A $z \sim 5.7$ Ly$\alpha$ EMISSION LINE WITH AN ULTRABROAD RED WING

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ABSTRACT

Using the Ly$\alpha$ emission line as a tracer of high-redshift, star-forming galaxies, hundreds of Ly$\alpha$ emission line galaxies (LAEs) at $z > 5$ have been detected. These LAEs are considered to be low-mass young galaxies, critical to the re-ionization of the universe and the metal enrichment of the circumgalactic medium (CGM) and the intergalactic medium (IGM). It is assumed that outflows in LAEs can help both ionizing photons and Ly$\alpha$ photons escape from galaxies. However, we still know little about the outflows in high-redshift LAEs due to observational difficulties, especially at redshift $> 5$. Models of Ly$\alpha$ radiative transfer predict asymmetric Ly$\alpha$ line profiles with broad red wings in LAEs with outflows. Here, we report a $z \sim 5.7$ Ly$\alpha$ emission line with a broad red wing extending to $> 1000 \text{ km s}^{-1}$ relative to the peak of Ly$\alpha$ line, which has been detected in only a couple of $z > 5$ LAEs until now. If the broad red wing is ascribed to gas outflow instead of active galactic nucleus activity, the outflow velocity could be larger than the escape velocity ($\sim 500 \text{ km s}^{-1}$) of a typical halo mass of $z \sim 5.7$ LAEs, which is consistent with the idea that outflows in LAEs disperse metals to CGM and IGM.

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

Online-only material: color figures

1. INTRODUCTION

High-redshift, star-forming galaxies can be detected by optical to near-infrared observations of rest-frame ultraviolet (UV) light. One efficient method selects Lyman break galaxies (LBGs) via the distinctive step, which is introduced into their blue, UV light. Another efficient method selects Ly$\alpha$ emission line galaxies (LAEs) by the large equivalent width (EW) of their Ly$\alpha$ recombination lines caused during star formation. The standard approach that has been used to detect high-redshift LAEs is the wide-field, narrowband imaging survey which is administered in the gaps of the telluric OH-bands (Cowie & Hu 1998; Rhoads et al. 2000; Ouchi et al. 2003, 2008; Hu et al. 2004; Wang et al. 2005; Gawiser et al. 2006; Gualda et al. 2010; Tilvi et al. 2010; Nakajima et al. 2012; Clément et al. 2012; Krug et al. 2012; Shibuya et al. 2012). The photometric samples could have contamination rates as large as $\sim 40\%$ (e.g., Wang et al. 2009), and spectroscopic follow up is necessary to remove interlopers (Hu et al. 2004). Generally, LAEs are small, low-mass, weakly clustered, young galaxies (Gawiser et al. 2006; Kováč et al. 2007; Pirzkal et al. 2007; Malhotra et al. 2012) and considered to be a subset of LBGs with fainter continuum and smaller dust extinction (Pentericci et al. 2009; Kornei et al. 2010).

Almost every extreme, star-forming galaxy has gas outflows. Traced by the blueshifted interstellar metal absorption lines in the rest-frame UV or optical spectra, galactic gas outflows are common in local starburst galaxies (Heckman et al. 2000; Veilleux et al. 2005) and ubiquitous in LBG samples at high redshifts (Pettini et al. 2001; Adelberger et al. 2003; Shapley et al. 2003; Steidel et al. 2010). It is not yet clear whether gas outflows are also prevalent in LAEs, as LAE samples are biased to galaxies with dim stellar continuums, thus it is difficult to detect the absorption lines. Outflows in LAEs and LBGs can regulate star formation in galaxies and are assumed to help ionizing photons escape to ionize the universe and spread metal to the circumgalactic medium (CGM) and the intergalactic medium (IGM; e.g., Oppenheimer & Davé 2006).

Outflows are also key to Ly$\alpha$ photon escape and Ly$\alpha$ emission line profiles. Ly$\alpha$ is expected to be strong in star-forming galaxies. However, due to the large scattering cross section of Ly$\alpha$ photons by H$\text{I}$, Ly$\alpha$ emission could be greatly altered in intensity, kinematics, and apparent spatial distribution (Charlot & Fall 1993). Outflows can help Ly$\alpha$ photons escape out of local starburst galaxies (Kunth et al. 1998), resulting in the P-Cygni profile of the Ly$\alpha$ line (Mas-Hesse et al. 2003). In $z \sim 2–3$ LBGs with Ly$\alpha$ emission lines, the peaks of Ly$\alpha$ lines are redshifted relative to the galactic systemic redshift, while the low-ionization interstellar metal absorption lines (tracing gas outflows) are blueshifted, and the EWs and velocity offsets of Ly$\alpha$ lines are closely related to those of the low ionization interstellar metal absorption lines (Shapley et al. 2003; Steidel et al. 2010). In a $z \sim 4–6$ LBG sample, peaks of Ly$\alpha$ emission lines are also redshifted relative to the low-ionization, interstellar, metal absorption lines (Vanzella et al. 2009; Jones et al. 2012). Profiles of Ly$\alpha$ lines in LBGs are complex, varying from damped absorption to double-peaked emission, which can be reproduced by models of Ly$\alpha$ radiative transfer in outflowing gas (Verhamme et al. 2006; Tapken et al. 2007). In $z \sim 1.8–4.5$ gamma-ray burst host galaxies with Ly$\alpha$ emission, the velocity centroid of the Ly$\alpha$ lines are also redshifted with respect to the galactic systemic velocity, similar to what is seen for LBGs (Milvang-Jensen et al. 2012).

Consistently, in a few $z \sim 2–3$ LAEs with rest-frame optical emission lines detected (such as [OIII] and H$	ext{α}$), Ly$\alpha$ lines are redshifted by $\sim 100–300 \text{ km s}^{-1}$ relative to the optical lines (McLinden et al. 2011; Finkelstein et al. 2011; Hashimoto et al.
2013). Furthermore, the composite spectra of eight $z \sim 2−3$ LAEs (Hashimoto et al. 2013) show blueshifted interstellar absorption lines relative to optical H$\alpha$ lines. These studies all suggest the existence of outflows in LAEs.

However, in most LAEs the Ly$\alpha$ emission line is the only detectable feature in spectroscopic observations. Since the Ly$\alpha$ emission lines are luminous and their profiles strongly depend on the gas and dust distribution and kinematics, Ly$\alpha$ line profiles alone can also be used to trace the interstellar medium properties. Hundreds of LAEs at $z > 5$ have been spectroscopically confirmed by asymmetric Ly$\alpha$ line profiles that show a sharp blue cutoff (Dawson et al. 2004; Kashikawa et al. 2006, 2011; Sawicki et al. 2008; Hu et al. 2010; Ouchi et al. 2010). The asymmetric profile may be caused by the absorption and scattering of photons that are bluer than the Ly$\alpha$ line center of the IGM at lower redshift. However, a few $z > 5$ LAEs show Ly$\alpha$ emission lines with very broad red wings, which are ascribed to the scattering of Ly$\alpha$ photons from a shell of gas outflows driven by a powerful starburst (Dawson et al. 2002; Ajiki et al. 2002; Westra et al. 2005). Models of Ly$\alpha$ radiative transfer in galaxies with gas outflows (e.g., Verhamme et al. 2006) also predict asymmetric Ly$\alpha$ profiles with broad red wings. We note that in some $z > 5$ LBGs with Ly$\alpha$ emission lines detected, the Ly$\alpha$ line profiles also show very broad red wings (e.g., Vanzella et al. 2010; Curtis-Lake et al. 2012).

In this work, we report a $z = 5.7$ Ly$\alpha$ emission line with a broad red wing located at R.A.(J2000) = 03:35:39.335, decl.(J2000) = $-27:53:15.99$ (hereafter J0335), which was discovered in the spectroscopic follow-up of narrowband selected LAE candidates near the Chandra Deep Field South (CDF-S) field. We discuss the implications of the broad red wing for outflow in LAEs and the potential of using Ly$\alpha$ as a tracer of galactic outflow at $z > 5$. We adopt a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{m} = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. OBSERVATION AND SPECTRA ANALYSIS RESULTS

J0335 was selected as a candidate $z \sim 5.7$ LAE in a deep narrowband imaging survey in a field next to the CDF-S. We obtained deep NB823 narrowband images using the Mosaic II CCD imager at the Cerro Tololo Inter-American Observatory (CTIO) 4 m V. M. Blanco telescope on 2005 September 9–11 (UT). The narrowband filter, NB823, has a central wavelength $\lambda_c$ of 823 nm and an FWHM transmission of 7.5 nm. The broadband $B$, $V$, and $I$ images used for candidate LAE selection are from the ESO Image Survey$^4$ in the same field. The optical thumbnail images of J0335 are given in Figure 1. The 5$\sigma$ limiting Vega magnitudes in a 2′/5 aperture of the $B$, $V$, $I$, and NB823 images are 25.92, 25.15, 23.83, and 23.84 mag, respectively. The galaxy J0335 is only detected in NB823 with a narrowband flux of $3.2 \pm 0.6 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$. As the source is non-detected in the underlying broadband (I band), we use a $1\sigma$ (2$\sigma$) upper limit of I band flux to estimate the lower limit to the EW of the line. Assuming the line is the Ly$\alpha$ line at $z \sim 5.7$ and simply following Malhotra & Rhoads (2002), we obtained a lower limit to the rest-frame line EW of $>106$ Å ($>48$ Å).

The spectroscopic observations of J0335 were taken with the Inamori-Magellan Areal Camera & Spectrograph (IMACS; Dressler et al. 2006) in multi-slit mode on Magellan I Baade telescope on 2012 October 11. The slit width was 1′′0 and the typical seeing during the observation was between 0′′5 and 0′′7. The exposures were taken with a CTIO-I band filter and a 300 1 mm$^{-1}$ grism with a blaze angle of 26.7 deg, resulting in spectra coverage of 7000–9000 Å and a dispersion of 1.25 Å pixel$^{-1}$. A total of 9000 s exposure was obtained.

The science frames were bias-subtracted, internal flat corrected, and wavelength calibrated with the IMACS data reduction package COSMOS.$^6$ Sky subtractions were performed following the two-dimensional (2D) spectroscopy background subtraction method (Kelson 2003). We combined the clean 2D spectra from each individual exposure, and extracted the one-dimensional (1D) spectrum by summing up counts in the 0′′8 apertures of the 2D spectra. Flux calibration was done using the spectroscopic standard star LTT1788.

The emission line of J0335 clearly showed an asymmetric profile with a broad red wing in both the 2D and 1D spectra (Figure 2). The asymmetric line profile and non-detections of other emission lines confirm that the line is in fact Ly$\alpha$ emission, but not [O ii] $\lambda\lambda 3727, 3729$ doublet. In particular, the [O ii] $\lambda\lambda 3726, 3729$ doublet would be resolved at this wavelength with a spectral resolution of $\sim$6 Å.

The observed line flux is $(1.71 \pm 0.04) \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (measured in a larger 1′′6 aperture to avoid aperture loss; the error here represents only statistical uncertainties in the spectrum). The line luminosity is $6.13 \pm 0.17 \times 10^{42}$ erg s$^{-1}$, close to $L^*$ ($7\sim10 \times 10^{42}$ erg s$^{-1}$) of the Ly$\alpha$ luminosity function.

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4 http://www.eso.org/sci/activities/projects/eis-surveys/strategy_DPS.html

5 In the calculation, the IGM absorption to the broadband continuum and the Ly$\alpha$ line were ignored since they may cancel each other out in the calculation of Ly$\alpha$ EW, see Malhotra & Rhoads (2002).

6 http://code.obs.carnegiescience.edu/cosmos
at $z \sim 5.7$ (Ouchi et al. 2008; Hu et al. 2010; Kashikawa et al. 2011). To estimate spectroscopic line EW, we fit the continuum redward of the Lyα line (8221.2–8800.8 Å in the observed frame) with a constant, and obtain a continuum flux of $0.021 \pm 0.005 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$ and a rest-frame Lyα line EW of 121 $\pm$ 29 Å (without correction to IGM absorption to the Lyα line).

The Lyα profile showed a marginally resolved narrow-line core and a broad red wing. The commonly adopted approach to fit high $z$ Lyα profiles is to use a red continuum plus a half-Gaussian profile (setting both components blueward of the line center to zero) convolved with an instrument profile. For J0335, this approach can fit the narrow-line core, but it ignores the broad red wing. Therefore, we add an extra broad Gaussian component to the fitting (Figure 2). The resulting narrow-line core is centered at 8180.5 $\pm$ 0.09 Å, with FWHM(narrow) = 6.6 $\pm$ 0.3 Å. If we neglect the possible offset of the Lyα line to the galaxy systemic redshift, the narrow-line center wavelength gives a redshift of 5.7274 $\pm$ 0.0001. As the instrument profile resolution is FWHM(instru) $\approx$ 5.9 Å, estimated by fitting the sky line with the Gaussian profile, the intrinsic FWHM of the narrow component is $\sim$3.0$^{+0.6}_{-0.8}$ Å (108 km s$^{-1}$). Since the seeing during the observation (0′.5–0′.7) was smaller than the slit width (1′.0), and considering that high-redshift LAEs are usually compact in continuum (Malhotra et al. 2012) and in Lyα emission (Bond et al. 2010), our spectral resolution may be better than 5.9 Å, and the intrinsic FWHM of the narrow Lyα core could be $\sim$5–6 Å (180–220 km s$^{-1}$). The broad component, with signal-to-noise ratio (S/N) = 5.0, is centered at 8188.4 $\pm$ 2.1 Å with FWHM(broad) = 23 $\pm$ 4 Å (852 km s$^{-1}$). Its velocity offset, relative to the narrow component, is 290 $\pm$ 77 km s$^{-1}$.

### 3. DISCUSSION

#### 3.1. AGN or Starburst

Both an active galactic nucleus (AGN) and a starburst can ionize the surrounding gas and generate Lyα emission. Assuming $z = 5.7274$, the expected N v λ1240 line from an AGN is sitting on the edge of a strong sky line, and is non-detected. We can only obtain a loose 3σ upper limit to N ν λ1240/Lyα < 0.13 (the typical value of narrow lines in AGNs is $\sim$10%; Alexandroff et al. 2013). The Si iv λ1398 and C iv λ1549 lines are out of the spectral range. The archived mid-IR and X-ray data are too shallow to constrain the AGN activity. However, because only $\lesssim 5\%$ of high-redshift LAEs are possible AGNs (Malhotra et al. 2003; Wang et al. 2004, 2009; Zheng et al. 2010, 2012, 2013), and J0335 was identified among only a couple of spectroscopically confirmed $z \sim 5.7$ LAEs in our sample, it is unlikely to be an AGN. Although we cannot securely rule out AGN activity in J0335, based on currently available data, the more likely possibility is that the Lyα emission line is due to a starburst. While Lyα luminosity is admittedly a poor indicator of star formation rate due to radiative transfer effects in galaxies, assuming the Lyα line is totally due to star formation and taking the standard case B conversion of Lyα to Hα, we estimate an SFR $\sim 6 M_\odot$ yr$^{-1}$ (Kennicutt & Evans 2012).

#### 3.2. Interpretations of Lyα Profile with Broad Red Wing

##### 3.2.1. Outflow Shell Model

To interpret the Lyα profile of LBGs and LAEs, previous studies have explored the Lyα emission line profile as a result...
of a thin shell of outflowing gas driven by starbursts (Verhamme et al. 2006, 2008). In their model, gas at the far side of the outflow can scatter Lyα photons back toward the observer’s direction, making photons, redshifted relative to galaxy systemic redshift, avoid absorption by the material on the near side. A diversity of profiles can be generated by changing model parameters such as outflowing velocity, H\textsubscript{i} column density, velocity dispersion, and dust attenuation. The Lyα line profile (with a broad red wing) of J0335 is qualitatively comparable to those generated by the outflow shell model (Verhamme et al. 2006, 2008; Schaerer et al. 2011). In particular, a red wing extending to > 1000 km s\textsuperscript{-1} can be generated from a very dusty, high column density outflow shell with outflow velocity \( \sim \) 300–600 km s\textsuperscript{-1} (see Figure 7 of Schaerer et al. 2011). However, considering the relatively low spectral resolution (FWHM = 220 km s\textsuperscript{-1}) here, and that we are unable to determine the model parameters uniquely based on a single line profile, we do not fit the profile with radiative transfer models in this work.

However, although a thin shell outflow model can successfully explain the Lyα line profiles in many LBGs and LAEs, there are also discrepancies between the outflowing thin-shell model and observations. Kulas et al. (2012) fitted a sample of \( z \sim 2–3 \) LBGs with double-peaked line profiles and reported clear discrepancies between the models and data. Chonis et al. (2013) fitted high resolution Lyα profiles in three \( z \sim 2.4 \) LAEs and also found that the model cannot fit the profiles well, especially for the two line profiles with a weak and highly blueshifted line peak.7 Furthermore, the best fit models usually result in a low internal velocity dispersion of the outflowing thin shell in these works. This is contrary to the detected broad interstellar absorption-line profiles, which instead suggest a large bulk velocity range of outflowing gas if we assume that the outflowing shells are of the same material responsible for the interstellar absorption line (Quider et al. 2009; Kulas et al. 2012).

3.2.2. Clumpy Outflow at a Large Range of Radii

Steidel et al. (2010) simultaneously considered the profiles of Lyα emission and low-ionization interstellar absorption lines in LBGs and suggested a scenario in which the gas outflows are clumpy, spread over a large range in radius, and have gradual velocity gradients. Photons scattering from the surfaces of discrete clumps would acquire a Doppler shift that reflects the velocity of the last scattered clump. So the velocity distribution and covering fraction of clumps are most responsible for the kinematics of the observed Lyα emission line. To reproduce the profile and velocity offset of the Lyα line (\( \Delta v_{\text{Ly}\alpha} \)) and the low-ionization interstellar absorption lines in a sample of \( z \sim 2–3 \) LBGs, Steidel et al. (2010) constructed a kinematic model where optically thick gas is presented in two kinematic components. One component is at the galaxy systemic redshift and the other is outflowing with a velocity distribution. The apparent peak of the Lyα emission is modulated primarily by gas at the galaxy systemic redshift. When the velocity range spanned by the gas at the galaxy systemic redshift is broader, the Lyα emission core is more redshifted (larger \( \Delta v_{\text{Ly}\alpha} \)) and weaker.

Interestingly, an anti-correlation between the EW(Lyα) and \( \Delta v_{\text{Ly}\alpha} \) (the velocity offset between Lyα emission and the low-ionization interstellar absorption lines or optical emission lines) has been detected in \( z \sim 2–3 \) LBGs and LAEs (Adelberger et al. 2003; Shapley et al. 2003; Hashimoto et al. 2013), supporting the scenario that a smaller Lyα velocity offset suggests less absorption by gas at the galaxy systemic redshift, thus resulting in a stronger Lyα line. If J0335 is on that trend, its large EW(Lyα) implies weak absorption and small \( \Delta v_{\text{Ly}\alpha} \). The relatively low flux of the broad wing compared to the narrow-line core suggests that gas clumps with an outflow velocity ranging from zero to larger than 1000 km s\textsuperscript{-1} has a small sky coverage.

We can compare this outflow velocity with the estimated velocity required for gas to escape the dark matter halo. For LAEs at \( z \sim 5.7 \) with Lyα luminosity about 10\textsuperscript{42.0} erg s\textsuperscript{-1}, the average dark matter halo mass is about \( 6.1 \times 10^{11} M_{\odot} \) (Kovač et al. 2007; Ouchi et al. 2010). For an isothermal gravitational potential that extends to a maximum radius of \( r_{\text{max}} \), a very rough estimation of the escape velocity at radius \( r \) is \( v_{\text{esc}}(r) = \sqrt{2} v_{\text{c}}[1 + \ln(r_{\text{max}}/r)]^{1/2} \) (Veilleux et al. 2005). Taking \( r_{\text{max}} = 100 \) kpc, \( r = 1 \) kpc, and \( v_{\text{c}} = \sqrt{(GM_{\text{halo}}/r_{\text{max}})} \), we obtain an escape velocity of \( v_{\text{esc}} = 536 \) km s\textsuperscript{-1}. In the equation, \( r_{\text{max}} \) is in the square root term and \( r_{\text{max}}/r \) is in the logarithmic term. Changes in the assumed \( r_{\text{max}} \) and/or \( r \) by a factor of two would result in less than a 50% change in \( v_{\text{esc}} \). The max outflow velocity in J0335 is larger than the estimated escape velocity, being consistent with the suggestion that low-mass galaxies at \( z > 4 \) dominate the dissipation of heavy elements into the CGM (Martin et al. 2010) and the enrichment of IGM (Matda et al. 2001; Scannapieco et al. 2002).

3.3. Prevalence of Broad Red Wing in Lyα Profiles of LAEs

In this subsection we discuss the prevalence of broad red wings in profiles of \( z \sim 5–6 \) LAEs by comparing our result with published Lyα profiles. Among the published Lyα profiles at \( z = 4.5, 5.7, \) and 6.5 (Dawson et al. 2007; Hu et al. 2010; Ouchi et al. 2010; Kasihkawa et al. 2011), we note that a few Lyα line profiles seem to have broad red wings comparable to our result (e.g., 2HC124128+622022 in Figure A2 of Hu et al. 2010, and J1425554+353039 in Figure 2 of Dawson et al. 2007) but a large fraction of profiles with good S/N do not show a broad red wing. The reasons why only a small fraction of LAEs show a broad red wing may be: (1) Some LAEs intrinsically lack gas outflows with large velocity, or the covering fraction and/or the column density of outflowing gas is too small, so the broad red wing is too weak to be detected; (2) Because of the large, optical depth of gas at the galaxy systemic redshift, and/or the radiative transfer effect in outflowing gas the apparent peak of Lyα emission line shifts greatly redward, reducing the significance of broad red wing; (3) The gas outflow is anisotropic, as suggested by simulations (e.g., Barnes et al. 2011), so that a broad red wing can only be observed along particular directions. By studying Lyα line profiles with high spectral resolution, good spectral S/N, and other detectable nebulae emission/absorption lines (mostly doable for LAEs at lower redshifts; Finkelstein et al. 2011; McLinden et al. 2011; Chonis et al. 2013; Guaita et al. 2013) it is possible to obtain a better understanding of the production of broad Lyα red wing and the role outflows have in shaping Lyα line profiles, and it enables the use of the Lyα line as a tracer of gas kinematics at higher redshifts (such as at \( z > 5 \)).

7 But see http://www.nordita.org/docs/agenda/slides-alpha2013-schaerer.pdf for a conference presentation by Daniel Schaerer in 2013 September, which gave different results.
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