Active Galactic Nucleus Environments and Feedback to Neighboring Galaxies at $z \sim 5$

Probed by Ly$\alpha$ Emitters*

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Abstract

Active galactic nuclei (AGNs) in the high-redshift universe are thought to reside in overdense environments. However, recent works provide controversial results, partly due to the use of different techniques and possible suppression of nearby galaxy formation by AGN feedback. We conducted deep and wide-field imaging observations with the Suprime-Cam on the Subaru Telescope and searched for Ly$\alpha$ emitters (LAEs) around two quasi-stellar objects (QSOs) at $z \sim 4.9$ and a radio galaxy at $z \sim 4.5$ by using narrowband filters to address these issues more robustly. In the QSO fields, we obtained additional broadband images to select Lyman break galaxies (LBGs) at $z \sim 5$ for comparison. We constructed a photometric sample of 301 LAEs and 170 LBGs in total. A wide field of view (34' $\times$ 27', corresponding to 80 $\times$ 60 comoving Mpc$^2$) of the Suprime-Cam enabled us to probe galaxies in the immediate vicinities of the AGNs and in the blank fields simultaneously and compare various properties of them in a consistent manner. The two QSOs are located near local density peaks ($\sim 2\sigma$), and one of the QSOs has a close companion LAE with projected separation of 80 physical kpc. The radio galaxy is found to be near a void of LAEs. The number densities of LAEs/LBGs in a larger spatial scale around the AGNs are not significantly different from those in blank fields. No sign of feedback is found down to $L_{\text{Ly} \alpha} \sim 10^{41.8}$ erg s$^{-1}$. Our results suggest that high-redshift AGNs are not associated with extreme galaxy overdensity and that this cannot be attributed to the effect of AGN feedback.

Key words: galaxies: formation – galaxies: high-redshift – quasars: general – quasars: individual (SDSS J080715.2+132805, SDSS J111358.3+025333, 4C 04.11)

1. Introduction

Supermassive black holes (SMBHs) at the center of galaxies provide us with various insights into key physics of galaxy formation and evolution. The correlation between the properties of SMBHs and those of the host galaxies, such as masses and velocity dispersions of spheroidal components (Magorrian et al. 1998; Ferrarese & Merritt 2000), indicates that active galactic nuclei (AGNs; rapidly growing SMBHs) and star formation activities are physically connected and that AGNs play a crucial role in galaxy formation. However, details of their formation and growth history still remain largely unknown. To date, SMBHs with BH masses in excess of $10^9 M_\odot$ are known to already exist at the very beginning of the universe ($z > 6$; e.g., Mortlock et al. 2011; Wu et al. 2015).

Where and how these SMBHs are formed and evolved in place with their host galaxies is a fundamental question to elucidate galaxy evolution.

It is expected that high-redshift SMBHs should reside more frequently in highly biased regions of the universe where the dark matter and galaxies are overly clustered (e.g., Volonteri & Rees 2006). Locating such overdense regions in the high-redshift universe, the so-called “protoclusters” (Shimasaku et al. 2003; Matsuda et al. 2010; Toshikawa et al. 2012, see Overzier 2016 for a recent review), has the potential to provide us with opportunities to probe how environmental differences in galaxy evolution observed in the local universe (Dressler 1980; Cappellari et al. 2011) are established. Since searching for protoclusters without signposts like AGNs is difficult because of their rarity, probing AGN environments gives us clues to environmental effects on galaxy evolution, as well as the growth history of SMBHs.

Environments of high-redshift quasi-stellar objects (QSOs; luminous type 1 AGNs) and radio galaxies (RGs; radio-loud type 2 AGNs) have been extensively studied with the motivation described above. Radio-loud AGNs (RGs and radio-loud QSOs) are typically found in overdense regions using various methods to locate galaxies around them, including the Lyman break technique, narrowband imaging, and Spitzer/Infrared Array Camera (IRAC) color selection (Zheng et al. 2006; Venemans et al. 2007; Matsuda et al. 2009; Wylezalek et al. 2013). On the other hand, the situation is different for (radio-quiet) QSOs. While measurements of QSO clustering show that they should reside in massive dark matter halos ($M_{200} > 10^{12} M_\odot$) up to $z < 4$ (Shen et al. 2007; Trainor & Steidel 2012; Garcia-Vergara et al. 2017; see also Eftekharzadeh et al. 2015), many authors found both galaxy overdensity associated with QSOs (Utsumi et al. 2010; Capak et al. 2011; Falder et al. 2011; Swinbank et al. 2012; Huband et al. 2013; Morselli et al. 2014) and normal or underdensity around QSOs (Francis & Bland-Hawthorn 2004; Kashikawa et al. 2007; Kim et al. 2009; Bañados et al. 2013; Simpson et al. 2014; Adams 2015).

* Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.
et al. 2015; Mazzucchelli et al. 2017), again using various techniques to identify galaxies in the QSO fields. Even in fields around intermediate-redshift QSO multiples, their environments are not always rich (Boris et al. 2007; Farina et al. 2013; Sandrinelli et al. 2014), though Hennawi et al. (2015) found an overdensity around a quasar quartet.

Several authors suggest that strong UV radiation from AGNs can suppress the formation of low-mass galaxies around them by heating and photoevaporating their gas (Kashikawa et al. 2007; Utsumi et al. 2010; Bruns et al. 2012) and thereby dilute any sign of overdensity and mitigate the discrepancy observed to date. The deficit of H I gas with column density \( N_{\text{HI}} < 10^{17} \text{ cm}^{-2} \) (Ly\( \alpha \) forest) within a few to several physical Mpc (pMpc) from QSOs has been well known as the QSO proximity effect (Bechtold 1994; Calverley et al. 2011). However, it is unclear whether this QSO’s radiative feedback is indeed strong enough to suppress the formation of neighboring low-mass galaxies (\( N_{\text{HI}} > 10^{20} \text{ cm}^{-2} \)). On the other hand, Cantalupo et al. (2012) claimed that fluorescently illuminated gas around a hyperluminous QSO can boost Ly\( \alpha \) luminosity of galaxies around the QSO.

Mixed results about QSO environments obtained so far can be partly due to the use of different observational techniques, survey depths, and field coverages, as well as various feedback effects. Many studies used the Lyman break technique to identify high-redshift galaxies around QSOs. However, this technique samples galaxies from a wide redshift range of, say, \( \Delta z \sim 1 \) (Yoshida et al. 2006). At \( z \sim 5 \), this corresponds to \( \sim 100 \text{ pMpc} \). This scale is far larger than the expected size of the largest protocluster and known QSO proximity; hence, galaxies selected by this method contain many foreground and background, physically unrelated galaxies. Moreover, even if AGNs have associated structures of a scale of a few to several pMpc, or if AGNs affect surrounding galaxies within this scale, it should be smeared out by the projection effect. If one wants to study AGN environments and feedback to their neighbors, it is particularly important to pick up galaxies within the AGN’s proximity in both tangential and radial (redshift) directions.

Wide-field, narrowband imaging observations are currently the best way to securely investigate AGN environments and feedback even if a large spectroscopic sample is available. Narrowband filters have FWHMs of \( \lesssim 100 \text{ Å} \), and they enable us to select line-emitting galaxies from a narrow redshift range of \( \Delta z \lesssim 0.1 \). In particular, galaxies whose redshifted Ly\( \alpha \) emission falls inside a narrowband filter, the so-called Ly\( \alpha \) emitters (LAEs), are commonly found at \( z \gtrsim 2 \). At \( z \lesssim 5 \), \( \Delta z \lesssim 0.1 \) corresponds to \( \sim 10 \text{ pMpc} \). This scale is sufficiently small to detect protoclusters of this redshift (Chiang et al. 2013) and matches measured QSOs’ proximity sizes (Calverley et al. 2011). With narrowband filters, we can select LAEs within the AGN’s proximity in the radial (redshift) direction, by minimizing the contamination from physically unrelated foreground and background galaxies. Furthermore, the majority of LAEs are known to have low stellar mass (Gawiser et al. 2006; Finkelstein et al. 2007; Ono et al. 2010a, 2010b) and therefore are more susceptible to AGN feedback than massive galaxies. Thus, LAEs are best suited to observationally scrutinize whether and how the properties of low-mass galaxies around AGNs are altered compared to general fields, by overcoming the uncertainties in previous works.

In this paper, we present the results of our deep and wide-field observations around two QSOs at \( z \sim 4.9 \) and one RG at \( z \sim 4.5 \) using the Suprime-Cam (S-Cam; Miyazaki et al. 2002) on the Subaru Telescope. Narrowband filters well covering the proximity of these AGNs in the radial direction and the wide field of view (FOV) of S-Cam (\( 34' \times 27' \), or \( 13 \times 10 \text{ pMpc} \) at \( z = 5 \)) enable us to detect galaxies within and outside of the AGN’s proximity simultaneously, as opposed to previous narrowband studies with smaller FOVs (Swinbank et al. 2012; Bañados et al. 2013; Mazzucchelli et al. 2017). We try to identify the effect of AGN feedback by comparing the luminosity functions (LFs) within and outside of the AGN’s proximity, because radiative feedback affects galaxies differently depending on their mass.

The structure of this paper is as follows: In Section 2 we describe our imaging observations and data reduction. In Section 3 we present our photometric selection of LAEs and Lyman break galaxies (LBGs) and subsequent analyses. We show our main results and discuss them in Section 4, and we present the summary and conclusion in Section 5. Throughout this paper, we use the AB magnitude system and adopt a LCDM cosmology, with \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.27 \), and \( \Omega_\Lambda = 0.73 \) (Komatsu et al. 2009).

### 2. Observations and Data Reduction

We conducted imaging observations of two fields around QSOs at \( z \sim 4.9 \), SDSS J080715.2+132805 (08\(^h\)07\(^m\)15\(^s\), \( z = 4.885 \), hereafter J08 field; Trakhtenbrot et al. 2011) and SDSS J111358.3+025333 (11\(^h\)13\(^m\)58\(^s\), \( z = 4.870 \), hereafter J11 field; Trakhtenbrot et al. 2011) using the S-Cam (Miyazaki et al. 2002) on the 8.2 m Subaru Telescope on 2014 December 21–26, and 2015 December 16–17 (UT; Program ID: S14B-006 and S15B-010, PI: M. Imanishi). As we illustrate in Figure 1, we used broadband filters (R, i', and z') and a narrowband filter \( N\beta 711(\text{Ly} \alpha) = 7126 \text{ Å}, \Delta \lambda = 73 \text{ Å} \) to sample LAEs in the redshift range of \( 4.83 \lesssim z \lesssim 4.89 \) and LBGs at \( z \sim 5 \). The redshifts of J08 and J11 are measured to be within this range in Trakhtenbrot et al. (2011) using the Mg II emission line, which is known to be a good redshift indicator of type 1 AGNs (Hewett & Wild 2010; Shen et al. 2016). Note that, because their redshifts fall in the redder part of the sensitivity of \( N\beta 711 \) and their redshifts fall in the redder part of the sensitivity of \( N\beta 711 \).
Table 1

Information about Our Targets and Observations

| Object Name       | Redshift | log $M_{BH}$ | log $L_{bol}$ | Exposure Time (s) and Seeing |
|-------------------|----------|-------------|--------------|-------------------------------|
| SDSS J080715.2+132805 | 4.885    | 9.24        | 47.07        | B: 6000 R: 4500 i': 4200 z': 9000 |
| SDSS J111358.3+025333 | 4.870    | 9.12        | 46.89        | B: 13''1 R: 15'' i': 15'' z': 0''9 |
| 4C 04.11          | 4.514    | $\geq 9$    | ...          | B: 4500 R: 3600 i': 5400 z: 24000 |

Notes.

* From Trakhtenbrot et al. (2011) (J08 and J11) and Parijskij et al. (2014) (4C 04).

* Exposures during poor conditions were discarded.

* NB711 for the J08 and J11 fields and NB671 for the 4C 04 field.

and LAEs are more easily selected on the bluer side of the NB711 bandpass, there is a possibility that we detect LAEs at slightly different redshifts. If true systemic redshifts of the AGNs are larger than the observed values, our measurements are affected further. The median and intrinsic scatter of Mg ii redshift with respect to the narrow [O II] line are measured to be $-62 \text{ km s}^{-1}$ and $220 \text{ km s}^{-1}$, respectively (Shen et al. 2016). Assuming Gaussian distribution, the probability of J08 having redshift higher than 4.89 is thus $\lesssim 6\%$. $M_{BH}$ of these two QSOs are also derived from the Mg ii line and found to be very massive at $z \sim 5$. Specifically, they have SMBHs with mass of $10^{12.24} M_{\odot}$ for J08 and $10^{12.12} M_{\odot}$ for J11.

Additionally, we obtained S-Cam broadband ($B$, $R$, and $i'$) and narrowband (NB671, $\lambda_c = 6712 \text{ Å}$, $\Delta \lambda = 120 \text{ Å}$) images of an AG at $z = 4.514$ from the data archive (Program ID: S09B-070N; PI: Y. Matsuda). We can detect LAEs at $z = 4.47-4.57$ with NB671. This AG, namely, 4C 04.11 (also known as RC J0311+0507; 03h11m48s00, +05°08′01″5 at $z = 4.514$, hereafter 4C 04 field) has an estimated luminosity at rest-frame 500 MHz of $3 \times 10^{29} \text{ W Hz}^{-1}$, or luminosity at rest-frame 2.7 GHz of $L_{2.7 GHz} = 6 \times 10^{34} \text{ erg s}^{-1} \text{ Hz}^{-1} \text { sr}^{-1}$. For reference, the sample in Venemans et al. (2007) has at most a radio luminosity of $L_{2.7 GHz} = 2 \times 10^{32} \text{ erg s}^{-1} \text{ Hz}^{-1} \text { sr}^{-1}$. Its very high radio luminosity and a highly asymmetric Fanaroff–Riley type II (FR II) structure jet suggest that it is powered by an SMBH of mass $\sim 10^{9} M_{\odot}$ (Kopylov et al. 2006). The redshift of the AG is confirmed by various emission lines, such as the Ly$_\alpha$, [O II], and [Ne III] lines (Nesvadba et al. 2017), and well constrained within $z = 4.504-4.514$ (see the inset of Figure 1).

At $z \sim 5$, we can construct a sufficiently large sample of galaxies with reasonable integration time. For J08 and J11 fields, the individual integration times in $R$, $i'$, $z'$, and NB711 were 300 s, 300 s, 300 s, and 900 s per pointing, respectively. For 4C 04 fields, the individual integration times in $B$, $R$, $i'$, and NB671 were 450 s, 450 s, 360 s, and 1200 s per pointing, respectively. Each exposure was dithered by $\geq 60''$. An N-point circular dithering pattern ($N = 6, 9$) was used. Details of our targets and observations are listed in Table 1.

The raw data were reduced in a standard manner with the dedicated software package SDFRED2 (Ouchi et al. 2004), which includes bias subtraction, flat-fielding, distortion correction, sky subtraction, image alignments, and stacking. The NB711-band images were processed with L. A. Cosmic algorithm (van Dokkum 2001) to remove cosmic rays after the flat-fielding process. The world coordinate system of images was calibrated by comparing the USNO-B1.0 catalog. Mean offset from the catalog is $\sim 0''.72$. After we matched seeing of the images of each field to the worst one (see Sections 3.1 and 3.2), we perform object detection and photometry using the double-image mode of SExtractor version 2.1.6 (Bertin & Arnouts 1996). We used the narrow bands and the $z'$ band as detection bands for LAEs and LBGs, respectively. Spikes and halos around bright stars and low-S/N regions near the edge of the FOV are masked during object detection. Objects in the masked regions or with SExtractor flags of $>2$ are eliminated from our catalogs. SExtractor flag 1 means that an object has a close neighbor or bad pixels that affect photometry. SExtractor flag 2 means that an object was originally blended with another one. We first include these sources and later visually check and eliminate obvious spurious and heavily blended ones to maximize the detection rate.

We use magnitude colors measured in 1.7 times point-spread function FWHM diameter apertures unless otherwise stated. Photometric calibration for the J08 and J11 fields was obtained from the spectrophotometric standard stars, GD 108 (Oke 1990) and GD 153 (Moehler et al. 2014), observed during the same night of the observations. Photometric calibration for the 4C 04 field was obtained from Sloan Digital Sky Survey (SDSS) stars in the field. We corrected the measured magnitudes for Galactic extinction of $E(B - V) = 0.03$ mag (J08), 0.04 mag (J11), and 0.19 mag (4C 04; Schlegel et al. 1998). We note that the stellar colors measured in the J08 field are offset by $\sim 0.1-0.2$ mag from the Gunn & Stryer (1983) stellar templates on $R-NB711$ versus $NB711-i'$ and $R-i'$ versus $i'-z'$ color–color diagrams. Since the $R$- and $i'$-band magnitudes of stellar sources in the field are confirmed to be well matched with those of SDSS sources, we manually corrected the zero points of NB711 and $z'$ band. The reason for this offset is unclear, but it may partly be due to the unstable weather conditions of our observations. Finally, the locus of stellar sources on a color–color diagram in all the fields became consistent with those of Gunn & Stryer (1983) within $\pm 0.05$ mag. Limiting magnitudes of our observations are given in Sections 3.1 and 3.2.
3. Analyses

3.1. Selection of LAEs

As the image quality of our \( z' \)-band image is not as good as we expected because of weather conditions and \( z' \)-band magnitude is not required for LAE selection below, we matched seeing of images of the J08 and J11 fields to that of \( R \) band (the worst one except for \( z' \) band; see Table 1) when we constructed the LAE sample. The 3\( \sigma \) limiting magnitudes after all corrections in \( (R, i', NB711) \) are (27.5, 27.1, 26.6) and (27.5, 27.3, 26.7) for the J08 and J11 fields, respectively. We chose LAEs at \( z \sim 4.9 \) from our catalog using the criteria below (Ouchi et al. 2003):

\[
R_i - NB711 > \max(0.8, 3\sigma(R_i - NB711)), \quad (1)
\]
\[
R - i' > 0.5, \quad (2)
\]
\[
i' - NB711 > 0, \quad (3)
\]
\[
NB711 < 5\sigma_{NB711}, \quad (4)
\]

where \( R_i \equiv 0.5 \times R + 0.5 \times i' \) and \( \sigma(R_i - NB711) \) denotes the expected deviation of the quantity \( R_i - NB711 \) for a flat continuum source. For objects fainter than 2\( \sigma \) in \( R \) band, we replace the \( R \)-band magnitude by its 2\( \sigma \) limiting magnitude as a lower limit. Ouchi et al. (2003) showed that these criteria effectively remove contaminants such as low-redshift emitters and objects with a trough feature blueward of the \( NB711 \)-band filter. Shimazaki et al. (2003) conducted follow-up spectroscopy of five candidates selected by these criteria and found a contamination rate of about \( \sim 20\% \), which is sufficiently low for our purpose.

In 4C 04 field, 3\( \sigma \) limiting magnitudes in \( (B, R, i', NB711) \) are (27.0, 26.8, 26.5, 26.5). We chose LAEs at \( z \sim 4.5 \) using the criteria below:

\[
R_i - NB671 > \max(0.5, 3\sigma(R_i - NB671)), \quad (5)
\]
\[
i' - NB671 > 0, \quad (6)
\]
\[
NB671 < 5\sigma_{NB671}, \quad (7)
\]

where \( R_i \equiv 0.8 \times R + 0.2 \times i' \) and \( \sigma(R_i - NB671) \) denotes the expected deviation of the quantity \( R_i - NB671 \) for a flat continuum source. Similar criteria were used in a large-area Ly\( \alpha \) survey (e.g., Rhoads et al. 2000) to detect LAEs at \( z \sim 4.5 \), and the success rate based on their spectroscopic follow-up campaign is about \( \sim 70\% \) (Dawson et al. 2007; Zheng et al. 2013). In Figure 2 we show color–magnitude diagrams in each field.

Finally, we visually checked the images and eliminated some spurious sources, such as ones clearly blending with other sources and ones on stellar halos or saturation spikes. Finally, we find 60, 136, and 105 LAEs in the J08, J11, and 4C 04 fields, respectively. Then we divide LAEs into two subgroups: one is the “proximity” sample, which is located within 3 Mpc (J08 and J11 fields) or 5 Mpc (4C 04 field) of the central AGNs; the other is the “blank fields” sample, which is the rest of the sample. The size of the “proximity” of 3 or 5 Mpc is set by the FWHM of employed narrowband filters (\( \Delta \lambda_{NB711} = 72 \text{Å}, \Delta \lambda_{NB671} = 120 \text{Å} \)), and these values are sufficiently small to detect overdensities or galaxies affected by AGN feedback at \( z \sim 5 \) (Calverley et al. 2011; Chiang et al. 2013). The sample size of proximity LAEs in the J08, J11, and 4C 04 fields is 14, 34, and 32, respectively.

3.2. Selection of LBGs at \( z \sim 5 \)

When we matched the seeing of images to that of \( z' \) band, the limiting 3\( \sigma \) aperture magnitude in \( (R, i', z') \) is (26.8, 27.3, 26.0) and (27.1, 27.3, 26.3) for the J08 and J11 fields, respectively. We chose LBGs at \( z \sim 5 \) from our catalog using the criteria below (Yoshida et al. 2006):

\[
R - i' > 1.0, \quad (8)
\]
\[
i' - z' < 0.7, \quad (9)
\]
\[
R - i' > 1.2(i' - z') + 0.9, \quad (10)
\]
\[
z' < 5\sigma_i. \quad (11)
\]

In Figure 3 we show color–color diagrams of the J08 and J11 fields.

In Yoshida et al. (2006), the contamination rate of this \( R'z' \)-LGB sample is estimated via Monte Carlo simulation based on a photometric redshift catalog of galaxies in the Hubble Deep Field. The derived value of \( \lesssim 0.05 \) is negligibly low. After visual inspection, the number of LBGs detected in the J08 and J11 fields is 33 and 137, respectively. LBGs are also divided into a “proximity” sample and “blank fields” sample, as done for LAEs. The number of LBGs in the proximity sample is 10 and 35 in the J08 and J11 fields, respectively.

3.3. Physical Properties of LAEs and LBGs

We derived Ly\( \alpha \) and UV luminosity and rest-frame equivalent width (EW\( _{\text{Ly}\alpha} \)) of LAEs assuming that the UV continuum slope is flat, and the \( i' \)-band and narrowband fluxes
of LAEs are expressed as

\[ f_r = f_{\text{cont}} + F_{\text{Ly}\alpha}/\Delta_i \]

in the J08 and J11 fields and

\[ f_{NB711} = f_{\text{cont}} + F_{\text{Ly}\alpha}/\Delta_{NB711} \]

in the 4C 04 field, where \( F_{\text{Ly}\alpha} \) and \( f_{\text{cont}} \) denote the \( Ly\alpha \) flux in units of erg s\(^{-1}\) cm\(^{-2}\) and the continuum flux in units of erg s\(^{-1}\) cm\(^{-2}\) \( \AA^{-1}\), respectively; \( f_r \), \( f_{NB711} \), and \( f_{NB671} \) denote \( i' \)-, \( NB711 \)-, and \( NB671 \)-band flux in units of erg s\(^{-1}\) cm\(^{-2}\) \( \AA^{-1}\), respectively; and \( \Delta_i \), \( \Delta_{NB711} \), and \( \Delta_{NB671} \) denote the FWHMs of \( i' \), \( NB711 \), and \( NB671 \) band in units of \( \AA \), respectively. Then \( Ly\alpha \) luminosity and \( EW_0 \) of LAEs are expressed by the following formulae:

\[
L_{\text{Ly}\alpha} = 4\pi d_l^2 F_{\text{Ly}\alpha}
\]

or

\[
L_{\text{Ly}\alpha} = 4\pi d_l^2 \frac{\Delta_{NB711}(f_{NB711} - f_r)}{1 - \Delta_{NB711}/\Delta_i},
\]

and

\[
EW_0 = F_{\text{Ly}\alpha}/f_{\text{cont}} \left(1 + z \right)
\]

or

\[
EW_0 = \frac{\Delta_{NB711}(f_{NB711} - f_r)}{f_r} \frac{1}{1 + z},
\]

Equations (12) and (14) are used in the J08 and J11 fields, and Equations (13) and (15) are used in the 4C 04 field. The UV luminosity of LBGs is directly derived from \( z' \)-band magnitude.

To derive the number density and LF of LAEs and LBGs, we have to calculate the effective volume surveyed and the completeness. These can be obtained by using Monte Carlo simulations in the same manner as done in many surveys, such as Ouchi et al. (2003) and Yoshida et al. (2006). For LAEs, we derived the effective volume by simply multiplying the surface area probed by the depth determined by the narrowband filters we used. This gives a total surveyed volume of \( \sim 1.5 \times 10^5 \) cMpc\(^3\) for the J08 and J11 fields and \( 2.9 \times 10^5 \) cMpc\(^3\) for the 4C 04 field.\(^8\) When we calculate the LAE completeness, we used colors of LAEs with >5σ detection in the \( i' \) band as artificial LAEs. We randomly distributed artificial point sources in the real images. Then we ran SExtractor and applied the same selection criteria to them as the real sample constructions. The completeness is defined as a ratio of the number of reproduced objects that again passed the criteria to the number of all of the input objects in unmasked regions. Completeness (\( C_{\text{NB}}(m_{\text{NB}}) \)) correction was done by weighting an LAE that has NB magnitude \( m_{\text{NB}} \) by \( 1/C_{\text{NB}}(m_{\text{NB}}) \). This simple method gives sufficiently reliable estimates (Shimasaku et al. 2006). Note that our main purpose here is to compare the relative shape of LFs in and out of the proximity and not to compare the absolute values of them. On the other hand, the effective volume and completeness of LBGs cannot be obtained immediately. We derive the effective surveyed volume \( V_{\text{eff}}(m) \) as follows:

\[
V_{\text{eff}}(m) = \int_0^\infty C(m, z) \frac{dV_c(z)}{dz} dz
\]

or

\[
V_{\text{eff}}(m) = \int_0^\infty C(m, z) \frac{C}{H_0 E(z)} d^2 l dz dz,
\]

where \( C(m, z) \) is the completeness of an LBG at redshift \( z \) with apparent magnitude of \( m \), \( V_c(z) \) is a comoving volume at redshift \( z \), \( dc \) is comoving distance, and \( E(z) = \sqrt{\Omega_m(1 + z)^3 + \Omega_\Lambda} \).

The completeness \( C(m, z) \) is calculated in a similar way to that in Yoshida et al. (2006): we generate mock LBGs using the stellar population synthesis model of Bruzual & Charlot (2003) with varying dust extinction \( (E(B-V) = 0.0-0.5) \). For the dust extinction, we adopt Calzetti’s extinction law; Calzetti et al. (2000). The distribution of \( E(B-V) \) values is taken from that of \( z \sim 4 \) LBGs measured in Ouchi et al. (2004). Age and metallicity are kept to the constant values of 0.1 Gyr and 0.2 Z\(_\odot\), respectively. We used an exponentially decaying star formation history with an e-folding time of 5 Gyr. After redshifting the spectra to \( z = 4.4-5.3 \), we corrected for the effect of intergalactic absorption by neutral hydrogen by adopting the model of Madau (1995). Then we derive the colors of the model LBGs and input them as point sources into the real images. Source detection and photometry were done in the same manner as in the real sample constructions. Finally, we derived the completeness as functions of \( z' \)-band magnitude and redshift.

\(^8\) These values include the masked regions. The masked regions are at most 10% and thus negligibly small.
4. Results and Discussion

4.1. Environments of High-redshift AGNs

We show in Figure 4 the sky distributions of the central AGNs, LAEs, and LBGs (J08 and J11 fields only) selected in Sections 3.1 and 3.2. The two QSOs are located close to the local peaks of surface density, while the RG is isolated. The significance of the peaks near the QSOs is lower than 2σ in either case. This level of variance is found in other blank field surveys (Ouchi et al. 2003, 2005; Shioya et al. 2009). Chiang et al. (2013) derived the median and 1σ scatter of overdensities of galaxies with SFR > 1 M_☉ yr⁻¹, δ_{gal} = (n - n_0)/n (see their Figure 13 for the z = 3 case) as a function of Δz by using a semianalytic model. In our cases δ_{gal} is at most ~1. Note that the area of the window of 15 × 15 cMpc used in Chiang et al. (2013) is close to our aperture size (circle of 8 cMpc radius). At least they are not likely to be associated with the most massive overdensity at z ~ 5 or evolve into “Coma”-type clusters with M_{halo} > 10^{15} M_☉, though there remains the possibility of them being “Fornax”-type clusters (M_{halo} < 3 × 10^{14} M_☉). Though the density peak of LBGs in the J08 field is also near J08 itself, the distribution of LBGs as a whole is clearly different from that of LAEs.

The trend of no massive overdensity becomes clearer in Figures 5 and 6, in which we respectively show the Lyα LFs of LAEs and UV LFs of LBGs in each field. The error bars represent 84% single-sided confidence levels based on the Poisson statistics (Gehrels 1986) alone. We find no significant excess of LFs in the proximities compared to that in blank fields. Rather, we find no LAEs in the two brightest bins in the proximities of the two QSOs at z ~ 4.9. We also find no LBG in the two brightest bins and the brightest bin in the J08 and J11 fields, respectively. This is reasonable considering the small volume probed and the smaller number density of brighter LAEs and LBGs. Indeed, if we assume that the number of these galaxies follows the Poisson distribution and that the surface densities of galaxies in proximity are the same as that in the outer region, the probability of finding no LAEs with Lyα > 10^{42.75} (and LBGs with M_{UV} < -21.6) in the proximity of J08 and J11 is 36% and 14% (36% and 10%), respectively. These threshold values correspond to those of the second-brightest bin in the LFs in Figures 5 and 6. On the other hand, if we assume...
that the surface density of LAEs (LBGs) in the QSO proximity is twice as high as blank fields, probabilities of nondetection decrease to 13% and 1.9% (13% and 1.1%), respectively. As we discuss further in Section 4.2, the impact of AGN feedback seems to be negligible in our data; even at the fainter side, there is no significant difference. This trend holds true for the case of LBGs (Figure 6), which suggests that these QSOs do not reside in overdensities of much larger scales considering large \( \Delta z \) of the LBG selection function.

The RG 4C 04 is found to be near a void. The number density of LAEs in the proximity of the RG is somewhat lower than in the outer region. This is at odds with the results in the literature (Ajiki et al. 2006; Zheng et al. 2006; Venemans et al. 2007), in which the authors report overdensity of LAEs around radio-loud QSOs and RGs at various redshifts with a high success rate (\( >70\% \)). We note that 4C 04 has extremely luminous \( L_{\text{Ly} \alpha} > 10^{44} \text{ erg s}^{-1} \) and extended \( >60 \) kpc \( \text{Ly} \alpha \) halos around it (Figure 7). High-redshift RGs (HzRGs) often have such extended \( \text{Ly} \alpha \) halos. They usually align with their radio jets (Venemans et al. 2007; Nesvadba et al. 2017). However, the 4C 04 halo is rather extended almost perpendicular to the jet direction (arrows in Figure 7). The \( \text{Ly} \alpha \) nebula extending far beyond the radio-emitting region, the nondetection of overdensity, and the C IV and He II lines (Kopylov et al. 2006) that are frequently detected in HzRGs with line ratios suggestive of an enriched outflow origin all suggest that this RG is a different class of objects from other HzRGs. Additionally, though the upper limits of the line ratios of the halo are consistent with bright (type 1) QSOs (Borisova et al. 2016), the moderately broad \( \text{Ly} \alpha \) line width (\( \sim1500 \) km s\(^{-1}\), Kopylov et al. 2006) is not consistent with those QSOs. Further observations are needed to conclude the origin of this \( \text{Ly} \alpha \) nebula.

Considering a large scatter in the number of galaxies even with the S-Cam FOV (can be as large as \( \sim0.3 \) depending on the bias factor of LAEs; e.g., Shimasaku et al. 2004; Gawiser et al. 2007; Trenti & Stiavelli 2008), it is hard to draw a firm conclusion from our observations alone. Nonetheless, observing more and more AGN fields with small \( \Delta z \) and comparing the results with theories greatly help us understand the true nature of AGN environments. Besides our results, there is growing observational evidence that redshift AGNs do not reside in overdensities when one probes them with narrowband filters \( \Delta z \leq 0.1 \) at least on a scale smaller than 3 \( \) pMpc (Bañados et al. 2013; Mazzucchelli et al. 2017, at \( z = 5.7 \)). These results suggest that an overdensity on this scale (and possibly galaxy merger) is not always a necessary condition for AGN activity. Some semianalytical models predict that halos of high-redshift AGNs are not the most massive ones at that epoch (Overzier et al. 2009; Fanidakis et al. 2013; Orsi et al. 2016). Recently Di Matteo et al. (2017) suggested that the most massive BHs at the earliest epoch (\( z > 8 \)) can be preferentially formed in regions where tidal fields are weak because gas can directly fall onto BHs along filaments, rather than mere overdense regions. On the other hand, Costa et al. (2014) argued that SMBHs of \( 10^9 M_\odot \) at \( z \sim 6 \) only formed in the most massive halos as a result of their cosmological hydrodynamical simulations. The environments identified in theoretical works depend largely on their assumptions about BH seeding, BH growth, and AGN feedback. For example, models usually assume that AGNs are triggered only by galaxy–galaxy mergers. Furthermore, we have to rely on simple subgrid physics because nuclear regions are impossible to resolve in galaxy-scale simulations. Clearly models need to be tested and updated with recent observational indications. Although AGN luminosity is still important in terms of AGN feedback, it is also crucial to investigate the AGN environment as a function of BH mass. This is because AGN luminosity is rather an instantaneous, time-changing (“differential”) physical

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**Figure 5.** \( \text{Ly} \alpha \) LFs of LAEs in the (a) J08, (b) J11, and (c) 4C 04 fields. Red circles and blue triangles represent LFs in proximity and in the outer region, respectively. The dotted line is an LF of LAEs at \( z \sim 4.5 \) derived in Zheng et al. (2013) using spectroscopically confirmed LAEs with \( L_{\text{Ly} \alpha} > 10^{42.5} \).
quantity determined by SMBH mass and accretion rate at the observed time. On the other hand, BH mass is a more fundamental “cumulative” one that reflects its growth history and thus is more likely to be related to its large-scale environments.

Finally, we mention another possibility: we failed to trace the environments with LAEs and LBGs because, for example, most of the galaxies around AGNs may be dusty and UV/optically elusive. Many lines of evidence suggest that LAEs are typically young (≤100 Myr), low-mass (≤10^8 M_☉), and non-dusty (E(B−V) ≤ 0.2) galaxies (Gawiser et al. 2006; Finkelstein et al. 2007, 2009; Ono et al. 2010a, 2010b), with some massive and dusty outliers. As there are many systems with a large amount of dust even at this high redshift (Riechers et al. 2013), we could largely miss such a population. Recently, Trakhtenbrot et al. (2017) observed six z ~ 4.8 QSOs from the same parent sample we used with ALMA and detected companion SMGs in three of the observed AGNs. A high probability of finding companion SMGs in a small FOV of ALMA and faintness of the companions in other wavelengths (not detected even in the Spitzer data) indicate that there may be many optically elusive galaxies around AGNs in our fields. Since the techniques utilizing the UV/optical feature are biased against dust-obscured galaxies, wide-field (far-)infrared observations are needed to complement such techniques.

4.2. Feedback from AGNs

It has long been theoretically argued that ultraviolet background (UVB) radiation can suppress the formation of low-mass galaxies by heating their gas (Efstathiou 1992; Thoul & Weinberg 1996; Kitayama et al. 2000, 2001; Benson et al. 2002; Dijkstra et al. 2004; Susa & Umemura 2004; Mesinger & Dijkstra 2008; Okamoto et al. 2008; Sobacchi & Mesinger 2013a, 2013b; Liu et al. 2016). In principle, we can confirm this suppression by identifying flattening of the faint-end slope of the LF, though observationally this turned out to be extremely difficult (Alavi et al. 2014, 2016; Weisz et al. 2014; Castellano et al. 2016); no evidence of an LF turnover has been found down to M_UV ~ −12. On the other hand, there are a handful of candidate ultrafaint dwarf galaxies at the local universe (Brown et al. 2014, M_V > −8 or M_b < 10^4 M_☉) whose star formation seem to have been suppressed by a synchronized external process such as the reionization. This kind of negative feedback is often provoked to explain why we do not always find high-redshift QSOs in overdensities because local UV radiation fields around luminous QSOs are much stronger than the UVB. Previous studies originally considered situations where a pregalactic cloud is collapsing under the UVB in the reionization era and studied its evolution as a function of various parameters such as the intensity of the UVB, the time at which the UVB is switched on and the pregalactic cloud starts to collapse (see also Kashikawa et al. 2007). As a result, they derived the threshold dynamical mass below which a pregalactic cloud cannot collapse and form stars. The results showed a range of the threshold mass of ~10^9–10^10 M_☉, depending on the details of calculations (e.g., 1D/3D, including radiative transfer effect or not). They also found that once the clouds begin to collapse and their density gets higher, even very strong UV radiation cannot affect the evolution of the clouds and finally allows the clouds to form stars, whereas clouds that are irradiated well before they start to...
collapse can be affected significantly (Kashikawa et al. 2007; Sobacchi & Mesinger 2013b; Roos et al. 2015). In many cases the strength of the UVB is kept constant, but in some cases gradually evolving UVB is assumed. The impact of UVB feedback is maximized when clouds are irradiated by constant UVB before they begin to collapse.

Although the assumptions in the above theoretical studies are not exactly matched to the situation studied in this paper (i.e., UVB vs. the AGN proximity), we can refer to these results to infer in what circumstances the impact of radiative AGN feedback becomes significant. First, a semianalytic model predicts halo masses of faint ($10^{11} < M_{h,21} < 10^{12}$ erg s$^{-1}$) LAEs, moderate-luminosity ($10^{12} < L_{\text{Ly}\alpha} < 10^{13}$ erg s$^{-1}$) LAEs, and LBGs with UV magnitude brighter than $M_{\text{UV}} = -20.8$ at $z \sim 5$ of $\sim 10^{16.4} M_\odot$, $10^{11.1} M_\odot$, and $10^{11.7} M_\odot$, respectively (Garel et al. 2015). The halo mass of faint LAEs is in agreement with the threshold mass. Second, the strength of the UV radiation field at 3 pMpc from our QSOs is stronger than that of the UVB at $z \sim 5$. It is parameterized as $J(\nu) = J_{21} \times (\nu/\nu_0)^{\alpha} \times 10^{-21}$ erg s$^{-1}$ Hz$^{-1}$ cm$^{-2}$ s$^{-1}$, where $\nu_0$ denotes the Lyman limit frequency and $\alpha$ denotes continuum slope. We derive $J_{21}$ at 3 pMpc from the QSOs assuming UV continuum slope $\alpha = -0.99$ (Fan et al. 2001) and using the measured luminosity at 1450 Å, $L_{\text{Ly}\alpha}$ from Trakhtenbrot et al. (2011), to find $J_{21} = 1.2$ and 0.7 for J08 and J11, respectively. Inferred UVB radiation $J_{21}$ at $z \sim 5$ is of order 0.1 (Calverley et al. 2011) and is similar to the assumed value in previous calculations that predict strong feedback. Thus, taken at face value, fainter LAEs in our sample can be significantly affected by those QSOs.

However, there are some caveats in the above arguments. First, in order to suppress the formation of LAEs significantly, QSOs should be switched on before LAEs around them start to form. This can be the case if the lifetime of the QSO phase is similar to an estimated maximum value of $\sim 10^{8}$–$10^{9}$ yr (Marconi et al. 2004), since the estimated age of LAEs is roughly a few $\times 1$–100 Myr (Finkelstein et al. 2009). Second, the short-timescale variability of the UV source is not taken into account in the theories, QSOs show strong variability on timescales as short as days. At the same time, many simulations showed that AGNs change their luminosity dramatically in the course of major mergers, and also there are some indications of AGNs flickering on timescales of $\sim 10^5$ yr (Schawinski et al. 2015). If the variability is taken into account, the impact of AGN feedback is further weakened because high-redshift AGNs probed so far are considered to be near its peak luminosity and its time-averaged luminosity may be lower (Hopkins et al. 2006; Hopkins & Hernquist 2009). Third, although primordial gas is assumed in the calculations, pregalactic clouds can contain metals and dust grains that do not originate from in situ star formation but from neighboring galaxies via various mechanisms such as galactic winds and radiation pressure. This makes cooling and heating processes more complex: metals (Wiersma et al. 2009) and dust emission contribute cooling once the temperature and density get high enough ($> 10^6$ K) and make star formation easier, whereas photoelectric dust heating could be quite efficient and negative feedback could be stronger at the temperature, UVB strength, and density condition of the earlier stage of collapse considered here (Nath et al. 1999; Montier & Giard 2004).

Though the effect of metals and dusts is unknown, if a QSO activates well before surrounding galaxies start to collapse and retains its high luminosity for $10^8$–$10^9$ yr, the suppression of faint galaxies due to a QSO can be observable. These conditions may not be always fulfilled (e.g., there are many works claiming an episodic and short QSO phase; see Martini 2004). Even if it exists, only LAEs fainter than $L_{\text{Ly}\alpha} = 10^{42}$ erg s$^{-1}$ and LBGs fainter than $M_{\text{UV}} = -18.3$ seem to be critically affected. Since limiting magnitudes of observations conducted in the past are much brighter, it is difficult to explain the deficit of overdensity around QSOs reported so far by radiative feedback, unless halo masses of LAEs are overestimated. More realistic calculations and much deeper observations are clearly needed to qualitatively examine AGN radiative feedback.

### 4.3. Fluorescent Emission

High-EW LAEs are interesting because such high Ly$\alpha$ EW ($> 240$ Å) is unlikely to be due solely to normal star formation (Charlot & Fall 1993; Schaerer 2003). It is usually attributed to clumpy, dusty intergalactic medium (Hansen & Oh 2006; Finkelstein et al. 2008; Kobayashi et al. 2010) or fluorescent Ly$\alpha$ emission (Adelberger et al. 2006; Cantalupo et al. 2005, 2007) especially in the case of QSO environments. Cantalupo et al. (2012) reported that many Ly$\alpha$ fluorescent systems illuminated by a hyperluminous QSO at $z \sim 2.4$ are clustered around the QSO and argued that, as opposed to the case of feedback (Section 4.2), the fainter side of the Ly$\alpha$ LF of LAEs around the QSO becomes steeper owing to these sources. In our sample, only two LAEs in the J11 field have such high EW. One of the LAEs is located at $< 0.7$ pMpc (projected) from J11. The other is located at $\sim 5$ pMpc (projected) from J11. Though the former can be significantly affected by radiation from the QSO, the latter are unlikely to be significantly affected, since at that distance QSO radiation is comparable to UVB. Cantalupo et al. (2012) predicted that if fluorescence is dominant in the field, $L_{\text{Ly}\alpha}$ of LAEs should decrease with increasing distance from the QSO. Figure 8 shows the number, Ly$\alpha$ EWs, and Ly$\alpha$ luminosities of LAEs as a function of the projected distance from the central AGNs. In panel (a), we see the possible signature of local peak seen in Figure 4, i.e., the rising trend of the number of LAEs at $< 2$ pMpc in the J08 and J11 fields. However, in panels (b) and (c), we find no dependence on the distance in any field. This suggests that the properties of most of the LAEs in these fields are not affected by the central AGNs.

There is one interesting source in the J11 field: a close companion LAE located at 80 pkpc away from J11. We show the pseudo-color image and the continuum-subtracted Ly$\alpha$ image of J11 and the companion in Figure 9. The companion clearly shows a Ly$\alpha$ halo that extends toward the QSO direction and may suggest interactions between these two galaxies. Though $\Delta z$ of the NB711 filter is large compared to 80 pkpc, if the companion is at the same redshift as J11, $J_{21}$ will be $\sim 1000$. Following Cantalupo et al. (2005), we derived the “effective boost factor” $b_{\text{eff}}$ to be $\sim 3000$. Thus, if there exist optically thick clouds, they can be detected with our imaging observations. The Ly$\alpha$ luminosity of the QSO near side is $\sim 1.8$ times that of the far side. Thus, although EW is not high (EW$_{\alpha}$ $\sim 48$ Å), fluorescent emission may contribute to its $L_{\text{Ly}\alpha}$, if not all. We also note that the QSO J11 itself showed asymmetric, extended Ly$\alpha$ emission toward the opposite side of the companion. This may imply a giant filamentary structure
is partly due to the use of different techniques and possibly radiative feedback from AGNs. The conventional Lyman break technique only gives us an unclear picture because it selects galaxies from a wide redshift range (\(\Delta z \sim 1\) corresponds to \(\sim 100\) physical Mpc at the redshift of interest of this study, \(z \sim 5\)), making it difficult to discuss local (a few to several physical Mpc corresponds to \(\Delta z \sim 0.1\)) environments around AGNs. In order to test whether AGN environments are rich and whether AGN feedback is indeed strong enough to suppress formation of neighboring galaxies, we conducted deep and wide-field imaging observations with the S-Cam on the Subaru Telescope and searched for LAEs around two QSOs at \(z \sim 4.9\) and an RG at \(z \sim 4.5\) by using narrowband filters. In QSO fields, we also obtained additional broadband images to select LBGs at \(z \sim 5\) for comparison. We constructed a photometric sample of 301 LAEs and 170 LBGs in total. A wide FOV (34\arcmin \times 27\arcmin) of the S-Cam enabled us to probe these galaxies in the immediate vicinities of the AGNs and in the blank fields simultaneously and compare various properties of them in a consistent manner. We find that the QSOs are located near low peaks of galaxy surface density, though the data suggest that they are not uncommon (with \(<2\sigma\) significance), and one of the QSOs has a close companion LAE with a projected distance of \(\sim 80\) physical kpc. However, the LFs of LAEs/LBGs around the QSOs and RGs are consistent with or lower than those in blank fields, as opposed to the expectation that they should reside in the most massive overdensities. Moreover, we find no evidence of feedback even in the faintest luminosity bin (down to \(L_{\text{Ly}\alpha} = 10^{41.8}\) erg s\(^{-1}\)).

Through our discussion in Section 4.2, we conclude that radiative feedback is unlikely to affect our sample and galaxies around high-redshift AGNs observed to date. Therefore, our results suggest that high-redshift AGNs do not necessarily trace overdense regions of the universe and that is not due to radiative feedback. Note that most of the currently known QSO fields with significant overdensity of neighboring galaxies are detected with LBGs and that spectroscopic follow-up of them is very challenging with the existing instruments. Thus, there still remains a possibility that the photometric sample around those overdense regions is significantly affected by the projection effect. Further observations with narrowband filters around high-redshift AGNs are the best way to know the true nature of their environments. In parallel, observations around them with submillimeter/millimeter facilities like ALMA (Trakhtenbrot et al. 2017) are crucial for detecting possible dusty galaxies. Large-area surveys will find more and more AGNs at high redshift with their redshifted Ly\(\alpha\) emission line falling into the existing narrowband filters. For example, many narrowband filters are installed on the Hyper S-Cam (Miyazaki et al. 2012), which has a much wider FOV (17.5\arcsec in diameter) than the S-Cam and thus is the most powerful instrument for this study. Particularly, Subaru High-z Exploration of Low-luminosity Quasars (Matsuoka et al. 2016) will find many high-redshift, low-luminosity QSOs, including QSOs with very massive SMBHs but with low accretion rates, and will help us reveal more general trends of high-redshift AGN environments.

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