_{\text{rest}} = 900–1660$ Å) and NIR ($\lambda_{\text{rest}} = 3020–7500$ Å) part of spectra in this paper.

The observations were carried out over 8 nights and 14 observing blocks (OBs) of 1 hr duration each. The sky condition was either clear or photometric, and the guide camera seeing ranged from 0.6′′ to 1.2′′ with a median of 0.8′′ depending on the OB. We adopted 1′′ wide and 1/2′′ wide slits for UVB and NIR, yielding a spectral resolution of $R \approx 3300$ and $R \approx 3900$, respectively. The slit length is rather small (12′′) compared to typical long slits. In each OB, we placed the slit on a target using a blind offset from a nearby star. Using acquisition images taken after the blind offset, we estimate that the telescope pointing and position angle of the slit are accurate within 0′′:2 and 0′′:5 on average, respectively. The individual exposure times were 680 s and 240 s for UVB and NIR, respectively, and the telescope was nodded along the slit by ± 2′′ while keeping the science targets always on the slit but at different detector positions. Total exposure times were 0.8–3.2 hr depending on the targets. In general, we were always able to detect both Lyα and at least one of the optical nebular lines within one OB.

For accurate wavelength calibration, we took ThAr lamp frames through the pinhole mask right before the science exposures and at the same telescope pointing to compensate for the effect of instrument flexure. For the UVB arm, we obtained another ThAr arc frame at the end of each OB in order to verify the wavelength solution where no bright sky lines are available. Telluric standard stars (B type) were taken after or before the science targets with similar airmass to correct for atmospheric
absorption in the NIR. Spectrophotometric standard stars were observed with 5″ wide slits once during the night as a part of the observatory’s baseline calibration plan.

2.3. Data Reduction

We reduce the data using the ESO X-shooter pipeline (version 1.3.7). In the UVB arm, the frames are overscan-corrected, bias-subtracted, and flat-fielded with halogen and deuterium lamps. The sky background is then subtracted in the “stare” mode of the pipeline by modeling the sky in 2D as described in Kelson (2003). In the NIR arm, dark current and sky background are removed from each science frame by subtracting the dithered “sky” frame (“nodding” mode of the pipeline). Then, we flat-field the data and correct for cosmic-ray hits and bad pixels. In both arms, these flat-fielded, sky-subtracted frames were corrected for the spatial distortions using multi-pinhole arc frames.

Because we will compare the velocity centers of the Lyα and Hα lines, we carefully verify the wavelength calibration.
In the NIR, we compare the wavelength solutions obtained from the OH sky lines in the science frames to those from the daytime arc lamps and flexure-compensation frames, i.e., the pipeline solutions. In the UVB, we also compare the wavelength solutions obtained from the attached ThAr arc frames with the pipeline solutions. Our wavelength calibration is accurate within $\sim 4 \text{ km s}^{-1}$ in both arms. Furthermore, in the cases where we visited sources multiple times, all spectra agree with each other. These frames are then rectified (resampled) and combined to create 2D spectra. We collapse the 2D spectra in the wavelength direction to measure the spatial extent of each emission line. Then we extract 1D spectra from $[-2\sigma, +2\sigma]$ apertures, where $\sigma$ is the Gaussian width of the spatial profile. The aperture sizes are $2''-3.5''$ in the UVB and $1.5''-2.5''$ in the NIR depending on the target. Finally, the 1D spectra are corrected to heliocentric velocities and transformed to the vacuum wavelength.

3. RESULTS

3.1. Systemic Redshift from [O III] and Hα

Various emission lines in the UVB and NIR arms confirm that Lyα blobs lie at the survey redshift, $z \sim 2.3$. In addition to Lyα and Hα, we cover other UV emission lines and the nonresonant [O II] $\lambda\lambda3727,3729$, [O III] $\lambda\lambda4959,5007$, and Hβ
λ4861 lines. In Figure 4 we show 1D and 2D spectra of the six Lyα blobs. The first three columns show the rest-frame UV emission lines (Lyα, C iv, He ii) from the X-shooter UVB arm, and the remaining columns show the rest-frame optical nebular emission lines ([O iii], Hβ, [O iii], Hα) from the NIR arm.

Among the rest-frame optical nebular lines, the [O iii] line is the brightest and detected with highest signal-to-noise ratio (S/N) in all cases, partly owing to the low sky background and thermal instrument background in H band. We determine the systemic redshift using [O iii] doublets. In one case (CDFS-LAB14), the brighter [O iii] line (λ5007) falls on top of an OH sky line, thus making it impossible to determine the line center. In this case we used the fainter [O iii] line (λ4959). The vertical dashed lines in Figure 3 indicate the line centers determined by [O iii] lines, which are then overlaid on other emission-line profiles. As expected, we find that the line centers of all nonresonant emission lines agree well with each other, to within ∼10 km s⁻¹, showing that all of these lines are good indicators of systemic velocity. Thus, the brightest [O iii] line can serve as the best emission line to target for this survey redshift and instrument.

### 3.2. 1D Lyα Profiles

The Lyα profiles are significantly broad compared to the nonresonant lines (Hα and/or [O iii]) in six cases out of the sample of eight Lyα blobs, including two from our previous work (Yang et al. 2011). These integrated 1D profile shapes range from an asymmetric single-peaked profile (CDFS-LAB06, 07, 10), to a double-peaked profile with a stronger red peak (CDFS-LAB02, 13), to a double-peaked profile with two similar intensity peaks (CDFS-LAB14). The Lyα profiles of even this small sample show extremely diverse morphologies consistent with simple radiative model predictions (Verhamme et al. 2006, 2008; Dijkstra et al. 2006a) with varying geometry and outflow velocities (see also Matsuda et al. 2006; Saito et al. 2008; Weijmans et al. 2010).

The remaining two Lyα profiles are narrower relative to the [O iii] lines and show slightly extended wings (CDFS-LAB01 and 11). Note that the Lyα line width of CDFS-LAB01 is one of the largest among our sample, but the blue side of its Lyα profile agrees well with its Hα profile (Yang et al. 2011). While there is an underlying broad component in CDFS-LAB11, the width of the dominant narrow component is small, comparable to that of the [O iii] line (see Section 4.4). These are the two Lyα blobs where He ii and C iv emission lines are also detected, indicating that they contain a hard ionizing source, possibly an AGN. If photoionization by an AGN is indeed responsible for the He ii and C iv emission, and possibly the extended Lyα emission as well, the discovery of narrow Lyα profiles suggests that the Lyα blob gas is highly ionized, i.e., that the resonant scattering of Lyα is not effective enough to alter the profile significantly. We will further investigate the details of these He ii and C iv emission lines and the implications for AGNs in a future paper (Y. Yang, in preparation).

The fraction of double-peaked profiles is significant: ∼38% (3/8), which is roughly consistent with the findings for LBGs and LAEs at z = 2–3. Among LBGs, Kulas et al. (2012) find that ∼30% of LBGs with Lyα emission show multiple-peaked profiles. Yamada et al. (2012) also find that ∼50% of LAE’s profiles have multiple peaks.

### 3.3. 2D Lyα and [O iii] Profiles

Using 2D spectra, we detect the extended Lyα lines and identify the exact locations from which the Lyα or [O iii] line originates. In Figure 4 we show close-ups of the 2D [O iii] and Lyα profiles in the first and second columns, respectively. To aid the comparison between the [O iii] and Lyα profiles, we overlay the rough boundary of the [O iii] spectrum on each Lyα panel with ellipses. The third column shows the spatial profiles along the slit, i.e., collapsed in the wavelength direction. The last column shows the 1D Lyα and [O iii] profiles that are extracted from the different parts of the slit, as indicated with vertical arrows in the third column.

In four cases (CDFS-LAB06, 10, 13, 14), the Lyα spectrum is spatially extended relative to the [O iii] line, confirming the narrowband imaging result that the Lyα-emitting gas extends beyond the embedded galaxies that are probably responsible for the [O iii] emission. Note that the X-shooter...
Figure 3. One-dimensional integrated line profiles for the rest-frame UV (Ly$\alpha$, C$\text{iv}$, He$\text{ii}$) and optical ([O$\text{ii}$], H$\beta$, [O$\text{iii}$], H$\alpha$) lines detected in the LOS toward the central, embedded galaxies. The velocity ranges are $\pm 1000$ km s$^{-1}$ and $\pm 550$ km s$^{-1}$ for the UV and optical spectra, respectively. The y-axis ticks are spaced every $1 \times 10^{-17}$ and $0.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ for the rest-frame UV and optical spectra, respectively. At the bottom of each spectrum, we show the 2D spectra with 4$''$ or 6$''$ width. The vertical lines indicate the systemic velocity determined from the [O$\text{iii}$] line. The other [O$\text{ii}$], H$\alpha$, and H$\beta$ lines are consistent with the [O$\text{iii}$] center, suggesting that all provide a good reference to the center of the Ly$\alpha$ blob defined by the galaxy or galaxies embedded in the blob core. In all cases, the Ly$\alpha$ lines are broader than the H$\alpha$ or [O$\text{iii}$] lines, implying that the Ly$\alpha$ is resonantly scattered by an optically thick medium. In CDFS-LAB11, the most compact of the sources, which is also detected in C$\text{iv}$ and He$\text{ii}$, the Ly$\alpha$ line is sharply peaked with broad wings. (A color version of this figure is available in the online journal.)

Spectroscopy reaches a much shallower Ly$\alpha$ surface brightness limit ($\sim 1.5-3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$) than the narrow-band imaging ($\sim 5 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, 3$\sigma$ limit).

In two Ly$\alpha$ blobs (CDFS-LAB06 and 10), the [O$\text{m}$] lines are spatially resolved. However, there is no evidence that the [O$\text{m}$] or H$\alpha$ lines are extended beyond the UV continuum emission arising from stars in the embedded galaxies seen in Figure 1. Deeper NIR spectroscopic, preferentially IFU, observations are required to better define the spatial extent of these lines and to measure the spatially resolved gas kinematics. Throughout the paper, we assume that the [O$\text{m}$] and H$\alpha$ lines originate from the central embedded galaxies, not from the extended
Figure 4. Two-dimensional [O\textsc{iii}] (first column) and Ly\textalpha{} (second column) spectra for Ly\textalpha{} blobs at $z \sim 2.31$. The Ly\textalpha{} spectra were smoothed to enhance low surface brightness features. Contours bounding the [O\textsc{iii}] spectra are overlaid on the Ly\textalpha{} panels to aid comparison between the two lines. The third column shows the spatial profile along the slits (collapsed in the spectral direction). The slit profiles are normalized for easy comparison, so the plots show different surface brightness scales on the top and bottom axes as indicated by different colors. The last column shows the extracted 1D spectra from different regions defined by the arrows in the third column. The Ly\textalpha{} profiles are significantly broader than the [O\textsc{iii}] lines owing to resonant scattering. Spectra toward three Ly\textalpha{} blobs show spatially extended Ly\textalpha{} spectra (CDFS-LAB06, 10, 14). In CDFS-LAB06, both [O\textsc{iii}] and Ly\textalpha{} are extended owing to a neighboring galaxy to the north. In the other two Ly\textalpha{} blobs, Ly\textalpha{} is more extended than the compact [O\textsc{iii}] line, implying that Ly\textalpha{} is originating from the gas outside the galaxies.

(A color version of this figure is available in the online journal.)
Lyα-emitting gas, and thus that their line centers represent the systemic velocity of the Lyα blob. In the next section we briefly describe individual systems in detail.

### 3.4. Notes for Individual Objects

#### 3.4.1. CDFS-LAB06

CDFS-LAB06 has two rest-frame UV sources with small separation (0′′8; 6.5 kpc) in the HST image (Figure 2). Both components (or clumps) were placed in the X-shooter slit and are detected in [O III] and Lyα (Figure 4). These two sources are separated by only ~50 km s⁻¹ in velocity space; thus, it is not clear whether they belong to one galaxy or are interacting with each other. We adopt the redshift of the brighter UV source as the systemic velocity of CDFS-LAB06. The Lyα emission detected in the spectrum (between Δv = −1″ and +2″) is spatially extended owing to the other galaxy, so it does not represent the IGM or circumgalactic medium (CGM).

#### 3.4.2. CDFS-LAB07

The galaxy within CDFS-LAB07 has a bar-like morphology in the HST image with which we align the slit. This galaxy or galaxy fragments were marginally resolved in the [O III] emission line. All optical nebular emission lines ([O III], Hβ, [O II], and Hα) are detected. Faint UV continuum emission is marginally detected, allowing us to study the gas kinematics with metal absorption lines (Section 3.5.2). The [O III] and Hα lines show asymmetric profiles extending toward the blue. This profile can be fitted with a narrow Gaussian component at the velocity center superposed on the blueshifted broad component (Section 3.5.3).

#### 3.4.3. CDFS-LAB10

CDFS-LAB10 is the most puzzling and complex source in the X-shooter sample. The Lyα emission in the narrowband image is elongated over 10″ (~80 kpc). In the NIR spectrum, three sources are detected: two with [O III] emission lines (galaxies B and C), and the other (galaxy A) with very faint continuum (Figure 5). This NIR continuum source (galaxy A) is located at the slit center, while the strongest [O III]-emitting source (galaxy C) is offset by ~1″ toward northeast from the center and barely detected in the HST image. The 2D [O III] spectrum of galaxy C shows a velocity shear indicative of a rotating disk. In the 2D Lyα spectrum, there are also three distinct components. Although the 1D Lyα spectrum of the entire blob looks single-peaked with a broad line width, it is in fact composed of these three components. We will investigate these various emission-line and continuum sources in Section 3.7.

#### 3.4.4. CDFS-LAB11

There are one compact UV source at the slit center and a diffuse emission toward northeast in the HST image. It appears that the [O III] emission originates from the central compact source. Unlike commonly observed broad Lyα profiles found in Lyα blobs and LAEs, CDFS-LAB11 has a peculiar Lyα profile that is almost symmetric and narrow. As will be discussed in Section 4.4, both narrow and underlying broad components are required to explain the Lyα profile. The Lyα is redshifted against Hβ by a small amount: Δv_{Lyα} = 84 ± 6 km s⁻¹. Both [O III] and Lyα are spatially compact (Figure 4). Both C iv λ1546 and He ii λ1640 emission lines are also detected (Figure 3), implying the presence of a hard ionizing source. A total of two Lyα blobs from our ECDFS sample (CDFS-LAB01 and 11; 2/8) show these emission lines. Note that C iv and narrow He ii line emission is commonly detected in bright Lyα blobs (Dey et al. 2005; Scarlata et al. 2009; Prescott et al. 2009; Yang et al. 2011), while the nature of the hard ionizing source is unknown.

#### 3.4.5. CDFS-LAB13

CDFS-LAB13 has a double-peaked profile with a stronger red peak and asymmetric [O III] profile (Section 3.5.3). Lyα in CDFS-LAB13 is likely more extended, but the low S/N of the [O III] line makes the comparison difficult. There are multiple galaxy fragments in the HST UV continuum image, but they were not spatially resolved in the X-shooter observations.
Table 2
Properties of Lyα Line

| Name            | Red Peak                      | Blue Peak                      | Profile
|-----------------|-------------------------------|-------------------------------|---------|
|                 | $\Delta v_{Ly\alpha}$ (km s$^{-1}$) | $\sigma_v$ (km s$^{-1}$) | Flux ($10^{-17}$ erg s$^{-1}$ cm$^{-2}$) | $v_{\text{offset}}$ (km s$^{-1}$) | $\sigma_v$ (km s$^{-1}$) | Flux ($10^{-17}$ erg s$^{-1}$ cm$^{-2}$) |
|-----------------|-------------------------------|-------------------------------|---------|
| CDFS-LAB01      | $-65 \pm 20$                | $228 \pm 14$                | $45.2 \pm 1.6$                         | ...                      | ...                      | ...                      |
| CDFS-LAB11      | $84 \pm 6$                  | $79 \pm 3$                  | $26.5 \pm 0.7$                         | ...                      | ...                      | ...                      |
| CDFS-LAB10      | $247 \pm 147$               | $425 \pm 97$                | $18.7 \pm 2.4$                         | $-277 \pm 8$            | $43 \pm 8$              | $4.0 \pm 0.5$            |
| CDFS-LAB13      | $152 \pm 14$                | $100 \pm 9$                 | $13.7 \pm 0.7$                         | ...                      | ...                      | ...                      |
| CDFS-LAB06      | $123 \pm 15$                | $150 \pm 13$                | $25.7 \pm 1.3$                         | $-342 \pm 117$          | $273 \pm 137$           | $3.3 \pm 1.3$            |
| CDFS-LAB02      | $211 \pm 43$                | $192 \pm 35$                | $8.2 \pm 0.9$                          | ...                      | ...                      | ...                      |
| CDFS-LAB07      | $181 \pm 15$                | $168 \pm 10$                | $22.2 \pm 0.8$                         | ...                      | ...                      | ...                      |
| CDFS-LAB14      | $371 \pm 34$                | $202 \pm 24$                | $18.0 \pm 1.2$                         | $-404 \pm 17$           | $176 \pm 18$            | $12.4 \pm 1.1$           |

Notes:

a Corrected for the instrumental profile in the UVB ($\sigma_{\text{inst}} \approx 39$ km s$^{-1}$).
b Line morphology: (1) single (red) peak, (2) double-peaked profile with a stronger red peak, (3) double-peaked profile with similar intensity peaks.

The profiles of CDFS-LAB01 and 11 are not significantly broader than the [O iii] lines.

The profile of CDFS-LAB10 is composed of multiple components (Figure 4). Here the total integrated profile is used for the fit.

3.4.6. CDFS-LAB14

In the HST and narrowband images, a UV source is located at the upper boundary of the Lyα emission contours. In the X-shooter 2D spectra (Figure 4), the [O iii] line is centered on this UV continuum source and Lyα is more extended toward the south in agreement with narrowband imaging. CDFS-LAB14 is one of two cases where extended Lyα emission is well detected in the spectroscopy. The Lyα profile has two peaks with similar intensities. The peak separation narrows as the slit distance from the central galaxy increases. Faint UV continuum is also detected at the location of the UV source, allowing us to measure outflow speed from metal absorption lines (Section 3.5.2). Combining the Lyα and the absorption profiles, we will put constraints on the gas kinematics and the neutral column density of this system (Section 3.6). [O iii] has a broad wing on top of the narrow component (Section 3.5.3).

3.5. Gas Kinematics

In this section we constrain the gas kinematics in the Lyα blobs using three different techniques and compare those results. First, for the six blobs in the X-shooter survey, we compare the optically thick Lyα and nonresonant [O iii] line (either $\lambda 5007$ or 39959 in the case of CDFS-LAB14) to measure Lyα velocity offsets from the systemic velocity of the Lyα blobs. For the two Lyα blobs from our previous work (CDFS-LAB01A and 02; Yang et al. 2011), where an [O iii] line is unavailable, we use Hα. As mentioned previously, the line centers of both [O iii] lines and Hα are all consistent. Second, we constrain the outflow speed from the interstellar metal absorption lines in three galaxies where we are able to detect the rest-frame UV continuum in the spectrum. Lastly, we present a new tracer of kinematics in four Lyα blobs, characterizing the breadth and asymmetry of the [O iii] line profile. Note that while we detect an asymmetric wing in some [O iii] line profiles, it does not affect the line centroid, which is essential in determining the systemic velocity in the first technique above.

3.5.1. Lyα–[O iii] Offset

We compare the peak of each Lyα profile with the center of a nonresonant nebular emission line, particularly [O iii]. Throughout the paper, the Lyα–Hα and Lyα–[O iii] offsets are used interchangeably to represent the Lyα offset from the systemic velocity: $\Delta v_{Ly\alpha}$. Figure 5 shows eight Lyα profiles from this work and from Yang et al. (2011), plotted with increasing $\Delta v_{Ly\alpha}$.

Because Lyα spectra are somewhat noisy because of the small spectral dispersion (20–30 km s$^{-1}$ per pixel), we measure $\Delta v_{Ly\alpha}$ using the following two methods. First, we measure the velocity of the Lyα peak after smoothing the spectra with a Gaussian filter with FWHM = 90 km s$^{-1}$, corresponding to our velocity resolution. Second, we fit the red peaks with an asymmetric Gaussian function, which consists of two Gaussian functions with different FWHMs being joined at the center. The two measurements agree to within $\sim 50$ km s$^{-1}$, except for CDFS-LAB06, where the second method gives $\Delta v_{Ly\alpha} = 120$ km s$^{-1}$ compared to 320 km s$^{-1}$ from simple smoothing owing to the very sharp edge at the blue side of the Lyα profile. We adopt the second measurements in this paper and show these fits in Figure 5 and Table 2. None of the conclusions in this paper are affected by this choice.

Figure 6 shows the distribution of $\Delta v_{Ly\alpha}$ of the 8 Lyα blob galaxies in comparison with 41 LBGs that have both Hα and Lyα spectra (Steidel et al. 2010). Because the spectral resolutions of our Lyα spectra obtained from VLT/X-shooter and Magellan/MagE are higher than those of the Lyα profiles of the LBGs (FWHM $\sim 370$ km s$^{-1}$), we test whether the different spectral resolutions affect the Lyα blob–LBG comparison. We repeat the measurement of $\Delta v_{Ly\alpha}$ after convolving our Lyα profiles to the spectral resolution of the LBG sample. The $\Delta v_{Ly\alpha}$ values change by a negligible amount (only $\pm 50$ km s$^{-1}$) except for CDFS-LAB02, where $\Delta v_{Ly\alpha}$ increases by $+100$ km s$^{-1}$ because of its sharp red peak. Therefore, we conclude that the $\Delta v_{Ly\alpha}$ distributions of Lyα blobs and LBGs can be compared directly.

The $\Delta v_{Ly\alpha}$ distribution for galaxies within our Lyα blobs reveals smaller velocity offsets than typical of LBGs, confirming previous claims (Yang et al. 2011, see also McLinden et al. 2013). Galaxies within blobs have $\Delta v_{Ly\alpha} = -60 \rightarrow +400$ km s$^{-1}$ with an average of $\langle \Delta v_{Ly\alpha} \rangle = 160$ km s$^{-1}$, while LBGs at similar redshifts have $\Delta v_{Ly\alpha} = 250$–900 km s$^{-1}$ with $\langle \Delta v_{Ly\alpha} \rangle = 445$ km s$^{-1}$.

The remaining question is how to interpret these small $\Delta v_{Ly\alpha}$ values. Two possibilities are as follows: (1) $\Delta v_{Ly\alpha}$ is a proxy for the gas outflow velocity ($v_{\exp}$), suggesting that the outflows here are weaker than in other star-forming galaxies (SFGs) at $z = 2$–3 (Verhamme et al. 2006), or (2) there is less neutral gas...
Therefore, we obtain higher-S/N struggles to detect their continuum for absorption-line studies.

The vertical dot-dashed line indicates the average of the LBG sample, \( \langle \Delta_{\text{Ly}\alpha} \rangle = 455 \text{ km s}^{-1} \). The \( \Delta_{\text{Ly}\alpha} \) offsets for blob galaxies are generally smaller than those of LBGs. If \( \Delta_{\text{Ly}\alpha} \) is a proxy for the outflow velocity of neutral material, the outflow speeds in Ly\( \alpha \) blobs are smaller than for typical star-forming galaxies at \( z = 2-3 \).

(A color version of this figure is available in the online journal.)

Figure 6. Distribution of \( \Delta_{\text{Ly}\alpha} \) for eight Ly\( \alpha \) blob galaxies in comparison with those of 41 LBGs (Steidel et al. 2010). The vertical dot-dashed line indicates the average of the LBG sample, \( \langle \Delta_{\text{Ly}\alpha} \rangle = 455 \text{ km s}^{-1} \). The \( \Delta_{\text{Ly}\alpha} \) offsets for blob galaxies are generally smaller than those of LBGs. If \( \Delta_{\text{Ly}\alpha} \) is a proxy for the outflow velocity of neutral material, the outflow speeds in Ly\( \alpha \) blobs are smaller than for typical star-forming galaxies at \( z = 2-3 \).

(A color version of this figure is available in the online journal.)

close to the systemic velocity of the embedded galaxies (Steidel et al. 2010), and \( \Delta_{\text{Ly}\alpha} \) is independent of the outflow speed. We discussed the caveats associated with interpreting \( \Delta_{\text{Ly}\alpha} \) in Yang et al. (2011) and revisit this issue in Section 4.2.

In the direction of the embedded galaxies, we do not find any Ly\( \alpha \) profile that is blue peak dominated, i.e., \( \Delta_{\text{Ly}\alpha} < 0 \text{ km s}^{-1} \). Therefore, there is no evidence along these LOSs for infalling gas (but see Section 3.7). While the statistics are still small, we place an upper limit on the covering factor of infalling gas (if any) detectable with the \( \Delta_{\text{Ly}\alpha} \) technique. Here the covering factor of any inflowing streams like those predicted by cold-mode accretion (Kereš et al. 2005; 2009; Dekel et al. 2009) must be less than \( \sim 13\% \) (1/8). We further discuss the covering factor of cold streams in Section 4.1.

3.5.2. Interstellar Metal Absorption Lines

While strong emission lines such as Ly\( \alpha \) and [O\text{III}] are relatively easy to detect, interstellar metal absorption lines provide a less ambiguous way to measure the outflow velocity of neutral gas lying in front of the galaxies targeted with our spectroscopic slit. However, owing to the faint UV continuum \( (B = 23.8-26.5 \text{ mag}) \) of our targets, even an 8 m telescope struggles to detect their continuum for absorption-line studies. Therefore, we obtain higher-S/N absorption-line profiles by stacking several lines in each galaxy. Our aim is to test the mild outflow interpretation of our \( \Delta_{\text{Ly}\alpha} \) results by comparing the velocity offset of the stacked ISM absorption profile with the systemic velocity of the galaxy: \( \Delta_{\text{IS}} \).

Among the six Ly\( \alpha \) blobs, only the UV continua of the galaxies in CDFS-LAB07 and CDFS-LAB14 have S/N higher than 1.5 per spectral pixel (\( \sim 20-30 \text{ km s}^{-1} \)), allowing us to marginally extract the absorption profiles. The top panel of Figure 7 shows the rest-frame UV spectra of these two galaxies in comparison with the LBG composite (Shapley et al. 2003). For comparison, we also show the boxcar-smoothed spectra over 20 pixels, corresponding to a velocity width of 450–600 km s\(^{-1} \). While it is difficult to identify the absorption lines in the unbinned spectra, the smoothed spectra show a good match to the composite spectrum, revealing several low- and high-ionization lines.

As suggested above, it is still difficult to measure individual absorption-line profiles, so we stack the five low-ionization lines, Si\( \text{II} \lambda 1260, \text{O} \text{I} \lambda 1302, \text{C} \text{II} \lambda 1334, \text{Si} \text{II} \lambda 1526, \) and Al\( \text{II} \lambda 1670 \), to increase the S/N. We do not include the C\( \text{IV} \) and Si\( \text{IV} \) lines in the stacking, as these high-ionization lines are contaminated with broader absorption features arising from stellar winds from massive stars (Shapley et al. 2003), which are hard to remove in our low-S/N spectra. Furthermore, it is possible that these high-ionization lines trace different states of gas, while the low-ionization lines show similar profiles (Steidel et al. 2010). In the bottom panel of Figure 7 we show the stacked absorption profiles for three galaxies, including the reanalyzed CDFS-LAB02 spectrum that we obtained earlier with Magellan/MagE (Yang et al. 2011).

The stacked absorption profiles here are consistent with weaker outflows than required by the super/hyperwind hypothesis for Ly\( \alpha \) blob emission (Taniguchi & Shioya 2000). These profiles are also consistent with the interpretation of small \( \Delta_{\text{Ly}\alpha} \) indicating small outflow speed, as discussed in Section 3.5.1.

In two galaxies (within CDFS-LAB02 and 07), the absorption profiles have minima around \( -200 \text{ km s}^{-1} \) and might extend up to \( -500 \text{ km s}^{-1} \), although the exact end of the profile is uncertain owing to the low S/N. The shapes of these two absorption profiles are similar to those of typical SFGs (i.e., LBGs) at the same epoch (Steidel et al. 2010), and the implied outflow velocities are comparable to or slower than those in the LBGs. By fitting a Gaussian profile, we obtain \( \Delta_{\text{IS}} = -177 \pm 31 \text{ km s}^{-1} \) and \( -236 \pm 31 \text{ km s}^{-1} \) for CDFS-LAB02 and CDFS-LAB07, respectively. We do not find any redshifted absorption component, which is consistent with the absence of any blueshifted Ly\( \alpha \) emission line associated with these galaxies.

In contrast, the profile of CDFS-LAB14’s galaxy has a minimum at \( v \approx 0 \text{ km s}^{-1} \) (\( \Delta_{\text{IS}} = -59 \pm 32 \text{ km s}^{-1} \)) without any significant blueshifted (outflowing) component. While the other two profiles terminate roughly at \( v \approx 0 \text{ km s}^{-1} \), CDFS-LAB14’s profile extends to \( v > 0 \text{ km s}^{-1} \). Thus, its ISM absorption and Ly\( \alpha \) profiles are both consistent with the simple RT model expectation that a symmetric, double-peaked Ly\( \alpha \) profile should emerge from static gas or the absence of bulk motions. Furthermore, the absorption profile is almost saturated, indicating that the column density in this Ly\( \alpha \) blob could be higher than for the other two systems. We will place a constraint on the Hi column density of its Ly\( \alpha \)-emitting gas in Section 3.6.

For CDFS-LAB14, the location of the dip between the blue and red Ly\( \alpha \) velocity peaks changes little for the two extraction apertures shown in Figure 4: one along the LOS toward the embedded galaxy (the [O\text{III}] source), and the other encompassing the spatially extended gas around \( \Delta \theta = -0.5'' \). Note that such a trough between Ly\( \alpha \) peaks is often interpreted as arising from absorption by the neutral media between the Ly\( \alpha \) source and observers. For example, Wilman et al. (2005) claim that their IFU spectra of an Ly\( \alpha \) blob (SSA22-LAB02; Steidel blob 2) suggest that the Ly\( \alpha \) emission is absorbed by a foreground slab of neutral gas swept out by a galactic-scale outflow. More recently, Martin et al. (2014) show instead that the absorption troughs in the Ly\( \alpha \) emission are actually located at the systemic velocity determined by the [O\text{III}] emission line, i.e., there are negligible velocity offsets between any foreground screen and the systemic velocity. CDFS-LAB14 also demonstrates that a
Figure 7. Top: rest-frame UV spectra of two embedded blob galaxies with S/N > 1.5 pixel$^{-1}$ (CDFS-LAB07 and 14). The noisy gray lines show the unbinned spectra, and the thick (blue) solid lines represent the boxcar-smoothed spectra with $\sim 500$ km s$^{-1}$. The thin (red) lines indicate the LBG composite spectrum (Shapley et al. 2003), showing that several absorption lines are detected in these two galaxies. Bottom: stacked absorption profiles for three galaxies, including CDFS-LAB02, which we have previously studied (Yang et al. 2011), and the two above. The velocity is relative to the systemic velocities determined from the [O\textsc{iii}] or H$\alpha$ lines. For each galaxy, we stack five low-ionization lines (two Si\textsc{ii}, O\textsc{i}, C\textsc{ii}, Al\textsc{ii}) to boost the S/N. The gray and blue lines are the unbinned spectra and the spectra binned over 4 pixels, respectively. The orange dot-dashed lines are the Gaussian fits. Two galaxies (CDFS-LAB02 and 07) have small outflow velocities around $\Delta v_{IS} = -177 \pm 31$ km s$^{-1}$ and $-236 \pm 31$ km s$^{-1}$, respectively. The profiles may extend up to $-500$ km s$^{-1}$, but there is no sign of strong outflows ($\sim 1000$ km s$^{-1}$). The absorption profile of another galaxy (CDFS-LAB14) is symmetric around $v \sim 0$ km s$^{-1}$ ($\Delta v_{IS} = -59 \pm 32$ km s$^{-1}$), suggesting no significant bulk motion. Therefore, at least for three galaxies that have Ly$\alpha$, [O\textsc{iii}] or H$\alpha$, and ISM absorption profiles, there is no fast ($\sim 1000$ km s$^{-1}$) outflowing material along the LOS, which excludes the super/hyperwind model (Taniguchi & Shioya 2000) for extended Ly$\alpha$ emission in Ly$\alpha$ blobs. The outflows here are similar to or weaker than in LBGs.

(A color version of this figure is available in the online journal.)

coherent velocity trough, at least over a $\sim 10$ kpc scale, can arise entirely from complicated RT effects even if there are no significant bulk motions in the Ly$\alpha$-emitting gas.

3.5.3. Broadening and Asymmetry in [O\textsc{iii}] Profile

The central galaxies in four Ly$\alpha$ blobs (CDFS-LAB06, 07, 13, 14) show a broad and/or shifted underlying component to the [O\textsc{iii}] profile, which provides additional constraints on the kinematics of warm ionized gas in the vicinity of the galaxies. To the authors’ knowledge, this is the first detection of broadened, asymmetric [O\textsc{iii}] profiles from narrowband-selected Ly$\alpha$-emitting galaxies at high redshifts, demonstrating that high spectral resolution is required to fully exploit the NIR spectroscopy of Ly$\alpha$ galaxies.

We emphasize again that these broad underlying components, even when shifted in velocity, do not affect our measurements of [O\textsc{iii}] line centers, because the [O\textsc{iii}] flux density at the core is dominated by the narrower component, which is likely to arise from nebular regions in the embedded galaxy. As discussed previously, the line centers determined from other nonresonant emission lines (e.g., H$\alpha$ and H$\beta$) agree to within $\sim 10$ km s$^{-1}$. Therefore, our measurements of systemic velocity, critical for determining $\Delta v_{Ly\alpha}$ and $\Delta v_{IS}$, remain unchanged.

In Figure 8 we show close-ups of the [O\textsc{iii}] profiles. In CDFS-LAB11, which has the narrowest and the most symmetric Ly$\alpha$ profile, the [O\textsc{iii}] line is also symmetric. CDFS-LAB10 is excluded from the following analysis because its [O\textsc{iii}] line is elongated in position–velocity space, suggesting some velocity shear, and the neighboring galaxy (CDFS-LAB10A) makes it difficult to reliably extract its profile (see Section 3.7 for more details of this system). In the remaining four Ly$\alpha$ blobs, the [O\textsc{iii}] profile has either an asymmetric wing (CDFS-LAB06, 07, 13) or a symmetric broad component or components (CDFS-LAB14). Note that the CDFS-LAB06 profile in Figure 8 also includes the light from a faint neighbor or clump to the northwest that is slightly blueshifted ($\sim 50$ km s$^{-1}$). Therefore,
Figure 8. Close-up of the [O\textsc{iii}] profiles of six galaxies embedded in Ly\(\alpha\) blobs. The dot-dashed and solid lines indicate the individual Gaussian components and the combined profiles, respectively. Four galaxies (CDFS-LAB06, 07, 13, 14) show a broad component in addition to a narrow component, suggesting a warm, ionized outflow. These broad components are slightly blue- or redshifted against the brighter narrow components in three galaxies (CDFS-LAB06, 07, and 13), making the [O\textsc{iii}] lines asymmetric. CDFS-LAB11 shows an almost symmetric single component only. CDFS-LAB10’s profile is contaminated by a neighbor. The maximum blueshifted velocity, which ranges from \(\Delta v_{\text{max}} = 50\) to 220 km s\(^{-1}\), is smaller than those found in \(z \sim 2\) SFGs (380–1000 km s\(^{-1}\); Genzel et al. 2011) and consistent with our outflow speed estimates from \(\Delta v_{\text{Ly}\alpha}\) and the ISM absorption lines. (A color version of this figure is available in the online journal.)

Owing to the low S/N in the \(K\) band, we are not able to reliably measure the broad-line components from permitted lines such as H\(\alpha\) or H\(\beta\), but similar broad wings are also present in the H\(\alpha\) profiles of at least two galaxies (CDFS-LAB07 and 14; see Figure 3).

What is the mechanism responsible for the broad component in the [O\textsc{iii}] profiles? A broad component with a larger line width (\(\sigma_v\)) of a few hundred km s\(^{-1}\) is generally interpreted as a signature of starburst-driven galactic winds and often observed in local dwarf starbursts (e.g., Westmoquette et al. 2007) and in local ultraluminous infrared galaxies (ULIRGs; e.g., Soto et al. 2012). While broad components in forbidden lines such as [O\textsc{iii}] are not related to the broad-line region of Type 1 AGNs, they might still arise from the shocked narrow-line region in AGNs. However, the composite spectrum of all of our X-shooter sample has a line ratio \(\log([\text{N\textsc{ii}}]/H\alpha) < -0.88\), excluding any significant contribution from AGNs (Y. Yang et al., in preparation). Furthermore, in CDFS-LAB11, whose He\textsc{ii} and C\textsc{iv} emission lines hint at the presence of an AGN, no broad component is detected.

At high redshift (\(z \gtrsim 2\)), broadened emission lines were first reported by Shapiro et al. (2009). They found that the stacked spectrum of \(z \sim 2\) SFGs shows broad (FWHM \(\sim 550\) km s\(^{-1}\)) emission underneath the H\(\alpha+[\text{N\textsc{ii}}]\) line complex. More recently, stacked spectra of higher-S/N data have revealed that the broad emission is spatially extended over a half-light radius (Newman et al. 2012). Broad emission lines are now detected from individual SFGs and even from giant star-forming

the somewhat redshifted wing of CDFS-LAB06 is not due to this contamination.

To extract the underlying broad components, we fit the line profiles with two Gaussian functions (the two dot-dashed lines in Figure 8) and list the results in Table 3. In the Appendix, we describe our fitting procedures in detail. We adopt a two-component fit for simplicity and for comparison with previous studies (although we cannot rule out the possibility that the velocity wings consist of multiple small narrow components). The line center of the broad component (\(v_{\text{broad}}\)) agrees with that of the narrow component in CDFS-LAB14, is blueshifted in CDFS-LAB07 and in CDFS-LAB13, and is marginally redshifted in CDFS-LAB06. The widths of the broad components, corrected for the instrumental resolution, are relatively small: \(\sigma_{v_{\text{broad}}} = 45–120\) km s\(^{-1}\) (FWHM = 100–280 km s\(^{-1}\)), which would not be detected with lower-resolution or lower-S/N spectra.

To quantify the contribution of the broad components, we measure the “broad-to-narrow ratio” (\(F_{\text{broad}}/F_{\text{narrow}}\)), which is defined as the ratio of the flux in the broad [O\textsc{ii}] emission line to the flux in the narrow component. Because the fluxes in the two Gaussian components are anti-correlated with each other, this ratio has large uncertainties. We also list the “broad flux fraction” (\(f_{\text{broad}}\)), which is the ratio of the flux in broad emission to the total [O\textsc{iii}] flux (\(F_{\text{broad}}/F_{\text{total}}\)). The broad emission component is significant, with \(F_{\text{broad}}/F_{\text{narrow}} = 0.4–0.8\) constituting 30%–45% of the total [O\textsc{iii}] line flux (although the uncertainties are fairly large). The measurements of the underlying components are highly dependent on the S/N of spectra.
clumps within them (Genzel et al. 2011). Genzel et al. (2011) show that $z \sim 2$ SFGs show broad wings of Hα emission with FWHM $\sim 300–1000$ km s$^{-1}$ ($\sigma_{\text{broad}} \sim 125–425$) and employ the maximum blueshifted velocity, $\Delta v_{\text{max}} = |v_{\text{broad}} - 2\sigma_{\text{broad}}|$, as a proxy of the outflow speed, finding that SFGs have $\Delta v_{\text{max}} \approx 380–1000$ km s$^{-1}$. Thus, the broad component in these galaxies is attributed to powerful galactic outflows. For compact LAEs, although there is an increasing number of detections of [O III] and Hα (e.g., McLinden et al. 2011; Finkelstein et al. 2011; Nakajima et al. 2012; Hashimoto et al. 2013), broad emission in [O III] has not been reported so far, perhaps owing to the lower spectral resolution or lower S/N of these studies. Therefore, at the moment, it is not clear whether the broad component and sometimes line asymmetry that we observe in Lyα blobs are general properties of Lyα-selected galaxies.

As in local ULIRGs and in high-redshift SFGs, the detection of a broad component in the [O III] profile here suggests warm ionized outflows from the galaxies within Lyα blobs, presumably driven by supernovae and stellar winds. However, while the flux fraction of our broad emission is comparable to those of SFGs, the broad [O III] wings are narrower ($\sigma_{\text{broad}} = 45–120$ km s$^{-1}$) and the inferred velocities much smaller ($\Delta v_{\text{max}} = 150–260$ km s$^{-1}$). Therefore, at face value, the warm ionized outflows from the Lyα blobs galaxies are not as strong as those in SFGs at similar redshift. Furthermore, these estimates for outflow velocity are roughly consistent with the values obtained from our two kinematic measures, $\Delta v_{\text{13-14}O}$ and $\Delta v_{\text{IS}}$ (Sections 3.5.1 and 3.5.2), independently discounting shock heating via super/hyperwinds as a viable powering mechanism.

### 3.6. Constraint on H i Column Density

Constraining the physical state of the Lyα-emitting gas in an Lyα blob is a critical step to understand its emission mechanism and to directly compare the observations with the numerical simulations (e.g., Faucher-Giguère et al. 2010; Rosdahl & Blaizot 2012; Cen & Zheng 2013; Latif et al. 2011), which predict the Lyα emissivity maps from the gas density, temperature, and UV radiation fields. In this section, as a first step, we estimate the H i column density of an Lyα blob, CDFS-LAB14.

The $\Delta v_{\text{13-14}O}$ and $\Delta v_{\text{IS}}$ analyses of CDFS-LAB14 are consistent with a simple RT model in which the surrounding gas is static or without bulk motions. The third kinematic indicator, the [O III] profile, which suggests a mild outflow, either contradicts the other indicators or is sensitive to gas in a different state (e.g., warm, ionized instead of cold, neutral) or distribution (e.g., around galaxy instead of in galaxy). Here we use the Lyα emission and ISM absorption-line profiles to place a constraint on the amount of neutral hydrogen in this Lyα blob. Ultimately, by comparing the Lyα profile with detailed RT models, one could extract a wealth of information, including outflow speed, optical depth, and column density (e.g., Verhamme et al. 2008). We defer such detailed analysis to future papers and consider the most simplistic case in this section.

Lyα line transfer in an extremely thick medium of neutral gas has been studied over many decades, and the analytic solutions for simple geometries (like a static homogeneous slab or uniform sphere) are known (Harrington 1973; Neufeld 1990; Dijkstra et al. 2006a). We consider a simple geometry in which an Lyα source is located at the center of a static homogeneous slab with optical depth of $\tau_0$ from the center to the edge. Because Lyα photons generated at the center escape the system through random scattering in the frequency space, the emergent line spectrum is a double-peaked profile with its maxima at $\Delta v_{\text{peak}} \equiv (v - v_0)/v_D = \pm 1.173(\alpha_{\text{D0}})^{1/3}$, where $x$ represents the line frequency in units of Doppler width $v_D$, $\alpha$ and $v_0$ are the Voigt parameter and Lyα optical depth at the line center, respectively (Dijkstra et al. 2006a). In terms of velocity, the separation between blue and red peaks with the same intensity is

$$
\Delta v_{\text{blue–red}} = 424 \text{ km s}^{-1} \left( \frac{b}{12.85 \text{ km s}^{-1}} \frac{N_{\text{H}i}}{10^{20} \text{ cm}^{-2}} \right)^{1/3}, \quad (1)
$$

where $b$ and $N_{\text{H}i}$ represent the Doppler parameter ($\sqrt{v_{\text{lin}}^2 + v_{\text{turb}}^2}$) and the column density of neutral hydrogen, respectively. If we adopt a uniform sphere geometry instead of a slab, the coefficient of the above equation will decrease to 336 km s$^{-1}$, and the product $(b N_{\text{H}i})$ will increase by a factor of two for a fixed $\Delta v_{\text{blue–red}}$ value. Note that the blue-to-red peak separation is degenerate between two parameters, $b$ and $N_{\text{H}i}$.

From the Lyα profile of CDFS-LAB14 (Figures 3 and 4), we measure the separation between the blue and red peaks,

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**Table 3**

| Name          | $\sigma_{\text{narrow}}$ (km s$^{-1}$) | $v_{\text{broad}}$ (km s$^{-1}$) | $\sigma_{\text{broad}}$ (km s$^{-1}$) | $F_{\text{broad}} / F_{\text{narrow}}$ | $F_{\text{broad}} / F_{\text{total}}$ | $\Delta v_{\text{max}}$ (km s$^{-1}$) |
|---------------|---------------------------------------|----------------------------------|--------------------------------------|---------------------------------------|---------------------------------------|--------------------------------------|
| CDFS-LAB06    | 38 ± 3                                | +39 ± 27                         | 55 ± 10                              | 0.51$^{+0.58}_{-0.29}$                 | 0.35 ± 0.17                           | 152 ± 15                             |
| CDFS-LAB07    | 44 ± 2                                | -97 ± 23                         | 64 ± 10                              | 0.44$^{+0.31}_{-0.18}$                 | 0.32 ± 0.12                           | 222 ± 11                             |
| CDFS-LAB13    | 35 ± 5                                | -56 ± 21                         | 60 ± 11                              | 0.84$^{+0.55}_{-0.38}$                 | 0.46 ± 0.13                           | 174 ± 18                             |
| CDFS-LAB14    | 67 ± 16                               | -12 ± 71                         | 125 ± 40                             | 0.47$^{+0.66}_{-0.20}$                 | 0.33 ± 0.20                           | 262 ± 75                             |
| CDFS-LAB10    | 71 ± 1                                | ...                              | ...                                  | ...                                   | ...                                   | ...                                  |
| CDFS-LAB11    | 47 ± 1                                | ...                              | ...                                  | ...                                   | ...                                   | ...                                  |

**Notes.**

a The line widths ($\sigma_{\text{narrow}}$ and $\sigma_{\text{broad}}$) are not corrected for the instrumental profile, because some of the line widths are comparable to the instrumental resolution ($\sigma_{\text{inst}} \approx 31$ km s$^{-1}$ in the NIR).

b $F_{\text{broad}}$ and $F_{\text{narrow}}$ are the fluxes in the broad and narrow components of the [O III] emission line, respectively.

c $F_{\text{total}} = F_{\text{narrow}} + F_{\text{broad}}$.

d The maximum blueshifted velocity $\Delta v_{\text{max}} \equiv |v_{\text{broad}} - 2\sigma_{\text{broad}}|$. For CDFS-LAB06 where the broad component is redshifted, we list $|v_{\text{broad}} + 2\sigma_{\text{broad}}|$.
Because of different data reduction modes, the spatial profiles wavelength range, $[1260 \, \text{Å}, 1600 \, \text{Å}]$ and $[4340 \, \text{Å}, 5400 \, \text{Å}]$, i.e., the continuum, we collapse the 2D spectra for the rest-frame are the same as in Figure 4. To obtain the spatial profiles for the continuum, we collapse the 2D spectra for the rest-frame wavelength range, $[1260 \, \text{Å}, 1600 \, \text{Å}]$ and $[4340 \, \text{Å}, 5400 \, \text{Å}]$, i.e., the continuum, and the emission lines (Ly$\alpha$). In other words, we assume that the observed velocity width of absorbing material is purely due to the turbulence or random motions inside the slab. The width of the absorption line is $\sigma_{abs} = 152 \pm 35 \, \text{km s}^{-1}$ from a single Gaussian fit (Section 3.5.2 and Figure 7) and after being corrected for the instrumental line width. For this range of $b$, we obtain $19.7 < \log N_{\text{HI}} < 20.6$.

Because the Ly$\alpha$ emission is spatially resolved in CDFS-LAB14, we further apply this technique to the extended Ly$\alpha$-emitting gas in a direction other than toward the embedded galaxy. As shown in Figure 4, the Ly$\alpha$ profile remains double-peaked as we move away from the LOS directly toward the embedded galaxy. The separation between the blue and red peaks decreases, indicating that $b N_{\text{HI}}$ also decreases. For $\Delta v_{\text{blue-red}} \approx 650 \, \text{km s}^{-1}$, we obtain slightly smaller estimates for the column density: $19.5 < \log N_{\text{HI}} < 20.6$.

Using the accurate measurement of systemic velocity, the metal absorption lines, and the symmetric double-peaked Ly$\alpha$ profile, we are able to place constraints on the $N_{\text{HI}}$ toward the galaxy and the extended Ly$\alpha$-emitting gas, albeit with large uncertainties. It is intriguing that this rough estimate of the H$\text{I}$ column density is similar to those of damped Ly$\alpha$ absorption (DLA) systems ($N_{\text{HI}} > 2 \times 10^{20} \, \text{cm}^{-2}$). While we have identified this Ly$\alpha$ blob by searching for extended Ly$\alpha$ emission, it would be interpreted as a DLA if there were a background QSO whose continuum spectrum showed absorption at the blob redshift. There are similar systems where extended Ly$\alpha$ emission is identified from DLAs very close to the QSO redshift (e.g., Möller et al. 1998; Fynbo et al. 1999; Hennawi et al. 2009).

### 3.7. Blueshifted Ly$\alpha$ without a Broadband Counterpart

Up to this point, we have examined only Ly$\alpha$ emission along the LOS to galaxies embedded in our blobs. In the 2D spectrum of CDFS-LAB10, however, we identify a region of blueshifted Ly$\alpha$ emission that does not spatially coincide with any of the blob galaxies identified with HST. This is the first case in our sample where we detect the Ly$\alpha$ emission from the extended gas itself. Given that a blueshifted Ly$\alpha$ line is a long-sought signature of gas inflows as described in Section 1 and Figure 1, we present a detailed analysis of CDFS-LAB10 here.

In the bottom panel of Figure 9 we show the HST F606W image of CDFS-LAB10 now rotated and smoothed with a Gaussian kernel to increase the contrast of faint sources. There are three broadband sources labeled CDFS-LAB10A, B, and C within the Ly$\alpha$ contour, which is elongated over $10''$ ($\sim 82$ kpc). The top panel of Figure 9 shows the spatial profiles of the stellar continuum and the emission lines (Ly$\alpha$ and [O$\text{III}$]). The latter are the same as in Figure 4. To obtain the spatial profiles for the continuum, we collapse the 2D spectra for the rest-frame wavelength range, $[1260 \, \text{Å}, 1600 \, \text{Å}]$ and $[4340 \, \text{Å}, 5400 \, \text{Å}]$, i.e., redward of Ly$\alpha$ and both sides of the [O$\text{III}$] lines, respectively. Because of different data reduction modes, the spatial profiles from the NIR arms ([O$\text{III}$]) cover only the central $\sim 6''$, while the profiles from the UVB arm (Ly$\alpha$) cover $\sim 14''$.

The brightest UV source in the HST image, CDFS-LAB10A at the slit center ($\Delta \theta = 0''$), is detected in both the rest-frame UV and optical continua, but not in Ly$\alpha$ or any strong emission lines ([O$\text{II}$], [O$\text{III}$], H$\beta$, H$\alpha$). It is still possible that there is a faint [O$\text{III}$] $\lambda 5007$ line under a sky line at $\Delta \nu \sim −550 \, \text{km s}^{-1}$.
(see Figure 4). Therefore, it is not clear whether galaxy A is at the same redshift as the Lyα-emitting gas or is a foreground or background galaxy. The galaxy B at $\Delta\theta \sim -3''$ is detected in Lyα, [O III], and UV continuum and is thus a member of the CDFS-LAB10 bll. Galaxy B’s Lyα emission is slightly offset from its UV continuum. CDFS-LAB10C, which has a filamentary or elongated morphology in the HST image, is the faintest ($m_{\text{F606W}} = 27.9 \pm 0.2$) of the three sources, but the brightest in Lyα and [O III]. Thus, galaxy C is the dominant source of Lyα emission from the known galaxies in this Lyα bll. It appears to be a classic example of an object heavily extended in the UV whose Lyα photons can still escape. Its 2D [O III] spectrum shows a velocity shear, suggesting a disk.

There is no obvious counterpart of the Lyα emission at $\Delta\theta = -1''$ and $\Delta v \sim -500$ km s$^{-1}$ in either the HST image or the X-shooter continuum spectrum. Therefore, this isolated Lyα emission probably arises from the extended gas. Its line profile is broad, double-peaked, and blueshifted from galaxy B and galaxy C (Figure 4). It is not possible to distinguish whether the bulk motion is inflowing or outflowing (at $\sim500$ km s$^{-1}$) with respect to galaxy C, the brightest [O III] source and marker of systemic velocity (Figure 4), because we do not know whether the gas lies in front of or behind galaxy C. This is the first unambiguous detection of a blueshifted Lyα line with respect to galaxies embedded within Lyα blls. It is likely that the blueshift is relative to the systemic velocity of the Lyα bll as well.

It is not clear what this blueshifted Lyα emission represents. We consider three possibilities. First, although unlikely, this Lyα component could be associated with a heavily extended galaxy that lies below the detection limit of the HST image ($m_{\text{F606W}} \gg 28$ mag) or with galaxy A, whose redshift is unknown. Second, this gas might be tidally stripped material arising from a galaxy–galaxy interaction: the two galaxies (B and C) are separated by $\sim30$ kpc in projected distance and $\sim200$ km s$^{-1}$ in velocity space. Lastly, but most interestingly, this blueshifted Lyα emission could be the long-sought but elusive cold gas accretion along filamentary streams (Kereš et al. 2005, 2009; Dekel et al. 2009).

Note that similarly blueshifted Lyα emission has been reported in a faint LAE at $z = 3.344$, which was discovered in an extremely deep, blind spectroscopic search (Rauch et al. 2011). The spectrum of this peculiar system also has very complex structure (e.g., diffuse fan-like blueshifted Lyα emission and a DLA system). Rauch et al. (2011) suggest that this blueshifted Lyα emission can be explained if the gas is inflowing along a filament behind the galaxy and emits fluorescent Lyα photons induced by the ionizing flux escaping from the galaxy. Discriminating among the above possibilities will require us to further constrain the Lyα line profile of this blueshifted component and to more fully survey possible member galaxies (or energy sources) within CDFS-LAB10.

Still, we were able to successfully link the Lyα and [O III] sources with the embedded galaxies in this complex system and to find blueshifted Lyα emission that might point to gas inflow. This example raises concerns about how to identify the sources of Lyα emission and to interpret the gas morphologies and kinematics solely from Lyα lines. Elongated or filamentary Lyα morphologies may be a sign of bipolar outflows (Matsuda et al. 2004) or related to filamentary cold streams. In CDFS-LAB10, the Lyα spectrum shows two kinematically distinct components around the brightest galaxy A: the upper ($\Delta\theta > 0''$) and lower parts are blue- and redshifted, respectively. In the absence of [O III] spectroscopy, the Lyα data appear to be consistent with either of the above outflow or infalling stream scenarios. However, our detailed analysis including the [O III] line clearly shows that one of the Lyα components arises from the faint galaxy C, which would be difficult to detect without HST imaging and is likely the dominant source of Lyα emission. Therefore, we stress that interpreting the Lyα morphology and spectra requires deep high-resolution imaging and the determination of the systemic velocity through NIR spectroscopy.

4. DISCUSSION

4.1. Covering Factor of Inflows and Outflows

Under the assumption that inflowing gas streams (if any) are randomly distributed, and from the nondetection of any blueshifted Lyα–Hα or Lyα–[O III] offset in the direction of the eight embedded galaxies tested here (although see Section 3.7), we constrain the covering fraction of inflows to be $<1/8$ (13%). Likewise, if all of our $\Delta v_{\text{LOS}}$ offsets are different projections of the same collimated outflow from the galaxies and are a proxy for outflow speed, the covering fraction of strong outflows, i.e., super-/hyperwinds, is less than $\sim 13\%$.

The covering fraction of gas flows to which we are referring here has a different meaning than often discussed in the literature (e.g., Faucher-Giguère & Kereš 2011; Kimm et al. 2011; Fumagalli et al. 2011). In these theoretical papers, the covering factor is defined as how many LOSs will be detected in metal or H I absorption when bright background sources close to the galaxies are targeted. What we measure in this paper is how often the inflowing gas is aligned with observer’s LOSs so that the column of neutral gas becomes optically thick and blueshifts Lyα lines against systemic velocity. Nonetheless, Faucher-Giguère & Kereš (2011) predict that the covering factor within the virial radius ($R_{\text{vir}} \simeq 75$ kpc) from their simulated galaxies with a halo mass of $M_h = 3 \times 10^{11} M_{\odot}$ at $z = 2$ is relatively small: $\sim 3\%$ and 10% for DLAs and Lyman limit systems, respectively. Within $0.5 \times R_{\text{vir}}$, this factor increases to $\sim 10\%$ and 30%, respectively, and presumably will be much higher directly toward the galaxies (i.e., for a pencil beam or looking down the barrel). Note that Faucher-Giguère & Kereš (2011) ignore galactic winds in order to isolate the inflowing streams, so we expect that there will be enough dense material arising from gas accretion to affect the transfer of Lyα photons in our experiments.

What is uncertain is how the velocity field of this dense material near the galaxy will shift the emerging Lyα profiles and the statistics of $\Delta v_{\text{los}}$, because answering this requires full Lyα RT treatment. Unlike RT models with simple geometry (e.g., Dijkstra et al. 2006a; Verhamme et al. 2006), cosmological simulations (Faucher-Giguère et al. 2010) predict that the gas inflow can only slightly enhance the blue Lyα peak, implying that the overall profile will be still red peak dominated if the effects of outflows from the galaxies and IGM absorption are fully considered. Therefore, according to these simulations, our nondetection of infall signatures does not contradict the cold stream model. The Lyα profiles calculated from cold-stream models are in general the integrated profiles of Lyα-emitting gas around the galaxies, which are not detectable by our study. What we need are the predictions for how Lyα profiles are modified and/or shifted against optically thin lines along the LOS to the galaxies embedded in the extended gas. In this way,
the distribution of predicted $\Delta v_{\text{Ly} \alpha}$ can be compared directly with the observations.

It is also critical to take into account the effect of simultaneous outflows and inflows. For example, the Hα and [O III] detections suggest that the galaxies embedded in the blobs are forming stars, which could generate mechanical feedback into the surrounding gas cloud. Thus, one might have expected that the innermost part of the gas cloud, close to the galaxies, has galactic-scale outflows similar to those of other SFGs at $z = 2$–3 (e.g., Steidel et al. 2010). Gas infall (if any) may dominate at larger radii (up to ~50 kpc, the typical blob size). In this case, the emerging Lyα profile will be more sensitive to the core of the Lyα blob, presumably the densest part of the CGM, than to the gas infall. As a result, it might be difficult to detect the infalling gas by measuring $\Delta v_{\text{Ly} \alpha}$. This kind of more realistic, infall+outflow model has not been considered yet in RT calculations, so its spectral signatures are unknown.

4.2. Outflow Speed versus $\Delta v_{\text{Ly} \alpha}$

In our sample of eight Lyα blobs, the embedded galaxies have smaller velocity offsets ($\langle \Delta v_{\text{Ly} \alpha} \rangle = 160$ km s$^{-1}$) than those of LBGs (445 km s$^{-1}$). The remaining question is how to interpret these small $\Delta v_{\text{Ly} \alpha}$ values. We consider two possibilities here.

First, if we assume a simple geometry where the outflowing material forms a spherical shell that consists of continuous media, $\Delta v_{\text{Ly} \alpha}$ originates from the resonant scattering of the Lyα photons at the shell as discussed in Verhamme et al. (2008). Note that the emerging Lyα profile is independent of the physical size of the shell as long as the shell has the same outflow velocity. Therefore, this model is applicable to Lyα blobs. In this shell model, a central monochromatic point source is surrounded by an expanding shell of neutral gas with varying column density ($N_{\text{HI}}$) and Doppler $b$ parameter (e.g., Verhamme et al. 2006, 2008). A generic prediction is that the Lyα emission is asymmetric, with the details of the line shape depending on the shell velocity, Doppler parameter $b$, and optical depth of H I column in the shell. In this simple geometry, the $\Delta v_{\text{Ly} \alpha}$ values can be used as a proxy for outflow velocity of expanding shell, i.e., $v_{\text{exp}} \approx 0.5 \Delta v_{\text{Ly} \alpha}$. If this is the case, outflow velocities from blob galaxies are much smaller than the values expected from models of strong galactic winds (~1000 km s$^{-1}$; Taniguchi & Shioya 2000; Taniguchi et al. 2001; Ohyama et al. 2003; Wilman et al. 2005). Furthermore, these offsets are even smaller than the typical Lyα–Hα offsets (250–900 km s$^{-1}$) of LBGs (Steidel et al. 2004, 2010). In particular, while CDFS-LAB14 has the largest $\Delta v_{\text{Ly} \alpha}$ for its red peak, its blue and red peaks have similar intensity, which is a characteristic of a static medium or no bulk motions (Verhamme et al. 2006; Kollmeier et al. 2010).

Second, in an “expanding bullet” or “clumpy CGM” model (Steidel et al. 2010), the outflowing material, which consists of small individual clumps, has a wide velocity range rather than a single value, and the Lyα profiles are determined by the Doppler shift that photons acquire when they are last scattered by the clumps just before escaping the system. In this case, the Lyα–Hα offsets are primarily modulated by the amount of gas that has a $v = 0$ component (though it is not clear where this material is spatially located); thus, $\Delta v_{\text{Ly} \alpha}$ is not directly correlated with outflow velocity. If this is the case, the small $\Delta v_{\text{Ly} \alpha}$ value of the galaxies in our Lyα blobs simply indicates that there is less neutral gas at the galaxies’ systemic velocity (presumably near the galaxy) compared to LBGs.

Testing these two hypotheses for Lyα blobs or LBGs first requires a detailed comparison between high-resolution Lyα profiles and RT predictions. This test is beyond the scope of this paper and will be discussed in the future. As emphasized by Steidel et al. (2010), one also needs to check the consistency of the Lyα profiles with ISM metal absorption profiles, which depends on high-S/N continuum spectra that are not available here. Nonetheless, we attempted such an analysis by stacking many low-ionization absorption lines in three galaxies (Section 3.5.2).

For those three embedded galaxies with measured $\Delta v_{\text{Ly} \alpha}$ and $\Delta v_{\text{IS}}$, the outflow velocity estimates from both methods roughly agree within the uncertainties arising from low S/N and from RT complications. However, closer inspection reveals a discrepancy between the observations and the simplest RT models in that we obtain $\Delta v_{\text{IS}} \sim –200$ km s$^{-1}$ and also $\Delta v_{\text{Ly} \alpha} \sim 200$ km s$^{-1}$ while the RT model with an expanding shell geometry predicts $\Delta v_{\text{IS}} = –v_{\text{exp}} = –0.5 \Delta v_{\text{Ly} \alpha}$. This discrepancy has also appeared in LBGs (Steidel et al. 2010), and Kulas et al. (2012) show that the stacked Lyα profile of LBGs with double-peak profiles cannot be reproduced accurately by the shell model. For a wide range of parameters ($v_{\text{exp}}, b, N_{\text{HI}}$), Kulas et al. (2012) cannot reproduce the location of the red peak, the width of the Lyα profile, and the metal absorption profile at the same time.

We attribute this discrepancy to the very simple nature of the shell model. By construction or by definition of the expanding “shell,” the internal velocity dispersion of the media that constitute the shell should be much smaller than the expansion velocity of the shell itself, i.e., $v_{\text{exp}}/b \gg 1$. Therefore, one expects that the metal absorption lines arising from this thin shell have very narrow line widths $\sigma_{\text{obs}}$ similar to $b$, typically ~tens of km s$^{-1}$. However, such narrow absorption lines are not observed in either LBGs or Lyα blobs. Clearly, RT calculations with more realistic geometries and allowing a more thorough comparison with the observed Lyα profiles are required.

4.3. $\Delta v_{\text{Ly} \alpha}$ in the Context of LAEs and LBGs

Given that the galaxies within our Lyα blobs were selected, by definition, as LAEs with high equivalent width (EW), the comparison with LAEs suggests that small $\Delta v_{\text{Ly} \alpha}$ values are a general characteristic of all high-EW Lyα-selected populations, be they compact or extended. In addition to this work and Yang et al. (2011), there are recent studies that measure $\Delta v_{\text{Ly} \alpha}$ for bright compact LAEs (McLinden et al. 2011; Finkelstein et al. 2011; Hashimoto et al. 2013; Guaita et al. 2013) and Lyα blobs (McLinden et al. 2013), which also find small Lyα–[O III] offsets for LAEs ranging from 35 to 340 km s$^{-1}$. A Kolmogorov–Smirnov test fails to distinguish the $\Delta v_{\text{Ly} \alpha}$ distribution of our 8 Lyα blobs from that of 10 compact LAEs compiled from the four studies mentioned above. Thus, we now have a fairly large sample of high-EW LAE profiles that have a $\Delta v_{\text{Ly} \alpha}$ distribution which is different from the distribution for LBGs (see Section 3.5.1).

The smaller $\Delta v_{\text{Ly} \alpha}$ of LAEs and LBGs might be related to their higher Lyα EWs. An anti-correlation between EW(Lyα) and $\Delta v_{\text{Ly} \alpha}$ in a compilation of LAE and LBG samples has been suggested (Hashimoto et al. 2013). Even within the LBG population itself there is an indication that $\Delta v_{\text{Ly} \alpha}$ decreases as EW(Lyα) increases. Shapley et al. (2003) find an anti-correlation between the EW(Lyα) and the velocity offsets between interstellar absorption and Lyα emission lines, $\Delta v_{\text{Ly} \alpha-\text{abs}}$. From the stacked spectra of LBGs binned at different EW(Lyα), they show that

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8 The notation $\Delta v_{\text{Ly} \alpha-\text{abs}}$ is used in Shapley et al. (2003).
with increasing Lyα line strength from $-15$ Å to $53$ Å, $\Delta v_{\text{Lyα-abs}}$ decreases from $800$ km s$^{-1}$ to $480$ km s$^{-1}$. Because $\Delta v_{\text{Lyα-abs}} = \Delta v_{\text{Lyα}} + |\Delta v_{\text{IS}}|$, we can infer that $\Delta v_{\text{Lyα}}$ is likely to decrease as EW(Lyα) increases unless the observed anti-correlation is entirely due to $|\Delta v_{\text{IS}}|$.

The origin of the apparent relationship between larger EW(Lyα) and smaller $\Delta v_{\text{Lyα}}$ is not understood. It is possible that other physical properties drive this anti-correlation: for example, LBGs tend to have brighter continuum magnitudes, thus certain galaxies have more spatially extended Lyα gas (i.e., blobs) than others (i.e., compact LAEs). Hashimoto et al. (2013) propose that low H$\text{I}$ column density, and thus a small number of resonant scatterings of Lyα photons, might be responsible for the strong Lyα emission and small $\Delta v_{\text{Lyα}}$ of LAEs.

What we do know from our $\Delta v_{\text{Lyα}}$ measurements is that LAEs and Lyα blobs are kinematically similar. Therefore, the mystery remains as to what powers Lyα nebulae, or, in other words, why certain galaxies have more spatially extended Lyα gas (i.e., blobs) than others (i.e., compact LAEs) with similar $\Delta v_{\text{Lyα}}$ and EW(Lyα). While the answer may be related to photoionization from (buried) AGNs (e.g., see Section 4.4 or Yang et al. 2014), an extended proto-intracluster medium that can scatter or transport the Lyα photons out to larger distances, or less dust to destroy Lyα photons (cf. Hayes et al. 2013), discriminating among these possibilities will require a multicolor analysis of a large sample of Lyα blobs. For now, the similarity here of LABs and LAEs suggests that differences in gas kinematics are not responsible for the extended Lyα halos.

4.4. CDFS-LAB11: Photoionization by AGNs?

From the nearly symmetric Lyα profile (Figure 10), C iv and He ii detection, and rest-frame optical line ratios, we hypothesize that an AGN in CDFS-LAB11 ionizes the gas surrounding the galaxies, making Lyα relatively optically thin and preventing the resonant scattering of Lyα photons from dominating the shape of the profile. While fitting the profile requires an underlying broad component (FWHM $\simeq 480$ km s$^{-1}$), the narrow component (redshifted by $\simeq 80$ km s$^{-1}$) has a small velocity width (FWHM $\simeq 110$ km s$^{-1}$), comparable to that of the [O iii] line ($\simeq 80$ km s$^{-1}$). Therefore, if we assume that Lyα and [O iii] photons originate from the same region, resonant scattering by the IGM/CGM does not broaden the intrinsic profile significantly. In other words, at least along our LOS, the optical depth of CDFS-LAB11’s IGM/CGM is smaller than for the other Lyα blobs in our sample and for typical LAEs at high redshifts.

A nearly symmetric and narrow Lyα profile such as CDFS-LAB11’s is rarely observed among high-$z$ Lyα-emitting galaxies. However, Lyα RT calculations show that such Lyα profiles can be generated in the presence of a central ionizing source. For example, Dijkstra et al. (2006a) investigate the emerging Lyα profiles from a collapsing/expanding sphere centered on an ionizing source (an AGN) for different luminosities (see their Figures 11 and 12). They find that if the ionizing source is strong and the Lyα is relatively optically thin (line-center optical depth $\tau_0 < 10^3$), the separation of the characteristic double peaks becomes smaller ($\Delta v_{\text{blue-red}} \ll 100$ km s$^{-1}$) as the ionizing source gets stronger. The overall profile becomes symmetric and is blue- or redshifted depending on the flow direction, but again by a small amount ($\Delta v_{\text{Lyα}} \ll 100$ km s$^{-1}$). These authors were skeptical that the sign of the Lyα shift and the small Lyα offset ($\Delta v_{\text{Lyα}} \sim$ a few tens km s$^{-1}$) from the systemic velocity could be measured. However, with the right strategy (i.e., high spectral resolution and a careful choice of survey redshift), we are able to reliably measure the predicted small offset. Clearly, more detailed comparisons with the RT models are required.

A broad, asymmetric Lyα profile with a sharp blue edge (e.g., CDFS-LAB06 and 07) is characteristic of high-$z$ LAEs. In spectroscopic follow-up observations of LAE candidates, where spectral coverage is limited, these characteristics alone are often used to discriminate high-$z$ LAEs from possible low-$z$ interlopers. The example of CDFS-LAB11 demonstrates that caution is required because a narrow and symmetric Lyα line can also arise when the ISM or CGM of a candidate galaxy is significantly photoionized, e.g., by AGNs. On the bright side, our $\Delta v_{\text{Lyα}}$ velocity offset technique could be used for studying gas infall or outflow in high-$z$ QSOs instead of relying on only the Lyα line profile (e.g., Weidinger et al. 2004).

5. CONCLUSIONS

Exploring the origin of Lyα nebulae (“blobs”) at high redshift requires measurements of their gas kinematics that are difficult with only the resonant, optically thick Lyα line. To define gas motions relative to the systemic velocity of the nebula, the Lyα line must be compared with nonresonant lines, which are not much altered by RT effects. We made a first comparison of nonresonant H$\alpha$ to extended Lyα emission in two bright Lyα blobs in Yang et al. (2011), concluding that, within the context of a simple RT model, the gas was static or mildly outflowing at $\lesssim 250$ km s$^{-1}$. However, it was unclear whether these two Lyα blobs, which are the brightest in the sample, are representative of the general Lyα blob population. Furthermore, geometric effects—infall along filaments or bipolar outflows—might hide bulk motions of the gas when only viewed from the two directions toward these two Lyα blobs. With VLT X-shooter, we obtain optical and NIR spectra of six additional Lyα blobs from the Yang et al. (2010) sample. With a total of eight Lyα blobs, we investigate the gas kinematics within Lyα blobs using three techniques: the Lyα offset from the systemic velocity ($\Delta v_{\text{Lyα}}$), the shape and shift ($\Delta v_{\text{IS}}$) of the ISM metal absorption-line profiles, and the breadth of the [O iii] line profile.

Our findings are as follows:

1. Both Lyα and nonresonant lines confirm that these blobs lie at the survey redshift ($z \sim 2.3$). We also detect the [O iii]
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λλ3727,3729, [O III] λ4959, [O III] λ5007, and Hβ λ4861 lines. All nonresonant line velocities are consistent with each other and with arising from the galaxy or galaxies embedded in the Lyα blob. [O III], which is observed at high S/N in all cases and whose profile is an RT-independent constraint on the gas kinematics, is a particularly good diagnostic line for this redshift and instrument.

2. The majority of the blobs (6/8) have broadened Lyα profiles indicating RT effects. These Lyα profiles are consistent with being in the same family of objects as predicted by RT, with profile shapes ranging from symmetric double-peaked, to asymmetric red peak dominated, to a single red peak. The fraction of double-peaked profiles is ∼38% (3/8).

3. The narrow Lyα profile systems (CDFS-LAB01A, CDFS-LAB11), whose Lyα profile is not significantly broader than the [O III] or Hα lines, have the smallest ΔvLyα offsets, the most spatially compact Lyα emission, and the only C IV and He II lines detected, implying that a hard ionizing source, possibly an AGN, is responsible for the lower optical depth toward the embedded galaxies.

4. With a combination of ΔvLyα, the interstellar metal absorption-line profile, and a new indicator, the spectrally resolved [O III] line profile, we detect gas moving along the LOS to galaxies embedded in the Lyα blob center. Although not all three indicators are available for all Lyα blobs, the implied speeds and direction are roughly consistent for the sample, suggesting a simple picture in which the gas is stationary or slowly outflowing at a few hundred km s⁻¹ from the embedded galaxies. These outflow speeds are similar to those of LAEs, suggesting that outflow speed is not the dominant driver of extended Lyα emission. Furthermore, these outflow speeds exclude models in which star formation or AGNs produce “super” or “hyper” winds of up to ∼1000 km s⁻¹ (Taniguchi & Shioya 2000).

More specifically,

(a) We compare the nonresonant emission lines [O III] and Hα to the Lyα profile to obtain the velocity offset ΔvLyα. The galaxies embedded within our Lyα blobs have smaller ΔvLyα than those of LBGs, confirming the previous claims (Yang et al. 2011). The galaxies within Lyα blobs have ΔvLyα = -60 → +400 km s⁻¹ with an average of ⟨ΔvLyα⟩ = 160 km s⁻¹, while LBGs at similar redshifts have ΔvLyα = 250–900 km s⁻¹. The small ΔvLyα in the Lyα blobs are consistent with those measured for compact LAEs.

(b) By stacking low-ionization metal absorption lines, we measure the outflow velocity of neutral gas in front of the galaxies in the Lyα blobs. Galaxies in two Lyα blobs show an outflow speed of ∼250 km s⁻¹, while another has an almost symmetric absorption-line profile centered at ΔvIS = 0 km s⁻¹, consistent with no significant bulk motion. The ISM absorption-line profiles here have low S/N but are very roughly consistent with those of some LBGs (at the level of several hundred km s⁻¹ outflows).

(c) The high spectral resolution of our data reveals broad wings in the [O III] profiles of four Lyα blobs. This new kinematic diagnostic suggests warm ionized outflows driven by supernovae and stellar winds. These broad-line components are narrower (σFWHM = 45–120 km s⁻¹) and have a maximum blueshifted velocity (Δvmax = 150–260 km s⁻¹) smaller than those of z ∼ 2 SFGs, implying weaker outflows here than for LBGs and SFGs at similar redshifts.

(d) If we assume that the detected outflows are different projections of the same outflow from the Lyα blob center, we can estimate the effects of flow geometry on our measurements given that our large sample size allows averaging over many LOSs. The absence of any strong (∼1000 km s⁻¹) outflows among the eight galaxies tested is not a projection effect: their covering fraction is <1/8 (13%). Likewise, the lack of a blue-peak-dominated Lyα profile, at least in the direction of the embedded galaxies (see point 6 below), implies that the covering factor of any cold streams (Kereš et al. 2005, 2009; Dekel et al. 2009) is less than 13%. The channeling of gravitational cooling radiation into Lyα may not be significant over the radii probed by our techniques here.

5. Constraining the physical state of Lyα-emitting gas in an Lyα blob is a critical step in understanding its emission mechanism and in comparing to simulations. For one Lyα blob whose Lyα profile and ISM metal absorption lines suggest no significant bulk motion (CDFS-LAB14), at least in its cool and neutral gas, we assume a simple RT model and make the first column density measurement of gas in an embedded galaxy, finding that it is consistent with a DLA.

6. For one peculiar system (CDFS-LAB10), we discover blueshifted Lyα emission that is not directly associated with any embedded galaxy. This Lyα-emitting gas is blueshifted relative to two embedded galaxies, suggesting that it arose from a tidal interaction between the galaxies or is actually flowing into the blob center. The former is expected in these overdense regions, where HST images resolve many galaxies. The latter might signify the predicted but elusive cold gas accretion along filaments.

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APPENDIX

DECOMPOSITION OF [O III] PROFILES

To test whether two velocity components are needed to fit our spectrally resolved [O III] profiles and to extract the line
parameters, we employ the [O\textsc{iii}] profiles with two Gaussian functions using a Markov Chain Monte Carlo (MCMC) technique. We use the 	extit{emcee} software (Foreman-Mackey et al. 2013) to sample the distributions of six parameters: line center, width, and fluxes for the two Gaussian profiles. We require that (1) the line widths of both components are larger than the instrumental line width ($31$ km s$^{-1}$; the vertical dotted lines in Figure 11), (2) the peak of each component should be at least 5% of the observed peak intensity, and (3) the peak of the narrow component is higher than that of the broad component. The latter two priors are imposed to prevent the MCMC chains from getting stuck in parameter spaces with extremely broad lines but with negligible fluxes.

In Figure 11 we show the likelihood distributions of the line widths of the two components: $\sigma_{\text{narrow}}$ and $\sigma_{\text{broad}}$. Note that we exclude CDFS-LAB10 in this analysis because its neighboring...
galaxy (CDFS-LAB10A) makes it difficult to reliably extract its profile (see Sections 3.5.3 and 3.7). Except for CDFS-LAB11, the likelihood distributions of the two line widths do not overlap significantly, and the peaks of the joint 2D distributions are not located near the $\sigma_{\text{narrow}} = \sigma_{\text{broad}}$ line (dashed line). Therefore, we conclude that the remaining four systems (CDFS-LAB06, 07, 13, 14) are likely to consist of two components. The uncertainties of the parameters are determined from the 68.2% confidence interval of the marginalized distribution.

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