Suppression of Low-mass Galaxy Formation around Quasars at $z \sim 2$–3

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Abstract

We have carried out deep and wide field imaging observations with narrow bands, targeting 11 quasar fields to systematically study the possible photoevaporation effect of quasar radiation on surrounding low mass galaxies at $z \sim 2$–3. We focused on Lyα emitters (LAEs) at the same redshifts as quasars that lie within the quasar proximity zones, where the UV radiation from the quasars is higher than the average background at that epoch. We found that LAEs with high rest-frame equivalent width of Lyα emission ($E_{W0}$) of $\gtrsim 150 \, \text{Å}$ with low stellar mass ($\lesssim 10^8 \, M_\odot$) are predominantly scarce in the quasar proximity zones, suggesting that quasar photoevaporation effects may be taking place. The halo mass of LAEs with $E_{W0} > 150 \, \text{Å}$ is estimated to be $3.6 \times 10^9 \, M_\odot$ either from spectral energy distribution fitting or the main sequence. Based on a hydrodynamical simulation, the predicted delay in star formation under a local UV background intensity with $J(\nu_{Ly}) > 10^{-21} \, \text{erg} \, \text{cm}^{-2} \, \text{Hz}^{-1} \, \text{sr}^{-1}$ for galaxies having less than this halo mass is about $\gtrsim 20 \, \text{Myr}$, which is longer than the expected age of LAEs with $E_{W0} > 150 \, \text{Å}$. On the other hand, photoevaporation seems to be less effective around very luminous quasars, which is consistent with the idea that these are still in an early stage of activity.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: formation – quasars: general

1. Introduction

High-$z$ luminous quasars are thought to form through major mergers of gas-rich galaxies (e.g., Kauffmann & Haehnelt 2002). The typical bolometric luminosity of $\sim 10^{46} \, \text{erg} \, \text{s}^{-1}$ can be achieved by releasing the huge gravitational energy of gas falling toward a central supermassive black hole (SMBH). It is hence speculated that quasars preferentially reside in overdense regions, where galaxy mergers occur frequently (e.g., Hopkins et al. 2008). The co-evolution of SMBHs and galaxies is supported by a tight correlation between the mass of central SMBHs and bulge stellar mass or velocity dispersion (e.g., Magorrian et al. 1998; Marconi & Hunt 2003). Strong clustering of galaxies around quasars has been found beyond redshift $\sim 2$ (e.g., Shen et al. 2007; Husband et al. 2013; Morselli et al. 2014; García-Vergara et al. 2017), while some high-$z$ protoclusters without active galactic nucleus (AGN) activity have also been observed (Toshikawa et al. 2014; Kang & Im 2015). Recently, Uchiyama et al. (2018) used wide field imaging of Hyper Suprime-Cam to statistically investigate the possible correlation between protoclusters and other overdensities and quasars at $z \sim 4$. It was found that the most luminous quasars tend to avoid the overdense regions, which is supported by other studies (e.g., Bañados et al. 2013; Kitamura et al. 2017; Mazzucchelli et al. 2017). Recent MUSE (Multi Unit Spectroscopic Explorer) systematic observation also showed that quasars do not inhabit the most dense environments at $z \sim 3$ and their environments seem to be similar to the field (Arrigoni Battaia et al. 2019). This is well explained by the fact that typical quasars occupy more average mass halos, but it has also been suggested that the most luminous quasars could suppress galaxy formation in their surroundings through feedback, even if some of these quasars reside in very massive dark matter halos. See Overzier (2016) for a more complete review.

Photoevaporation could be effective around quasars, in particular preventing the formation of low-luminosity galaxies. The latter are closely bound to the surrounding intergalactic medium. Photoionization heating by a strong UV background from quasars can evaporate the collapsed gas in the halo and further inhibit gas cooling (Barkana & Loeb 1999). This large-scale radiative feedback should be inefficient for bright ($L > L_\star$) galaxies residing in deep potential wells, but may heavily suppress star formation in lower-mass objects (Benson et al. 2002). After the reionization epoch, low-luminosity galaxies can form in the general field only if there are no nearby strong UV ionizing sources such as quasars and, consequently, it is expected that the luminosity function of galaxies around quasars is flatter than that of the general field population.

Kashikawa et al. (2007) carried out a survey for both Lyman break galaxies (LBGs) and Lyα emitters (LAEs) around a quasar, SDSS J0210-0018 at $z = 4.8$. They found that LBGs formed a filamentary structure including the quasar, while LAEs were distributed in a ring-like structure around the quasar, avoiding its immediate vicinity within a distance of $\sim 4.5$ comoving Mpc (cMpc). This clustering segregation could be caused by photoevaporation, resulting in a deficit of the lower-mass LAEs around a strong UV source. LAEs are young galaxies with low dust content, and relatively low stellar mass (Shapley et al. 2001); therefore, they are particularly prone to photoevaporation in the vicinity of strong radiation sources such as quasars. Recently, Ota et al. (2018) found a quasar residing in a low-density region of LAEs at $z = 6.6$, while
Kikuta et al. (2017) investigated distributions of LAEs around two quasars and a radio galaxy at $z \sim 4.9$ and did not find any evidence of the quasar photoevaporation effect. These previous studies at $z \sim 5–6$ did not go deep enough to probe galaxies with sufficiently low luminosity ($M_{\text{UV}} > -20.5$) or mass ($M_{\text{vir}} < 10^{10} M_{\odot}$), where more effective photoevaporation is expected. In addition, the small sample sizes did not allow us to derive a general picture of this effect around high-$z$ quasars.

In this paper, we carried out wide field imaging using Suprime-Cam mounted on the 8.2 m Subaru telescope targeting 11 fields with a strong local UV background from quasars at $z = 2–3$ in order to systematically study the radiative feedback effect on low-luminosity galaxies. The combination of narrow-band (NB) imaging with deep broad-band (BB) imaging can effectively isolate LAEs at $z = 2–3$ (Venemans et al. 2005), down to low luminosity of $M_{\text{UV}}^* + 2.0$, which is 1.5 magnitudes deeper than our previous study at $z = 4.8$.

The paper is organized as follows. In Section 2 we describe the selection and reduction of targeted quasar fields, and construct our LAE sample. In Section 3 we investigate the LAE galaxy density in the vicinity of the quasars and search for correlations between the galaxy density and the properties of the LAEs and the quasars (e.g., black hole mass and luminosity). The implications of our results are discussed in Section 4. In Section 5 we conclude and summarize our findings. We assume the following cosmological parameters: $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. Magnitudes are given in the AB system.

2. Data and Sample Selection

We conducted wide field imaging using Suprime-Cam (Miyazaki et al. 2002) on the 8.2 m Subaru telescope for 11 quasar fields at $z \sim 2–3$ in order to systematically study the photoevaporation effect. We selected quasars whose redshifted Ly$\alpha$ falls in the wavelength range of the Suprime-Cam NB filters, NB400 (500 Å, FWHM = 92 Å, $z_{\text{Ly} \alpha} = 2.29_{-0.04}^{+0.04}$), NB413 (513 Å, FWHM = 93 Å, $z_{\text{Ly} \alpha} = 2.40_{-0.03}^{+0.05}$), NB503 (503 Å, FWHM = 74 Å, $z_{\text{Ly} \alpha} = 3.14_{-0.01}^{+0.03}$), NB515 (515 Å, FWHM = 79 Å, $z_{\text{Ly} \alpha} = 3.24_{-0.01}^{+0.03}$), where $z_{\text{Ly} \alpha}$ shows the Ly$\alpha$ redshift ranges corresponding to the FWHMs of the NB filters (Figure 1). The systemic redshifts are determined by H$\beta$, [O III] emission lines (Shemmer et al. 2004; Netzer et al. 2007) or narrow low-ionization lines (Sulentic et al. 2014); these are more reliable than those measured by Ly$\alpha$ or C IV lines, which are easily influenced by quasar outflows (Uchiyama et al. 2018). We selected quasars with a wide range in UV luminosity (log $\lambda L_{\lambda}(912$ Å) = 45.6–47.8) in order to investigate the variation of the quasar photoionization feedback. In total, we observed 11 quasar fields, three of which contain radio-loud quasars (SDSS 1411, TXS1529, and SDSS 2135), and one contains a pair with the two quasars (SDSS 1623 and SDSS 1624) in close proximity with each other (e.g., Djorgovski et al. 1987; Onoue et al. 2018). The redshift and angular separation of the quasar pair are $\Delta z = 0.006$ and $\Delta \theta = 3.5$ arcmin (1.7 physical Mpc (pMpc)), respectively. The properties of the quasars are also summarized in Table 1.

Observations were made on six nights in UT 2014, 2015 and 2017. Suprime-Cam has 10 2k $\times$ 4k MIT/LL CCDs, and covers a contiguous area of 34' $\times$ 27' with a pixel scale of 0''202 pixel$^{-1}$. BB imaging is required to measure the flux excess in the NB filters. The integration time was 12,000–16,800 s in each band. For the BB filters, the typical unit exposure time was 600 s for B-band and V-band filters and 300 s for the r$'$-band filter, which was used because the V-band filter was not available during the observations of the SDSS 1551 quasar field, while for the NB filters, the exposure time was 1200 s. We adopted a common circle dithering pattern (full cycle) consisting of seven to nine pointings for the NB filters and four to eight pointings for the BB filters. The sky conditions were fairly good with a seeing size of 0.60–1.40 arcsec. The observation configuration is shown in Table 2.

We used SDFRED version 2.0 (Yagi et al. 2002; Ouchi et al. 2004) to conduct the data reduction of the NB and BB images. The L.A. Cosmic recipe (van Dokkum 2001) was used to remove cosmic rays, which was significant in the NB images taken with a long exposure time (1200 s). Flux calibrations of the NB images were made with the spectro-photometric standard stars Feige110 for the NB400, NB413 and NB515 images and Feige63 for the NB503 images. For the BB images, we used photometric standard stars SA110 and SA113 for the B-band images, and SA110 for the V-band images. The calibrations for the r$'$-band were done using stars in the Sloan Digital Sky Survey (SDSS) DR14 catalog. We carefully checked the estimated zero-point magnitudes using spectroscopic A-type stars, which have an almost flat spectrum in our observed wavelength ranges, found in SDSS DR14. The astrometric calibration of NB-detected objects was performed using the Naval Observatory Merged Astrometric Dataset. The astrometric accuracy was $\sim 0.3$ arcsec estimated using the SDSS DR14 catalog. The double image mode of SExtractor version 2.19.5 (Bertin & Arnouts 1996) was used for object detection and photometry. We detected objects that had at least 10 connected pixels above 1.5$\sigma$ times the sky background rms noise and made photometric measurements at the 1.5$\sigma$ level in the NB images. The sky background rms was estimated through SExtractor as follows. Each image was separated into several meshes of 24 arcsec. The mean and standard deviation of the counts in each mesh were estimated with 3$\sigma$ clipping, and the mesh values which were too bright were removed through the median filtering. Finally, each mesh had the sky background rms interpolated by a bicubic interpolation. We masked the area around bright objects and shallower regions around the edge of each image ($\sim 3$ arcmin). The magnitudes of detected objects were measured within apertures of 2 arcsec diameter. The 5$\sigma$ limiting magnitudes measured in the 2 arcsec apertures are summarized in Table 2 for all images.

2.2. LAE Selection

We used the following criteria, which are essentially the same as those of Mawatari et al. (2012) and Matsuda et al. (2005), to select LAEs in all quasar fields:

$$m_{\text{BB}} - m_{\text{NB}} > f(15-0\text{Å}),$$
$$m_{\text{NB}} < m_{\text{lim},5\sigma},$$
$$m_{\text{BB}} - m_{\text{NB}} > h + 3\sigma_{\text{color}},$$

where $m_{\text{lim},5\sigma}$ and $3\sigma_{\text{color}}$ are the 5$\sigma$ limiting magnitude and 3$\sigma$ color error, respectively. $h$ is the color term, for which we use the typical $m_{\text{BB}} - m_{\text{NB}}$ color of the galaxies without Ly$\alpha$ emission, assumed to be the mode in the color distribution of objects lying in a range of 18.0 $< m_{\text{NB}} < 24.0$. 

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Table 1

| Quasar Name | R.A. (J2000) | Decl. (J2000) | $z_{sys}$ | log $M_\odot$ (erg s$^{-1}$) | log $M_\odot$ (erg s$^{-1}$) | Radio | ref. 1 | ref. 2 |
|-------------|-------------|-------------|---------|-----------------|-----------------|------|------|------|
| SDSS J095143.3+013259.5 | 09°51'41.33 | +01°32'59.5 | 2.411 | 45.9534 | 8.90 | quiet | 1 | 1 |
| SDSS J215034.41–010510.5 | 12°35'02.6 | –11°30'29'' | 2.407 | 46.9242 | 9.89 | quiet | 2 | 2 |
| SDSS J170102.18 | 12°20'34.41 | –01°05'10.5 | 2.397 | 45.8869 | 9.060 | quiet | 1 | 1 |
| SDSS J114213.51+004253.0 | 14°11'23.5 | +00°42'53'' | 2.257 | 46.7248 | 9.37 | loud | 3 | 3 |
| SDSS J124656.18+602550.8 | 14°26'56.1 | +60°25'50'' | 3.202 | 44.8206 | 9.82 | quiet | 3 | 3 |
| TXS 1529–230 | 15°32'31.5 | –23°10'32'' | 2.280 | 46.3152 | 9.42 | loud | 2 | 2 |
| SDSS J155137.22+321307.5 | 15°51'37.22 | +32°13'07.5 | 3.143 | 46.0280 | 9.54 | quiet | 4 | 4 |
| SDSS J162359.21+554108.7 | 16°23'59.21 | +55°41'08.7 | 2.272 | 45.5920 | 8.96 | quiet | 2 | 2 |
| SDSS J162421.29+554243.0 | 16°24'21.29 | +55°42'43.0 | 2.278 | 45.6695 | 8.94 | quiet | 2 | 2 |
| SDSS J170102.18+612301.0 | 17°01'02.18 | +61°23'01.0 | 2.301 | 46.4573 | 9.72 | quiet | 3 | 3 |
| HB89–1835+509 | 18°36'14.50 | +51°01'45.0 | 2.272 | 46.4891 | 9.34 | quiet | 2 | 2 |
| SDSS J213510.60+013930.5 | 21°35'10.6 | +01°39'31'' | 3.199 | 46.2128 | 8.65 | loud | 3 | 3 |

Notes. (1) Netzer et al. (2007); (2) Sulentic et al. (2014); (3) Shenmer et al. (2004); (4) Saito et al. (2016).

$^a$ Systemic redshift.

$^b$ Logarithm of intrinsic luminosity at rest wavelength 912 Å in $L_\odot$, which is estimated by fitting a single power law to the continuum free of line emission (Section 3.1).

$^c$ Logarithm of black hole mass in $M_\odot$.

$^d$ Radio loud or not (Shemmer et al. 2004; Sulentic et al. 2014).

$^e$ The reference for the black hole mass. * shows that the black hole mass was estimated by us using the CIV-based black hole mass estimator of Shen et al. (2011) using the parameters given by Sulentic et al. (2014). Netzer et al. (2007) found that the errors of the black hole masses are estimated to be 20%–60%. We provided an error of 60% for their black hole masses. The typical uncertainties of the black hole masses estimated by Shemmer et al. (2004) are less than a factor of two. Their masses we list have an uncertainty of the factor of two.

$^f$ The reference for $z_{sys}$.

$f(\text{EW}_0 = 20 \text{ Å})$ is the color corresponding to the Ly$\alpha$ equivalent width (EW$_0$) of 20 Å at the rest frame, expected by our LAE model constructed in the Appendix. If the objects were not detected in the BB filter at 2$\sigma$, their BB magnitudes were replaced by the corresponding 2$\sigma$ limiting magnitudes. In addition, we carefully checked the images and removed fake detections by eye. As a result, we obtained 1171 LAEs in total, 195 of which had no UV continuum detection. These LAEs may appear due to the quasar fluorescence effect (e.g., Cantalupo et al. 2007). It was confirmed that even if the 195 LAEs were excluded, our results did not change within the 1$\sigma$ error. The number of LAE candidates obtained through the criteria in each field is also listed in Table 2 and the color–magnitude diagrams of each field are shown in Figure 2. Figure 3 shows the number counts of LAEs in each quasar field. The counts are consistent with those of previous work (Grove et al. 2009; Mawatari et al. 2012), which studied a field around the radio galaxy 53W002 (744 arcmin$^2$) and some blank fields, BRI 1202–0725, BRI 1346–0322, and Q 2138–4427 (133 arcmin$^2$). We can ignore the contamination of low-z emitters because the contamination rate is expected to be at most $\sim 1\%$ according to Mawatari et al. (2012) and Matsuda et al. (2005, 2006). There is no excess in the $m_{BB} - m_{NB}$ color of the SDSS 1551, SDSS 1701, and OH91–121 quasars due to strong absorption seen in the spectrum at the Ly$\alpha$ line. In addition, the flux of quasar SDSS 1426, which is not plotted in the color–magnitude diagram, could not be accurately measured due to saturation of the CCD. Two possible quasars, SDSS J125036.70–005531.7 (Lee et al. 2013) and QSO B1833+509 (Woodman 1985), whose redshifts determined by Ly$\alpha$ emission coincidentally fall in the NB filters, reside in the SDSS 1250 and OH91–121 quasar fields respectively, also shown in Figure 2 (black open stars). We confirmed that, even if the two quasars were included in our analysis, the results are unchanged.

The detection completeness of LAEs was estimated by Monte Carlo simulation. First, we distribute 5000 artificial objects with 18.0 < $m_{NB} < m_{lim,5\sigma}$ so that the EW distribution follows that of Mawatari et al. (2012), $f(\text{EW}_0) = C e^{-\text{EW}_0/w_0}$, where $C$ is a normalization constant and $w_0 = 43.7$ Å is the $e$-folding length. We conduct source detection, photometry, and LAE selection with the same parameters as we did for the real images. Then, we define the completeness as the fraction of the number of pseudo-LAEs detected in each magnitude bin (we take an ensemble average with 1000 realizations). The completeness is $\geq 60\%$ at the 5$\sigma$ limiting magnitude of the NB filter for each field.

3. Results

3.1. LAE Galaxy Density around Quasars

We applied the fixed aperture method to determine LAE surface density contour maps. We estimated a local number density by counting LAEs within the fixed aperture to evaluate the overdensity $\delta$ defined as $\delta = (N - \bar{N})/\bar{N}$, where $N$ is the number of LAEs in the aperture. The scale of 8.0 cMpc is used as the radius of distributed apertures in each field (Kikuta et al. 2017). $\bar{N}$ is the average of $N$ given by the all-quasar-fields average of the LAE number counts at the 5$\sigma$ NB limiting magnitude for each field. We confirmed that the LAE number counts are consistent each other for all our target regions. The surface density of the LAEs in masked regions is assumed to be the same as $\bar{N}$. 


Table 2
Observation Log

| Quasar Name                  | Filter | Exposure time (s) × shots | Seeing (arcsec) | \(m_{\text{lim},5\sigma}\) (mag) | Date          |
|-----------------------------|--------|--------------------------|----------------|-------------------------------|---------------|
| SDSS J095141.33+013259.5     | NB400  | 1200 × 9                 | 1\(^{\circ}\)24 | 25.23                         | 2014 May 25, 26, 27 |
|                             | B      | 600 × 5                  | 0\(^{\circ}\)96 | 26.44                         | 2014 May 27   |
| OH91–121                    | NB413  | 1200 × 7                 | 1\(^{\circ}\)20 | 25.45                         | 2015 Jun 17   |
|                             | B      | 600 × 7                  | 1\(^{\circ}\)20 | 26.23                         | 2015 Jun 16   |
| SDSS J125034.41–010510.5     | NB413  | 1200 × 8                 | 1\(^{\circ}\)40 | 25.77                         | 2014 May 26, 27 |
|                             | B      | 300 × 8                  | 1\(^{\circ}\)40 | 26.12                         | 2014 May 26   |
| SDSS J141123.51+004253.0     | NB400  | 1200 × 8                 | 1\(^{\circ}\)04 | 25.75                         | 2014 May 25   |
|                             | B      | 600 × 5                  | 1\(^{\circ}\)30 | 26.25                         | 2014 May 26   |
| SDSS J142656.18+602550.8     | NB515  | 1200 × 7                 | 0\(^{\circ}\)78 | 25.63                         | 2014 May 27   |
|                             | V      | 600 × 4                  | 0\(^{\circ}\)80 | 25.95                         | 2014 May 27   |
| TXS 1529-230                | NB400  | 1200 × 5                 | 0\(^{\circ}\)96 | 25.00                         | 2015 Jun 16   |
|                             | B      | 600 × 4                  | 0\(^{\circ}\)96 | 26.04                         | 2015 Jun 17   |
| SDSS J155137.22+321307.5     | NB503  | 900 × 4 + 600 × 10       | 0\(^{\circ}\)60 | 25.28                         | 2017 May 23   |
|                             | B      | 300 × 6                  | 1\(^{\circ}\)12 | 25.80                         | 2017 May 23   |
| SDSS J162359.21+554108.7     | NB400  | 1200 × 7                 | 1\(^{\circ}\)20 | 25.67                         | 2015 Jun 17   |
| SDSS J162421.29+554243.0     | B      | 600 × 4                  | 0\(^{\circ}\)98 | 26.88                         | 2015 Jun 17   |
| SDSS J170102.18+612301.0     | NB400  | 1200 × 9                 | 1\(^{\circ}\)10 | 25.72                         | 2014 May 25   |
|                             | B      | 600 × 4                  | 0\(^{\circ}\)70 | 27.12                         | 2014 May 27   |
| HB89–1835+509               | NB400  | 1200 × 8                 | 0\(^{\circ}\)84 | 25.73                         | 2015 Jun 16   |
|                             | B      | 600 × 4                  | 0\(^{\circ}\)94 | 26.59                         | 2015 Jun 17   |
| SDSS J213510.60+013930.5     | NB515  | 1200 × 8                 | 1\(^{\circ}\)10 | 24.95                         | 2014 May 26   |
|                             | V      | 600 × 4                  | 0\(^{\circ}\)80 | 25.48                         | 2014 May 27   |

Note.

a The \(\text{r}'\)-band was used because the \(V\)-band filter was not available for SDSS 1551.

Figure 1. Filter transmission curves. The solid lines show the transmission curves of the broad-band filters \(B\), \(V\), and \(\text{r}'\), from the left. The dashed lines indicate the curves of the narrow-band filters NB400, NB413, NB503, and NB515, from the left.

We also calculate the size of the quasar proximity zones, where the UV radiation from the quasars is higher than the UV background radiation. The isotropic UV intensity \(J(\nu)\) of radiation at the Lyman limit from a central quasar, \(J_{21}\), is important in evaluating the quasar photoevaporation effect (Kashikawa et al. 2007):

\[
J(\nu) = J_{21} \left( \frac{\nu}{\nu_L} \right)^{\alpha} \times 10^{-21} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1},
\]

where \(\nu_L\) is frequency at the Lyman limit, and \(\alpha\) is the slope of the flux density of the quasar, \(F_\nu(\nu) \propto \nu^{\alpha}\). We estimate the intrinsic monochromatic luminosity at the Lyman limit by fitting a single power law to the flux free of line emission at 1340–1360 Å, 1440–1450 Å, and 1700–1730 Å, using the rest-frame wavelength quasar spectrum from the SDSS Science Archive Server, with spectral resolution \(R \sim 1300–2500\). (Pâris et al. 2017), for the quasars obtained by the SDSS. The spectra of OH91–121, TXS1529, and HB89–1835 were taken from Sulentic et al. (2014). The intensity of the UV background radiation at \(z = 2–4.5\) was evaluated to be \(J_{21} = 1.0^{+0.5}_{-0.3}\) with weak dependence on redshift from the quasar proximity effect measurements of Cooke et al. (1997). The local UV radiation within the circle of the radius of \(r_{\text{prox}}\)

\[
r_{\text{prox}} = \frac{1}{4\pi} \frac{L(\nu_L)}{10^{-21}} \text{ pMpc},
\]

is expected to be enhanced compared with the UV background. Therefore, we used \(r_{\text{prox}}\) to search for possible photoevaporation effects on the properties of LAEs. For SDSS 1426, we used the \(J_{21} = 10\) radius instead of \(J_{21} = 1\) to evaluate the
environmental effect because the radius of $J_{21} = 1$ is larger than the field of view (FoV) due to the brightness of the quasar. We estimated $r_{\text{prox}}$ for each quasar using its own alpha. Assuming the fixed typical alpha of $-0.30$ (Selsing et al. 2016), the $r_{\text{prox}}$ varies by as little as $\sim 0.04$ arcmin ($\sim 0.07$ cMpc). The values of $r_{\text{prox}}$ are listed in Table 3. Figure 4 shows the density maps of the LAEs in each quasar field with $r_{\text{prox}}$ indicated for $J_{21} = 1$ and 10.

The average density near the quasars is $0.023$ cMpc$^{-2}$, which corresponds to an overdensity $\delta = 0.48$ with $0.82\sigma$ significance.
The quasars are found to reside in average density environments, which is consistent with the findings of Uchiyama et al. (2018). SDSS 1624 occupies the highest density of $0.045 \text{ cMpc}^{-2}$ which corresponds to overdensity $\delta = 1.539$. Interestingly, this quasar forms a close pair with another quasar. Onoue et al. (2018) found that quasar pairs statistically tend to reside in overdense regions at $z \sim 1$ and 4. The densities of the quasars are summarized in Table 3. We examine the possible relations between the overdensities and black hole masses and radio-loudness of the quasars, shown in Figure 5. There are no significant correlation as in the case of Uchiyama et al. (2018). In the Spearman rank correlation test, the $P$-value of a relation between the overdensity and the black hole mass is 0.17. Using only radio-quiet quasars, the $P$-value is 0.24.

3.2. UV Luminosity Distributions of LAEs in the Vicinity of Quasars

The UV luminosity of an LAE is estimated using our LAE model (see Appendix). Note that the derived $M_{UV}$ distribution is affected by the discrepancy of completeness between the NB and BB filters, since our Ly$_\alpha$-selected sample is constructed from an NB magnitude-limited sample. It is difficult to correct the sample for completeness, and we only

![Figure 3. Number count of LAEs. The blue dots show the number counts of LAEs in each quasar field. The error bars indicate the Poisson error. The gray shaded regions shown in the HB89−1835, SDSS 1623+1624, SDSS 1701, SDSS 1411, TXS1529, SDSS 0951, OH91−121, and SDSS 1250 quasar fields at $z \sim 2$ indicate the LAE number count of Mawatari et al. (2012), while in the SDSS 1551, SDSS 1426, and SDSS 2131 fields at $z \sim 3$ they indicate the count given in Grove et al. (2009).]
focus on the relative difference of the distributions found in the vicinity and outer regions of the quasars. Figure 6 shows the $M_{14}$ distribution of LAEs in the quasar fields. A deficit of faint ($M_{14} > -17$) LAEs in the proximity of a quasar can be seen in several fields. To see this trend more clearly, the average UV luminosity distribution for all quasar fields except SDSS 1426 is shown in Figure 7. We normalize the height of each distribution with that of SDSS 1701 when taking the average because we want to see only the difference in the shapes of the distributions. The $M_{14}$ distributions are almost identical between the vicinity and outer regions of the quasars at the bright end $M_{14} < -17.0$, while at the end, faint LAEs are significantly deficient in the vicinity of the quasars. This result suggests that fainter LAEs with $M_{14} > -17.0$ tend to avoid the central quasar, as expected if the photoevaporation effects are shown. Moreover, we found that faint LAEs with $M_{14} > -18.0$ only appeared around the four brightest quasars, SDSS 1426, OH91–121, SDSS 1411, and HB89–1835, whose bolometric luminosities are estimated to be brighter than that of a typical hyper-luminous quasar, $L_{\text{bol}} > 10^{47}$ erg s$^{-1}$ (Bischetti et al. 2017), using the bolometric correction of Runnoe et al. (2012). If we try to exclude these hyper-luminous quasars, the trend becomes clearer as shown in Figure 7. This trend did not change even if the two possible quasars in HB89–1835 and SDSS 1250 (white stars in Figures 2 and 4) were included. However, there is an uncertainty in that the difference can be seen only beyond the completeness limit (vertical gray line in Figure 7).

### 3.3. Equivalent Width Distributions of LAEs in the Vicinity of Quasars

It is well known that the EW$_0$ of Ly$\alpha$ emission is anti-correlated with the stellar masses of LAEs (e.g., Nilsson et al. 2009). The EW$_0$ of an LAE is estimated based on our LAE model (see the Appendix). The correlation coefficient $\rho$ and $P$-value between the EW$_0$ and $M_{14}$ distribution are 0.74 and $< 0.05$ in the Spearman rank correlation test. The distribution of the EW$_0$ of Ly$\alpha$ emission of LAEs for each field is shown in Figure 8, which suggests that the LAEs in the quasar proximity region tend to have lower EW$_0$, especially, in the case of SDSS 1701. The average EW$_0$ distribution for all fields apart from SDSS 1426 are shown in Figure 9 in order to make the trend clearer. We found a tendency that LAEs with EW$_0 > 150$ Å are scarcer in the proximity of quasars, while the abundance of LAEs with EW$_0 \lesssim 100$ Å is almost the same in the vicinity and outer region. In the quasar proximity region, high-EW$_0$ LAEs with EW$_0 > 150$ Å appear only around the four most luminous quasars. As is the case with the $M_{14}$ distribution, the trend becomes clearer if these hyper-luminous quasars are excluded (Figure 9). The EW$_0$–UV luminosity relation (Nilsson et al. 2009) suggests that an LAE with high EW$_0$ tends to have lower UV luminosity. In fact, $M_{14}$ of $> -18.0$ corresponds to EW$_0 > 150$ Å in our EW$_0$–UV luminosity relation. Our finding of a paucity of LAEs with high EW$_0$, which corresponds to low stellar mass objects around quasars, could be caused by the quasar photoevaporation effect. A more quantitative discussion is provided in Section 4. Again, even if we add the two possible quasars (white stars in Figures 2 and 4), the result is unchanged.

### Table 3

Results

| Quasar Name       | Volume (x10$^3$cMpc$^3$) | # LAEs | Overdensity | $r_{\text{prox}}$ (arcmin cMpc) | $N_{\text{exp.}}^{\text{UV}} (>150$ Å$)$ | $N_{\text{obs.}}^{\text{UV}} (>150$ Å$)$ |
|------------------|-------------------------|--------|-------------|-------------------------------|-----------------------------------------|----------------------------------|
| SDSS J095141.33+013259.5 | 1.27                    | 68     | 1.15        | 2.76 (4.60)                  | 0.368                                   | 0.00                             |
| OH91–121           | 1.26                    | 84     | 0.640       | 8.44 (14.0)                  | 4.22                                   | 3.63                             |
| SDSS J125034.41+010510.5 | 1.54                    | 157    | 0.437       | 2.56 (4.24)                  | 0.464                                   | 0.00                             |
| SDSS J141123.51+004253.0 | 1.42                    | 100    | 0.379       | 6.63 (10.7)                  | 2.17                                   | 2.52                             |
| SDSS J142658.18+602550.8 | 1.05                    | 137    | 0.741       | 25.5 (48.6)                  | 0.866 (#)                              | 7.45 (#)                        |
| TXS 1529–230       | 1.76                    | 48     | 0.653       | 4.15 (6.70)                  | 0.316                                   | 0.00                             |
| SDSS J155137.22+321307.5 | 1.06                    | 103    | 0.337       | 3.22 (6.08)                  | 0.00                                   | 0.00                             |
| SDSS J162359.21+554108.7 | 1.52                    | 142    | 0.653       | 1.80 (2.91)                  | 0.188                                   | 0.00                             |
| SDSS J162421.29+554234.0 | 1.52                    | 142    | 1.54        | 1.97 (3.19)                  | 0.253                                   | 0.00                             |
| SDSS J170102.18+612301.0 | 1.42                    | 162    | 0.216       | 4.89 (7.95)                  | 12.8                                   | 0.00                             |
| HB89–1835+509      | 1.27                    | 111    | −0.0406     | 5.06 (8.17)                  | 2.46                                   | 1.00                             |
| SDSS J213510.60+013930.5 | 0.967                   | 59     | −0.711      | 4.01 (7.63)                  | 0.163                                   | 0.00                             |

Notes.

a The effective volume in each field.

* The observed number of LAEs.

$\rho$ Overdensity which the quasar resides in: $\rho = (N - \bar{N})/\bar{N}$.

d The local UV radiation within the circle of the radius of $r_{\text{prox}}$, which is defined by Equation (5), is enhanced compared with the UV background by the radiation from each quasar.

e The expected completeness-corrected number of LAEs with EW$_0 > 150$ Å in each quasar proximity zone.

f The observed completeness-corrected number of LAEs with EW$_0 > 150$ Å in each quasar proximity zone.

g We used the $J_21 = 0.05$ radius instead of the $J_21 = 1$ radius, which is used in other quasar fields, because the radius of $J_21 = 1$ in the SDSS 1426 field is larger than its FoV.

h Total except for SDSS 1426.

i Total except for the four brightest quasars, SDSS 1411, SDSS 1426, OH91–121, and HB89–1835.
The deficit of LAEs with high EW0 in the vicinities of our quasars could be just due to the limited area rather than photoevaporation effects. We define \( N_{\text{obs}}^{150} (> 150 \, \text{Å}) \) and \( N_{\text{exp}}^{150} (> 150 \, \text{Å}) \), which are summarized in Table 3, as the observed and expected completeness-corrected number of LAEs with \( EW_0 > 150 \, \text{Å} \), respectively. \( N_{\text{exp}}^{150} (> 150 \, \text{Å}) \) is estimated assuming that the intrinsic LAE number density in the vicinity of a quasar is the same as that in the outer region. The highest expected number \( N_{\text{exp}}^{150} (> 150 \, \text{Å}) = 12.8 \) was found in the SDSS 1701 field even though \( N_{\text{obs}}^{150} (> 150 \, \text{Å}) = 0 \). The difference may occur due to two possible overdense regions not centered on the SDSS 1701 quasar. As seen in Table 3, the total \( N_{\text{obs}}^{150} (> 150 \, \text{Å}) \) is

![Overdensity maps in the quasar fields. The filled and open black stars show the quasars and possible quasars in each field, respectively. The black dots indicate the LAE candidates. The color contours show the overdensity. The radii of isotropic UV intensity \( J_{21} \) of 1 and 10 are indicated by the solid and dashed black circles, respectively. The gray shaded areas show the masked regions. The size of each panel is 30 × 25 arcmin\(^2\). The length of 8 cMpc, which is the scale used to derive the overdensity, is indicated by the black line in the lower right corner in each panel.](image-url)
significant smaller than the total $N_{\text{exp}}^{\text{EW}0} (>150 \, \text{Å})$. Interestingly, there are no LAEs with $\text{EW}_0 > 150 \, \text{Å}$ in the vicinity except for the four brightest quasars. This is unlikely to be caused by a possible optical vignetting of Suprime-Cam because our quasars always lie in the center of the images. We also perform $\chi^2$ fitting to the equation, $e^{-\text{EW}_0/w_0}$, which describes the EW$_0$ distribution in the outer region, and obtain $w_0 = 69^{+4}_{-5} \, \text{Å}$, which is consistent with Guaita et al. (2010) and Gronwall et al. (2007) who found that $w_0 = 83^{+10}_{-10} \, \text{Å}$ at $z \sim 2$ and $w_0 = 76^{+11}_{-8} \, \text{Å}$ at $z \sim 3$, respectively. On the other hand, the decay scale $w_0$ estimated by Nilsson et al. (2009) and Mawatari et al. (2012) at $z \sim 2$ is lower, $w_0 = 48.5^{+13}_{-13} \, \text{Å}$ and $43.7^{+20}_{-34} \, \text{Å}$, respectively, and they suggested more redder galaxies populate LAEs at lower redshift. If we focus on $z \sim 2$ in our sample, we get $w_0 = 73^{+11}_{-11} \, \text{Å}$. While some $w_0$ evolution is observed at a redshift range of $\sim 3$–6 (Hashimoto et al. 2017a), a consistent picture still needs to be derived for $z \sim 2$–3.

4. Discussion

Kashikawa et al. (2007) showed that a gas cloud in a halo with a small dynamical mass $M_{\text{vir}} \lesssim 10^9 M_\odot$ will experience a considerable delay in star formation under a local UV background with $J_{21} \gtrsim 1$ based on the hydrodynamical simulation of Kitayama et al. (2000, 2001). Recently, Hashimoto et al. (2017b) concluded that LAEs with large Ly$\alpha$, $\text{EW}_0 \sim 200$–400 Å, have notably small stellar masses of $10^7$–$10^8 M_\odot$, the median value of which is $7.1^{+4.8}_{-2.8} \times 10^7 M_\odot$ using the spectral energy distribution (SED) fitting method. Also, the stellar masses of LAEs with a smaller $\text{EW}_0$ of $\lesssim 150 \, \text{Å}$ are found to be $5.9^{+2.2}_{-2.2} \times 10^7 M_\odot$ (Shimakawa et al. 2017). The stellar masses of LAEs can also be estimated from the star formation rate (SFR)-stellar mass relation, the “main sequence.” The average SFR is 0.9 $M_\odot \, \text{yr}^{-1}$ for LAEs with $\text{EW}_0 > 150 \, \text{Å}$ and 6.4 $M_\odot \, \text{yr}^{-1}$ for those with $\text{EW}_0 < 150 \, \text{Å}$ (Kennicutt 1998). Based on the main sequence of LAEs by Vargas et al. (2014), the stellar mass is estimated as $10^{7.8} M_\odot$ and $10^{8.9} M_\odot$ for $\text{EW}_0 > 150 \, \text{Å}$ and $\text{EW}_0 < 150 \, \text{Å}$, respectively, which is consistent with the SED fitting result. The stellar to halo mass ratio (SHMR) of LAEs at $z \sim 2$ is estimated to be $0.02^{+0.07}_{-0.04}$, assuming that each halo hosts one galaxy (Kusakabe et al. 2018). Therefore, it is expected that LAEs with $\text{EW}_0 \gtrsim 150 \, \text{Å}$ have a halo mass $M_{\text{vir}} = 3.6^{+12.7}_{-2.3} \times 10^9 M_\odot$, and LAEs with $\text{EW}_0 \lesssim 150 \, \text{Å}$ occupy more massive halos of $M_{\text{vir}} = 2.9^{+14.0}_{-1.8} \times 10^{10} M_\odot$, using the stellar mass estimated by Hashimoto et al. (2017b) and Shimakawa et al. (2017) and the SHMR of Kusakabe et al. (2018). Note that the typical age of LAEs with $\text{EW}_0 > 150 \, \text{Å}$ is $\lesssim 20 \, \text{Myr}$ (Hashimoto et al. 2017b), which is shorter than the predicted delay time of $>20 \, \text{Myr}$ in star formation under a local UV background with $J_{21} \gtrsim 1$ for galaxies with a halo mass of $3.6 \times 10^9 M_\odot$ also based on hydrodynamical simulations (Kashikawa et al. 2007). Photoionization heating, which can raise the gas temperature via the strong UV radiation from a quasar, delays star formation in a small halo with mass smaller than $\sim 3 \times 10^9 M_\odot$ and its typical delay time is expected to be $>20 \, \text{Myr}$. In other words, young galaxies with an age of $<20 \, \text{Myr}$ are prevented from forming by quasar photoionization feedback. Therefore, quasar photoionization feedback can reasonably explain our finding of a deficiency of LAEs, especially for those having high $\text{EW}_0$ and low-mass halos in the proximity of quasars. It should be noted that quasar lifetime is also related to this effect. Even low-mass galaxies can collapse if they form before the quasar active phase. Also, if the quasar lifetime is longer than $\sim 20 \, \text{Myr}$, the possible star formation delay mentioned above will be washed out. Interestingly, the delay time is comparable to the fiducial value of quasar lifetime of $10^{7.5} \, \text{yr}$, which is in agreement with observational results (Martini 2004; Shen et al. 2007) and models (Hopkins et al. 2006), though with a large uncertainty.

Uchiyama et al. (2018) found that the number density of g-dropout galaxies around SDSS quasars, whose median UV luminosity, log $L_{\text{1212}}$, is equivalent to this study, tends to be slightly deficient at $<0.5$ pMpc around quasars. This might also be caused by quasar photoionization feedback, though the scale is smaller than the proximity size, $r_{\text{prox}} = 1.6^{+3.0}_{-3.0}$ pMpc, probed by LAEs in the study.

On the other hand, we were not able to find evidence of the photoevaporation effect in four hyper-quasar fields, where the effect should perhaps be the strongest. According to the quasar evolution model of Kawakatu & Wada (2009), the brightness of a quasar is expected to monotonically decrease during the active phase. Note that SDSS 1426 has a large total IR luminosity, $L_{\text{IR}} = 10^{14.29}$ (Weedman et al. 2012), meaning that it is an X-ray-bright, optically normal galaxy (Schawinski et al. 2015) or dusty quasar, which is thought to be in the early stage of the quasar phase in the merger scenario (Kauffmann & Haehnelt 2002). The ionization feedback from the very luminous quasars might not yet have affected galaxies in their vicinity because they have just appeared. This result suggests that the timescale over which quasars can affect gas cooling is estimated to be at most $\sim 20 \, \text{Myr}$, which is shorter than the quasar active phase timescale of a few $\times 100$ Myr (Kawakatu & Wada 2009), because the typical age of an LAE with high $\text{EW}_0$ is $\lesssim 20 \, \text{Myr}$ (Hashimoto et al. 2017b). In addition, radio-loud quasars were found to reside in almost the same environment as radio-quiet quasars, as observed by Donoso et al. (2010) at $z \sim 0.5$. We further found that quasar photoionization feedback is independent of radio-loudness.

In the context of the AGN unification model, quasars are observed relatively face-on with respect to the AGN torus, suggesting that quasar photoionization feedback cannot affect directions that are transverse to the line of sight. The type 1 fraction of the AGN population is estimated to be around
50%–70% (Simpson 2005), by estimating the O[III] luminosity from UV luminosity using the bolometric correction factors of Runnoe et al. (2012) and Shen et al. (2011). Assuming that the fraction corresponds to the quasar viewing angle, the radiation solid angle of quasars is 0.47–0.79 rad. Thus, the expected number of LAEs with EW$_0$ > 150 Å, which happen to lie in the region where the quasar UV radiation is obscured by the torus, is 7.3–12.1 based on the average EW$_0$ distribution (Figure 9). This expectation number is consistent with the observed number of LAEs with EW$_0$ > 150 Å in the quasar proximity regions ($N_{\text{obs}}$ ($>150$ Å) = 7.15). In other words, the observed number of LAE with EW$_0$ > 150 Å in the quasar proximity regions can be explained by the possible anisotropic radiation field of quasars.

We compared our results with those of Marino et al. (2018) who investigated the photoionization effect in six quasar fields.

Figure 6. Distribution of $M_{\text{UV}}$ of LAEs. The red circles and blue squares show the UV luminosity distribution in the vicinity and outer regions of the quasars, respectively. The error bar assumes a binomial distribution (Gehrels 1986). The gray shaded area in each field shows the incomplete region where $M_{\text{UV}}$ is larger than the $M_{\text{UV}}$ limit, which corresponds to the 5σ NB limiting magnitude, assuming the typical EW$_0$ value of 69 Å, which is the e-folding length of EW$_0$ distribution in the field (see Section 3.3). For SDSS 1426, we used the $J_{21} = 10$ radius instead of the $J_{21} = 1$ to evaluate the environmental effect because the radius of $J_{21} = 1$ is larger than the field of view due to the brightness of the quasar. The upper limit for the case of no LAE detection (i.e., corresponding to $N = 1.841$; Gehrels 1986) is shown at $M_{\text{UV}} = -13.5$. 

Figure 9.
targeting galaxies with strong Ly$\alpha$ emission at $3 < z < 4$ using MUSE. They found an opposite, positive correlation, suggesting that LAEs with high EW$_0$ tend to cluster near the quasars. However, most of these high-Ly$\alpha$ EW objects are likely to be caused by faint fluorescence, which can be detected by MUSE with high sensitivity. If their sample was confined to objects with UV continuum detections, there is no significant difference in the EW$_0$ distributions in the vicinity and outer regions of their quasars. Five of the six quasars are very luminous, $M_B \sim -30.0$ (Véron-Cetty & Véron 2010), similar to SDSS 1426 in our sample, suggesting that our result is consistent with theirs. Even if we limit our SDSS 1426 LAEs to the sample with UV continuum detections only, this trend does not change. We found 195 LAEs which were not detected in the BB images. The fraction of these continuum-undetected LAEs to the total 1171 sample is small (17%). Even if the 195 LAEs were excluded, the EW$_0$ and UV luminosity distribution did not change within 1$\sigma$ errors. There is no difference in the number density of the continuum-undetected LAEs between the quasar vicinity and the outer region. Their continuum flux might not detected due to the shallowness of the BB images, while they could be caused by quasar fluorescence, which will be discussed in a forthcoming paper.

Another possible scenario to explain the scarcity of high-EW$_0$ LAEs, which are expected to be much younger than those with lower EW$_0$ (Hashimoto et al. 2017b), is that quasar fields could predominantly contain a more evolved population, such as LBGs. If quasars favor overdense environments, which enhance early galaxy formation, all the LAEs around them might have already evolved into LBGs. This is also related to the quasar duty cycle: LBGs might have already formed at the time of the active phase of the quasarhost galaxy. However, our recent statistical study showed that the most luminous quasars tend to avoid the overdense regions of LBGs, suggesting that quasars are not hosted by very massive halos that lack high-EW$_0$ LAEs alone (Uchiyama et al. 2018). This result raises some doubts on the above scenario. Simultaneous sampling for both LAEs and LBGs for quasar fields is required to validate this hypothesis.

5. Conclusion

We have carried out deep and wide imaging targeting 11 quasar fields to systematically study the photoevaporation effect for young, low-mass galaxies, LAEs. In order to examine variation of the photoionization effects, we selected quasars with a range of properties, such as radio-loudness, black hole mass (log $M_{BH}/M_\odot = 8.59\text{-}9.89$), and luminosity (log $\lambda_{\alpha}(912\,\text{Å}) = 45.6\text{-}47.8$). We selected LAEs in the quasar fields, and obtained 1171 LAEs in total up to 5$\sigma$ NB limiting magnitudes (~25--27) and carefully checked for false detections by eye. The proximity zone of a quasar is defined by the region where the local UV radiation from the quasar is comparable to the UV background.

We obtained the following results.

1. The 11 quasars tend to reside in average LAE density environments, whose average overdensity $\delta$ is 0.48 with 0.82$\sigma$ significance. One quasar pair in our sample appears in the most overdense region. These findings are consistent with previous results based on LBGs at $z \sim 4$ (Onoue et al. 2018; Uchiyama et al. 2018).

2. We compared the EW$_0$ and $M_{UV}$ distribution of LAEs in the vicinity and outer region of a quasar. We found that LAEs with high EW$_0$ (EW$_0 \gtrsim 150\,\text{Å}$) or equivalently, faint UV luminosity ($M_{UV} \gtrsim -17.0$), are relatively scarce in the vicinity of quasars. The range of EW$_0$ or $M_{UV}$ corresponds to notably smaller halo mass of $M_h \sim 10^{9-10} M_\odot$ estimated either from SED fitting or the main sequence, assuming $M_{BH}/M_h \sim 50$. LAEs with such low halo mass are expected to be subject to quasar photoevaporation.

3. Counter to the main trend, we find that feedback seems to be less effective in fields with hyper-luminous quasars, but this could be explained if these luminous quasars are in too early a stage of quasar activity to affect the gas cooling. The environment around radio-loud quasars is similar to that around radio-quiet quasars.

We have, for the first time, performed a systematic study of quasar negative feedback on the surrounding galaxies. Future cosmological baryonic simulations including this kind of feedback will be invaluable for the interpretation of our results. Finally, we note that another important feedback process, namely quasar fluorescence, will be discussed in a forthcoming paper.

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Appendix

Our Model for Ly\(\alpha\) Emitters

Here, we present our model of an LAE used to estimate the continuum and Ly\(\alpha\) emission luminosity from the galaxy based on BB and NB imaging. The continuum flux density \(f^\text{cont}_\nu\) is assumed as

\[
f^\text{cont}_\nu = a(\nu - \nu_{\text{Ly}\alpha}) + b \quad \text{at} \quad \nu < \nu_{\text{Ly}\alpha},
\]

\[
= 0 \quad \text{at} \quad \nu \geq \nu_{\text{Ly}\alpha},
\]

where \(\nu_{\text{Ly}\alpha}\) indicates the observed-frame frequency at the Ly\(\alpha\) emission, and \(a\) and \(b\) are constants. We discuss two different cases: (1) BB covers Ly\(\alpha\) emission, and (2) BB does not cover the emission.

Figure 8. Distribution of EW\(_0\) of LAEs in the vicinity of quasars. The filled red circles and blue squares show the distribution in the vicinity and outer regions of quasars, respectively. The error bar assumes a binomial distribution (Gehrels 1986). For SDSS 1426, we used the \(J_{21} = 10\) radius instead of the \(J_{21} = 1\) to evaluate the environmental effect because the radius of \(J_{21} = 1\) is larger than the field of view due to the brightness of the quasar. The upper limit for the case of no LAE detection (i.e., corresponding to \(N = 1.841\); Gehrels 1986) is shown at EW\(_0\) = 470 Å.
Figure 9. Average distribution of EW0 of LAEs in the vicinity of quasars. The red circles and blue squares show the distribution in the vicinity and outer regions of quasars, respectively. The error bars show the standard error of mean of the sample number in each bin. The dashed line indicates the best fit of the distribution in the outer region. The orange triangles show the distributions in the vicinity except for four of the most luminous quasars, SDSS 1411, SDSS 121, and HB89–1835. The upper limit for no LAE detection is shown at EW0 = 470 Å.

A.1. Case 1: BB Covers Lyα Emission

The observed flux densities in the NB and BB images are, to a first approximation, given by

\[
\langle f' \rangle_{\text{NB}} \Delta_{\text{NB}} = F_{\text{Ly} \alpha} + \frac{b \Delta_{\text{NB}}}{2} \tag{8}
\]

\[
\langle f' \rangle_{\text{BB}} \Delta_{\text{BB}} = F_{\text{Ly} \alpha} + b \delta - \frac{a \delta^2}{2} \tag{9}
\]

\[
\delta = \nu_{\text{Ly} \alpha} - \nu_{\text{BB}} + \frac{\Delta_{\text{BB}}}{2}, \tag{10}
\]

respectively. Here, \( F_{\text{Ly} \alpha} \) is the flux of Ly\( \alpha \) emission, and \( \Delta_{\text{NB}} \) and \( \Delta_{\text{BB}} \) are the FWHMs of the NB and BB filters in frequency space, respectively, and \( \nu_{\text{BB}} \) is the central frequency of the BB filter. In addition, we impose the following boundary condition:

\[
m_{\text{BB}} - m_{\text{NB}} = h \text{ at } F_{\text{Ly} \alpha} = 0. \tag{11}
\]

The quantity \( h \) indicates the color term (see Section 2).

Solving the Equation (8), (9) and (11), we can obtain Ly\( \alpha \) luminosity \( L_{\text{Ly} \alpha} \), UV flux density \( f_{\text{UV}} \), rest-frame EW0 of Ly\( \alpha \) emission \( \text{EW}_0 \), and \( f(\text{EW}_0 = 20 \text{ Å}) \) in Equation (1) as follows:

\[
L_{\text{Ly} \alpha} = \frac{4 \pi d_l^2 \Delta_{\text{BB}} \Delta_{\text{NB}}}{\Delta_{\text{NB}} - 10^{-0.4h} \Delta_{\text{BB}}} \left( \langle f' \rangle_{\text{BB}} - 10^{-0.4h} \langle f' \rangle_{\text{NB}} \right) \tag{12}
\]

\[
f_{\text{UV}} = 2 \frac{\Delta_{\text{NB}} \langle f' \rangle_{\text{NB}} - \Delta_{\text{BB}} \langle f' \rangle_{\text{BB}}}{\Delta_{\text{NB}} - \Delta_{\text{BB}} 10^{-0.4h}} \tag{13}
\]

\[
\text{EW}_0 = \frac{(1 + z) \lambda^2_{\text{Ly} \alpha} \Delta_{\text{NB}} \Delta_{\text{BB}} \langle f' \rangle_{\text{BB}} - 10^{-0.4h} \langle f' \rangle_{\text{NB}})}{2c \langle f' \rangle_{\text{NB}} \Delta_{\text{NB}} - \langle f' \rangle_{\text{BB}} \Delta_{\text{BB}}} \tag{14}
\]

where \( z \) is the redshift of the LAE, \( \lambda_{\text{Ly} \alpha} \) is the rest-frame wavelength of Ly\( \alpha \) emission, and \( c \) is speed of light. \( d_l \) is the luminosity distance at each redshift.

A.2. Case 2: BB Does Not Cover Ly\( \alpha \) Emission

The observed flux densities in the NB and BB images are obtained by

\[
\langle f' \rangle_{\text{NB}} \Delta_{\text{NB}} = F_{\text{Ly} \alpha} + \frac{b \Delta_{\text{NB}}}{2} \tag{16}
\]

\[
\langle f' \rangle_{\text{BB}} \Delta_{\text{BB}} = F_{\text{Ly} \alpha} + b \delta + \frac{a \delta^2}{2} \tag{17}
\]

\[
m_{\text{BB}} - m_{\text{NB}} = h \text{ at } F_{\text{Ly} \alpha} = 0 \tag{18}
\]

as in Case 1. Then, we get the following equations:

\[
L_{\text{Ly} \alpha} = 4 \pi d_l^2 \Delta_{\text{NB}} \left( \langle f' \rangle_{\text{NB}} - \langle f' \rangle_{\text{BB}} \right) \tag{19}
\]

\[
f_{\text{UV}} = 2 \langle f' \rangle_{\text{BB}} 10^{-0.4h} \tag{20}
\]

\[
\text{EW}_0 = \frac{(1 + z) \lambda^2_{\text{Ly} \alpha} \Delta_{\text{NB}} - \langle f' \rangle_{\text{BB}} \Delta_{\text{NB}}}{2c \langle f' \rangle_{\text{BB}}} \tag{21}
\]

\[
f = -2.5 \log_{10} \left[ \frac{(1 + z) \lambda^2_{\text{Ly} \alpha} \Delta_{\text{NB}}}{2c \text{EW}_0 + (1 + z) \lambda^2_{\text{Ly} \alpha} \Delta_{\text{BB}}} \right] \tag{22}
\]

We have assumed that the flux density of a LAE is zero at wavelengths shorter than the Ly\( \alpha \) wavelength, even though the residual flux could be as high as \(~60\%\) (Madau 1995). In that case, the \( \text{EW}_0 \) estimate increases by \(~60\%\).

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