EXTENDED LYα EMISSION FROM A DAMPED LYα ABSORBER AT Z=3.115

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Received 2013 September 29 2013; accepted 2013 November 18

ABSTRACT

We searched for star formation activity associated with high-z Damped Lyα systems (DLAs) with Subaru telescope. We used a set of narrow-band (NB) filters whose central wavelengths correspond to the redshifted Lyα emission lines of targeted DLA absorbers at 3 < z < 4.5. We detected one apparent NB-excess object located 3.80 arcsec (~28h−1 Mpc) away from the quasar SDSS J031036.84+005521.7. Follow-up spectroscopy revealed an asymmetric Lyα emission at zem = 3.115 ± 0.003, which perfectly matches the sub-DLA trough at zabs = 3.1150 with logN(Hi)/cm−2 = 20.05. The Lyα luminosity is estimated to be LLyα = 1.07x1042 erg s−1, which corresponds to a star formation rate of 0.97 M⊙ yr−1. Interestingly, the detected Lyα emission is spatially extended with a sharp peak. The large extent of the Lyα emission is remarkably one-sided toward the quasar line-of-sight, and is redshifted. The observed spatially asymmetric surface brightness profile can be qualitatively explained by a model of a DLA host galaxy, assuming a galactic outflow and a clumpy distribution of H i clouds in the circumgalactic medium. This large Lyα extension, which is similar to those found in Rauch et al. (2008), could be the result of complicated anisotropic radiative transfer through the surrounding neutral gas embedded in the DLA.

Subject headings: cosmology: observation — galaxies: high-redshift — galaxies: galaxies — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

Damped Lyα systems (DLAs) are the highest column density [N(H i)> 2 × 1020 cm−2] absorbers identified in the spectra of quasars, and are known to be major contributors to the neutral hydrogen gas available for vigorous star formation in early epochs. The majority of neutral hydrogen at z > 3 resides in DLAs (Péroux et al. 2005); therefore tracing their evolution over cosmic time is a complementarily approach towards understanding galaxy formation. Which galaxy populations harbor DLA systems and how do they evolve with time? Based on the similarity of H i contents and gas kinematics, DLAs have been suggested as possible progenitors of the present-day spiral galaxies (Prochaska & Wolfe 1997); however, the Zn/H abundance distribution and its evolution are inconsistent with the hypothesis (Pettini 2004). Other interpretations of possible DLA candidates include gas-rich dwarf galaxies, merging protogalactic clouds, building blocks of current galaxies, or outflows from protogalaxies. Deep imaging for DLAs at z < 1, where direct detection is easier, reveals diverse morphologies in the galaxy counterparts of DLA absorbers (hereafter “DLA galaxies”), including dwarf galaxies, low-luminosity galaxies, and normal disk galaxies (e.g., Chen & Lanzetta 2003; Chen, Kennicutt & Rauch 2003; Rao et al. 2011). Concerning the counterpart of high-z (z > 2) DLA systems, there are significantly fewer identifications (e.g., Krogager et al. 2012; Fynbo et al. 2013; and references therein.), but also here the detected counterparts display diverse morphologies. Studying the conversion process of gas into stars in a hierarchically evolving galactic halo can improve our understanding of galaxy formation, and constrain structure formation scenarios. Therefore, it is quite important to detect emissions from the DLA galaxies, followed by measuring the star formation rate (SFR) of this large gas reservoir. Although absorption studies of DLAs revealed their gas contents and chemical abundances, observations of DLA emissions would additionally tell us about their SFRs. However, the SFR estimate in DLAs has proven to be very difficult, because the stellar counterparts of DLAs are often too faint to be detected in emissions, except few cases (e.g., Møller et al. 2002; Krogager et al. 2013; Fynbo et al. 2013). DLA galaxies have been identified at z > 3 in only two cases (Djorgovski et al. 1996; Schulze et al. 2012).

On the other hand, the Lyman break technique has been remarkably successful at finding galaxies in the early universe at z > 3. The number of spectroscopically confirmed Lyman-break galaxies (LBGs) has grown to more than 103. Their bright UV continuum flux suggests active ongoing star formation, and the large LBG sample enables us to constrain the cosmic SFR history. However, metal enrichment in the gas can be investigated for only a few bright LBGs with the help of gravitational lensing (e.g., Smail et al. 2007). Both LBGs and DLAs are currently effective tracers of galaxy evolution at high-z, but it remains unclear how these populations are related to each other. The simple interpretations are that
DLAs are the early-stage reservoirs of gas from which the stars in LBGs are forming, the sub-\(L^\ast\) population of LBGs or Lyman \(\alpha\) emitters (LAEs) (Rauch et al. 2008; Yajima et al. 2012), or are arising in the outer regions of the LBG galactic halo (Wolfe, Gawiser & Prochaska 2005). The measured emission properties of DLA galaxies at \(z \sim 3\) fall within the range of emission properties for LBGs of the same luminosity (Moller et al. 2002; the same holds for \(\text{O} \, \text{III}\) properties (Weatherley et al. 2003). High-metallicity DLAs are naturally expected to have luminous galaxy counterparts because of its metallicity-luminosity relation [Fynbo et al. 2008; 2013]. However, the small sample of identified DLA galaxies still critically limits any systematic comparison between DLAs and LBGs/LAEs. The DLA-LBG connection is also attracting a great deal of attention in terms of a unique approach to measure the halo mass of DLAs from the DLA-LBG clustering amplitude (Cooke et al. 2006). Our understanding of the physical or evolutionary connections between these two distinctly selected populations, i.e., \(\text{H} \, \text{I}\) cross section-selected vs. color selected, in the early universe is still in its infancy.

The galactic outflow is another aspect of the connection between DLAs and star-forming galaxies. Large-scale galactic outflows are ubiquitously found in LBGs and LAEs at \(z \sim 3\) (e.g., Shapley et al. 2003; Jones et al. 2012; Chonis et al. 2013). These outflows, which are generally referred to as “feedback” from star-formation activity, are powered by supernovae, stellar winds, photons from young stars, or some combination of the above, leading to self-regulated growth. Outflow driven by starbursts or active galactic nuclei significantly blows out gas from the galaxy, carrying metal-polluted material to the surrounding IGM. This galactic feedback plays an important role in the history of star formation and the early universe. The galactic wind, which expels gas from galaxies and modifies their chemical evolution by preferentially ejecting metals from those with lower masses, is generally regarded as a plausible origin of the mass-metallicity relation (Tremonti et al. 2004; Ledoux et al. 2006). Surprisingly, the IGM metallicity, which was primarily enriched by galactic winds from galaxies, showed almost no evolution during \(2 < z < 6\) (Songaila 2004) and a possible downturn at \(z > 6\) (Ryan-Weber et al. 2009; Simcoe et al. 2011). This implies that the IGM at \(z > 6\) had already been sufficiently metal-enriched by feedback from early galaxies. In fact, recent studies (e.g., Rauch et al. 2008; Noterdaeme et al. 2012; Kroagener et al. 2013) indicate that outflowing gas is associated with the DLA galaxies. Theoretically, Nagamine et al. (2004) suggested that strong galactic winds are required to reproduce the observed \(\text{H} \, \text{I}\) column density distribution function.

As mentioned above, only few high-\(z\) DLA galaxies have been detected in emissions so far. In this study, we carried out a search for star formation activity associated with DLAs with Subaru telescope. We used a set of narrow-band (NB) filters, whose sensitive wavelengths corresponded to the redshifted Ly\(\alpha\) emission lines of target DLA absorbers at \(z > 3\). In deep broad-band imaging, it is too difficult to detect faint objects near the line-of-sight (LOS) of bright quasars, and detections are too vague to confirm the redshift of the detected object. The excellent image quality of HST has been successful at identifying faint candidates close to the quasar sight lines, but redshift determination is quite difficult (e.g., indistinguishable from the quasar host galaxy, or in the case of multiple detections of candidates, see Warren et al. 2001). In long-slit spectroscopy, a blind slit alignment has a slim chance of encountering the target DLA galaxy, and slit scanning would be time-consuming. The advantages of NB imaging for DLA galaxies are that high-sensitivity for emissions can be obtained and the background quasar light around the DLA trough is blocked. This is essential for the direct detection of DLA galaxies that have small impact parameters. Most of the previous detections of high-\(z\) DLA galaxies have been found as LAEs, which can be easily understood given that the DLA galaxy are young, gas-rich, less dusty, and undergoing an initial star burst. The DLA galaxies could be faint in continuum flux and fairly bright in emissions, which can be efficiently detected using NB imaging. There are previous NB searches for DLA galaxy [Fynbo et al. 2003; Grove et al. 2008], though they failed to detect a counterpart galaxy.

This paper is organized as follows: In § 2, we describe the NB imaging observation to search for DLA galaxy candidates. In § 3, we describe results of the search for the NB-excess objects, in which we found one good candidate. In § 4, we present follow-up spectroscopy to confirm that the candidate is actually associated with the target DLA. We found an extended Ly\(\alpha\) emission, the possible interpretations of which are discussed in § 5.

Throughout the paper, we assume a flat \(\Lambda\)CDM cosmology with \(\Omega_m = 0.27, \Omega_{\Lambda} = 0.73,\) and \(H_0 = 70\) km \(\text{s}^{-1}\text{Mpc}^{-1}\). These parameters are consistent with recent CMB constraints [Komatsu et al. 2011]. Magnitudes are given in the AB system and distances are quoted in proper units, unless otherwise denoted.

## 2. imaging observation and photometry

We observed 5 DLA fields with Subaru/FOCAS [Kashikawa et al. 2004]. The target DLAs were selected from the DLA catalog based on SDSS DR3 (Prochaska et al. 2005) by the following criteria: 1) \(3 < z_{\text{abs}} < 4.5\), 2) the redshifted Ly\(\alpha\) emission lines of the target galaxy were within the sensitive wavelength range of any of the FOCUS NB filters, 3) \(\Delta z (z_{\text{abs}} - z_{\text{em}}) > 3000\) \(\text{km s}^{-1}\) to exclude \(z_{\text{abs}} \sim z_{\text{em}}\) DLA systems (e.g., Moller & Warren 1993), that are likely to be different from intervening DLAs due to their special environments (Moller et al. 1998; Ellison et al. 2010). The FOCUS NB filters were carefully designed to avoid the strong OH night sky emission lines. The targets are listed in Table II. Observations were made on the nights of UT 2005 August 26 and September 23-24. The total integration time for the NB filters was 2400-7200 s and the typical unit exposure time was 1200 s. We also took short exposures with broadband filters of Johnson \(B, V,\) and \(R\) bands, to constrain the continuum flux of DLA galaxies, and to discriminate LAEs from low-\(z\) \(\text{H} \, \text{II}\) and \(\text{[O} \, \text{III}\) emitters. The two BB filters for each tar-
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TARGET QUASAR LOS WITHIN 20′′

A two-dimensional Moffat profile was fit to detect the faint objects after removing the bright quasar image. The typical unit exposure time was 900 s for B and 240 s for V and R; shorter exposures were used for redder filters because of the increase in sky brightness with wavelength. The sky conditions were fairly good with a seeing size of 0'.4-0.8 arcsec. The journal of observations is provided in Table 1.

The data were reduced in the standard manner following the FOCAS data reduction pipeline. Photometric calibration was made with photometric standard stars, PG1657+078 and PG0231+051 for the BB bands, and spectroscopic standard stars PG0205+134, PG1545+035, and PG1708+602, for the NB bands. We performed object detection and photometry by running SExtractor version 2.8.6 (Bertin & Arnouts 1996) on the images. Object detection was made in the NB band images. For all objects detected in a given band pass, the magnitudes and several other parameters were measured in the other band passes at exactly the same positions as in the detection-band image, using the ‘double image mode’ of SExtractor. We detected objects that had 6 connected pixels above 2σ of the sky background rms noise and took photometric measurements at the 2σ level. Aperture photometry was performed with a 2″ aperture to derive the colors of the detected objects.

Since we were looking for faint objects near bright target quasars, object detection and photometry were inefficient and unreliable. We applied GALFIT (Peng et al. 2010) to detect the faint objects after removing the bright quasar image. A two-dimensional Moffat profile was fit to the quasar images. We searched for NB-excess (NBe) objects around the target quasar LOS within 20″ radius. The NBe criterion due to Lyα emission was defined as

\[ \text{NBe} = \text{BB}_{\text{cont}} - \text{NB} > 1.0, \]

where \( \text{BB}_{\text{cont}} \) is the continuum magnitude at the NB central wavelength. It can be roughly estimated from

\[ \text{BB}_{\text{cont}} = \frac{\text{BB}_b \times (\lambda_c^{\text{BB}_r} - \lambda_c^{\text{NB}}) + \text{BB}_r \times (\lambda_c^{\text{NB}} - \lambda_c^{\text{BB}_b})}{\lambda_c^{\text{BB}_r} - \lambda_c^{\text{BB}_b}}, \]

where \( \lambda_c^{\text{BB}_r}, \lambda_c^{\text{NB}}, \) and \( \lambda_c^{\text{BB}_b} \) are the central wavelengths of the BB\(_r\), NB, and BB\(_b\) bands, respectively.

3. DLA GALAXY CANDIDATES

Out of 5 targets, we detected one apparent NB-excess object near to SDSS J031036.84+005521.7. As expected, we also detected the NB-excess object from Q2233+131, in which a DLA galaxy has already been detected by Djorgovski et al. (1996). We also detected a very red object very near to the quasar SDSS J001240.57+135236.7, though the quick follow-up spectroscopy revealed that it was a nearby overlapping object. We did not detect any NB-excess objects around two other targets within 20″ from the quasar-LOS. Notes on three individual detections follow.

3.1. SDSS J031036.84+005521.7, \( z_{\text{abs}} = 3.114 \)

This sub-DLA was listed at \( z_{\text{abs}} = 3.1142 \) with \( \log N(\text{HI}) = 20.20 \pm 0.15 \) in SDSS DR5. We detected an NB-excess object, which did not appear in the B filter (the 3σ limiting magnitude in 2″ aperture < 25.32) and V (< 25.50) images, 3.80 arcsec away from the quasar LOS in east-northeast direction as illustrated in Figure 1. The NB total magnitude is NB502 = 25.46 ± 0.13, and the NB excess is NBe > 1.54 (1σ). We found no additional NB-excess objects around 20″ from the quasar LOS. The NB-excess object was discovered at a relatively large impact parameter of \( \sim 28h^{-1}\text{kpc} \) away from the DLA. The NB emission is sufficiently bright to carry out follow-up spectroscopy, as discussed later.

3.2. Q2233+131, \( z_{\text{abs}} = 3.151 \)

The DLA was listed at \( z_{\text{abs}} = 3.150 \) with \( \log N(\text{HI}) = 20.2 \) in Curran et al. (2002). It was identified on J23619.19+132620.3 at \( z_{\text{abs}} = 3.151 \) with \( \log N(\text{HI}) = 20.0 \) in SDSS DR5. The metallicity was estimated as \( [\text{Fe}/\text{H}]=-1.4 \) (Lu et al. 1997). The galaxy was first detected by Steidel et al. (1996), and it was confirmed as a galaxy counterpart of the DLA by Djorgovski et al.

Fig. 1.— The images of 15′× 15′ surrounding the centered quasar SDSS J031036.84+005521.7 in B, V, and NB502 (from left to right). N is up and E is to the left. The DLA galaxy is seen east-northeast of the quasar at an impact parameter of 3.7′.

TABLE 1

| Quasar                  | \( z_{\text{abs}} \) | \( z_{\text{em}} \) | \( \log N(\text{HI}) \) | \( Q_{\text{r, mag}} \) | NB | \( \lambda_c(\text{Å}) \) | \( \Delta \lambda(\text{Å}) \) |
|------------------------|----------------------|----------------------|------------------------|--------------------------|-----------------|-----------------|-----------------|
| Q2233+131              | 3.151                | 3.296                | 19.95                  | 18.77                    | NB502           | 5025            | 60              |
| SDSS J031036.84+005521.7 | 3.114‡              | 3.782                | 20.20                  | 19.71                    | NB502           | 5025            | 60              |
| SDSS J001240.57+135236.7 | 3.022                | 3.187                | 20.55                  | 19.61                    | NB487           | 4882            | 53              |
| SDSS J162626.50+275132.4 | 4.495                | 5.275                | 21.35                  | 21.65                    | NB670           | 6681            | 85              |
| SDSS J224147.76+135202.7 | 4.283                | 4.448                | 21.15                  | 19.50                    | NB642           | 6428            | 127             |

† This value is taken from SDSS DR5. This study evaluated as 3.150 ± 0.0001.
‡ This value is taken from SDSS DR5. This study evaluated as 3.151 ± 0.005.
is comparable to their sensitivity of $4 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$, which is comparable to their sensitivity of $4 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$. The excellent image quality of Subaru revealed that the DLA galaxy has a rather compact Ly$\alpha$ structure. Based on GALFIT analysis, the Ly$\alpha$ image of the DLA galaxy has an effective radius of $R_e = 1.35$ arcsec $= 10.26$ kpc with a Sersic index of $n = 1.80$. The reason for the discrepancy between our observation and Christensen et al. (2004) is not clear at this moment.

3.3. SDSS J001240.57+135236.7, $z_{abs} = 3.022$

No NB-excess objects are found around the quasar LOS; however, there is an apparent overlapping object on the quasar (Figure 3). This was an obvious DLA galaxy candidate quickly found during our observation; therefore, we switched the observing mode to spectroscopy to verify its spectrum. The FOCAS observation was first made with the VPH520 grating, which covers 4450Å−6050Å; however, we did not obtain any signal except at long wavelengths. Then, we obtained a spectrum with the VPH650 grating and the Y47 order-cut filter. The spectra covered 5300−7700 Å, with a pixel resolution of 0.63 Å. The 0″.8-wide slit gave a spectroscopic resolution of $R \sim 1300$. The integration time was 1 hr. We did not take flux calibration data for spectrophotometric standard stars. The resultant spectrum is shown in Figure 4. This object was found to be a red galaxy at $z = 0.398$, based on the CaII, H$\delta$, G, H$\gamma$, and H$\beta$ absorption lines. We concluded that this low-$z$ galaxy happened to overlap to the quasar LOS, and is not responsible for the DLA at $z_{abs} = 3.022$.

4. SPECTROSCOPY

The spectroscopic data of the DLA galaxy candidate at SDSS J031036.84+005521.7 were obtained on UT 2007 October 3 using FOCAS at the Subaru telescope. The

### Table 2: Journal of Observations

| Quasar          | date(UT) | NB  | $T_{NB}$ integ (s) | BB  | $T_{BB}$ integ (s) | seeing(arcsec) |
|-----------------|----------|-----|-------------------|-----|-------------------|----------------|
| Q2233+131       | 26/05/05 | NB502 | 6000                | B, V | 180, 120          | 0.5            |
| SDSS J031036.84+005521.7 | 24/05/05 | NB502 | 7200                | B, V | 900, 600          | 0.4            |
| SDSS J001240.57+135236.7 | 23/09/05 | NB487 | 2400                | B, V | 900, 600          | 0.8            |
| SDSS J162626.50+275132.4 | 26/05/05 | NB670 | 6000                | R   | 900, 600          | 0.6            |
| SDSS J221417.76+135202.7 | 26/05/05 | NB642 | 4800                | R   | 600, 600          | 0.5            |
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5. RESULTS AND DISCUSSION

5.1. Galaxy counterpart of DLA at $z_{abs} = 3.115$

Given the almost perfect coincidence of redshifts, we concluded that the Lyα emission comes from the galaxy associated with the DLA. The velocity difference between the DLA and the Lyα emission is within the spectroscopic resolution of 220 km s$^{-1}$. Unfortunately, our relatively low resolution spectrum did not resolve any low-ionization absorption lines to precisely determine the DLA redshift. It should also be noted that the redshift estimate of Lyα emission may be affected by the HI gas absorption in the galaxy. The HI column density ($\log N({\text{HI}}) = 20.05$ at large impact parameter of $\sim 28h_{70}^{-1}$ kpc is consistent with an HI density profile of low-z DLAs (Chen & Lanzetta 2003; Rao et al. 2011). Bouché et al. (2013) detected a DLA galaxy at $z = 2.33$ with comparably large ($\sim 26$kpc) impact parameter. It is also consistent with the DLA model prediction that DLAs with lower gas density are expected to be discovered larger impact parameter (e.g., Yajima et al. 2012). Recent studies have detected quite a number of DLA galaxies at $z > 2$, intentionally targeting for metallicity-rich DLAs (e.g., Fynbo et al. 2013). It is interesting to compare the metallicity between our detection and these studies; however, there has been no metallicity measurement for the DLA at $z_{abs} = 3.115$ of SDSS J031036.84+005521.7.

5.2. Origin of extended Lyα emission

As shown in Figure 5, the Lyα emission detected from the DLA galaxy at SDSS J031036.84+005521.7 is spatially extended. The large extent of the line emission has a sharp peak, whose wavelength perfectly agree with...
the DLA absorption centroid on the quasar spectrum. The spatial extension is remarkably one-sided toward the quasar LOS, and is redshifted. The 1D-spectrum (Figure 6) shows Lyα emission at 5001.65 Å with FWHM = 459 km s⁻¹, which we call hereafter “center” component. The maximum spatial extent of the center component is almost 2″ (~ 15.5 proper kpc) down to a flux density of 2.5 × 10⁻¹⁹ erg s⁻¹ cm⁻² Å⁻¹, which corresponds to 1.03 × 10⁻¹⁸ erg s⁻¹ cm⁻² Å⁻¹ arcsec⁻². The extension is too diffuse, with a surface brightness of 1 × 10⁻¹⁸ erg s⁻¹ cm⁻² Å⁻¹ arcsec⁻², to be identified in the relatively short-exposure NB image. In addition, there seem to be two possible subcomponents: one at 5012.46 Å with FWHM = 188 km s⁻¹ (red component) and the other at 4993.99 Å with FWHM = 306 km s⁻¹ (blue component). Figure 7 shows the spatial profiles of the extended Lyα emission in four different wavelength ranges. The center component (second and third panels from the top) shows an apparently spatially extended profile toward the quasar LOS. The red component also seems to have 1″/2 extension toward the quasar LOS, while the blue component has no apparent spatial extension and its peak position is slightly shifted to the opposite side of the quasar LOS.

Although it is difficult to identify the origin of such extended Lyα emission, we suggest a simple scenario in which this DLA galaxy is accompanied by a galactic wind. Given a galactic outflow around the source, the far side of the outflowing cloud could backscatter redshifting Lyα photons, while the blue peak would be strongly absorbed by outflowing neutral hydrogen at the near side. Thus, the outflow model generally predicts a double-peaked Lyα line profile in which the red peak is stronger than the blue peak. This picture has been well studied using simple spherically symmetric expanding shell models (Verhamme et al. 2006, 2008). The predicted Lyα profile reproduces the observed one-dimensional spectra of high-z galaxies (Kashikawa et al. 2006; Tapken et al. 2007; Yamada et al. 2012). However, the shell models generally predict a very flat surface brightness profile (Barnes & Haehnelt 2010), which appears to be different from that observed showing a sharp peak in this study (Figure 7).

Alternatively, the Lyα radiative transfer calculation by (Barnes & Haehnelt 2010), which assumes a DLA galaxy with an expanding optically thick gaseous halo, reveals significantly more centrally peaked spatial distribution, and more extended Lyα emission as higher outflow velocities. According to their model, the central H i column density in massive halos is too high to escape the Lyα photons. The Lyα photon scatter, which is induced by a number of isolated clumps, is enhanced by large bulk motion further from the center. Interestingly, their predicted two-dimensional spectrum shows a spatial asymmetry due to the underlying clumpy distribution of H i clouds, even assuming a simple spherically symmetric gas distribution and bulk motion. The observed asymmetric two-dimensional spectrum qualitatively favors this picture. Blueshifted and extended Lyα emission is expected when assuming bipolar outflowing gaseous jets perpendicular to the disk; however, the blue Lyα extension cannot be seen on the opposite side (east-northeast direction) of the quasar LOS. This blueshifted Lyα component could be significantly absorbed by a thick H i cloud associated with the DLA galaxy.

Fig. 6.—The close-up 2D spectrum around the Lyα emission at 5000 Å of the galaxy corresponding to the DLA at zabs = 3.115 of the quasar SDSS J031036.84+005521.7. Vertical direction is east-northeast (ENE). The spectrum has been smoothed with a 3 × 3 pixel top hat filter. The red contours show flux density with a width of 2.5 × 10⁻¹⁹ erg s⁻¹ cm⁻² Å⁻¹. The outermost contour corresponds to a flux density of 2.5 × 10⁻¹⁹ erg s⁻¹ cm⁻² Å⁻¹, which corresponds to a 1.5σ background fluctuation.
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5.3. Other interpretations of extended Ly\(\alpha\) emission

Rauch et al. (2011a) found a galaxy with spatially asymmetric Ly\(\alpha\) diffuse emission. Interestingly, their object has blueshifted diffuse emission, which is in clear contrast to our findings. They interpreted that the spatially asymmetric emission was caused by partial covering by a DLA cloud in front of the galaxy, and that the blueshifted diffuse emission was fluoresced by infalling neutral hydrogen gas from the backside of the DLA host galaxy. We did not detect any stellar continuum counterparts of the DLA galaxy in this study, which also invokes a Ly\(\alpha\) fluorescence (e.g., Adelberger et al. 2006; Cantalupo et al. 2012); however, no bright nearby ionizing sources have been found. As discussed in Rauch et al. (2008), the expected fluorescent Ly\(\alpha\) emission signal due to general UV background is extremely low \(\sim 10^{-19}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\), which is much lower than our data. Typical fluorescent surface brightnesses of \(> 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) can be attained only if illuminated by nearby bright quasars (Cantalupo et al. 2012), which is not likely in this case. Unlike Rauch et al. (2011a), the object in this study has neither a disturbed morphology nor any sign of interactions on the NB image.

Another possible mechanism for extended Ly\(\alpha\) emission is due to multiple scattering in the accreting cool gas onto the dark matter halo of the galaxy (Haiman et al. 2000; Yang et al. 2006; Latif et al. 2011). Following the same prescription in Rauch et al. (2011a), using an analytic relation between the star-formation produced Ly\(\alpha\) luminosity and the halo mass of Faucher-Giguère et al. (2010), the observed Ly\(\alpha\) luminosity of \(L_{\text{Ly}\alpha} = 1.07 \times 10^{42}\) erg s\(^{-1}\) yields a halo mass of \(2.2 \times 10^{12}\) M\(_\odot\), comparable to that of Rauch et al. (2011b). The expected cooling Ly\(\alpha\) radiation from cold accretion is only 4% of stellar Ly\(\alpha\) emission at this halo mass, and this cooling is only effective in massive halos. Therefore, the observed extended Ly\(\alpha\) feature is unlikely to be produced by cooling radiation, though the derived halo mass based on Ly\(\alpha\) emission is largely affected by kinematics and H\(\alpha\) distribution in the halo.
Several studies suggested a more direct connection between DLA and galactic wind. The DLA arises in the LOS where a collimated wind intersects the DLA (Nulsen et al. 1998); however this is not the case for this object, because possible open up direction of the wind cone does not correspond to the relative position of the DLA on the LOS.

5.4. Outflow and DLA

Although Wolfe & Chen (2003) constrains the spatial extent of star formation in DLAs to be less than $<3$ kpc, the large spatial extent observed here is the result of complicated anisotropic radiative transfer through the surrounding neutral gas embedded in the DLA (Rauch et al. 2008; Barnes et al. 2011). Krogager et al. (2013) also suggested the existence of a galactic wind associated with the DLA galaxy at $z = 2.35$. Noterdaeme et al. (2012) proposed a similar picture, in which the DLA galaxy at $z = 2.2$ is associated with outflowing gas. They detected double-peaked Ly{$\alpha$} emission along with [O III] and H{$\alpha$} emission, providing stronger constraints on the Ly{$\alpha$} radiative transfer on the outflow model. They also argued for possible extended (FWHM $\sim 8$kpc) Ly{$\alpha$} emission, though the small (0.9kpc) impact parameter makes it difficult to reveal the real extent upon the DLA trough. One of the general difficulties of identifying a DLA galaxy is its small impact parameter. There are some claims that DLA galaxies could have much smaller impact parameters ($<1$ arcsec) than ever searched (Okoshi & Nagashima 2005), which is supported by the idea that the inner region of DLA galaxies would have the same high H I column density as the DLA criterion of $N$(H I)$\geq 2 \times 10^{20}$ cm$^{-2}$. Our object, at a relatively large separation from the quasar-LOS, may be a rare case that fortuitously revealed such a extended feature. It is unclear whether such a low-SFR galaxy can sustain an outflow. More accurate SFR measurements based on the H{$\alpha$} line, the UV continuum luminosity, or measurements of the virial mass based on object size and velocity dispersion are necessary for further discussion.

Further increasing the number of direct detections of high-$z$ DLA galaxies will enable us to determine the relationship between DLAs and other populations, star-formation processes in a galactic halo, and the feedback to the IGM. The large variety of 2D spectral shape among the observed sample of Rauch et al. (2008) and ours could be due to a viewing angle effect, as suggested by Barnes et al. (2011), which demonstrated similar variations based on their 3D radiative transfer simulation. Ly{$\alpha$} photons tend to escape through low-density paths in the circumgalactic medium; therefore, Ly{$\alpha$} morphology is strongly dependent on a clumpy distribution of H I clouds. Our interpretation of extended Ly{$\alpha$} emission due to the outflow in a clumpy ISM is consistent with the picture implied by Law et al. (2012) for star-forming galaxies and does not necessarily support a classical bipolar outflow, which is often probed by Mg II absorption at low-$z$ (Bouch{é} et al. 2012; Lundgren et al. 2012). Spatially extended Ly{$\alpha$} emission also strongly depends on the inflow/outflow implementation; conversely, it provides an important diagnostic to infer the relationship between the internal dynamics of high-$z$ galaxies and the circumgalactic medium. Although our sample is only one DLA galaxy, detection of certain emissions from these heavy absorbers would reveal the relation between “lights” and “shades” in the high-$z$ universe.

We thank the referee for his/her helpful comments that improved the manuscript. We thank Yuichi Matsuda for their useful discussions. We are grateful to the Subaru Observatory staffs for their help with the observations. This research was supported by the Japan Society for the Promotion of Science through Grant-in-Aid for Scientific Research 23340050.

Facilities: Subaru (FOCAS).

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