A LARGE NUMBER OF $z > 6$ GALAXIES AROUND A QSO AT $z = 6.43$: EVIDENCE FOR A PROTOCLUSTER?*

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ABSTRACT

QSOs have been thought to be important for tracing highly biased regions in the early universe, from which the present-day massive galaxies and galaxy clusters formed. While overdensities of star-forming galaxies have been found around QSOs at $2 < z < 5$, the case for excess galaxy clustering around QSOs at $z > 6$ is less clear. Previous studies with the Hubble Space Telescope (HST) have reported the detection of small excesses of faint dropout galaxies in some QSO fields, but these surveys probed a relatively small region surrounding the QSOs. To overcome this problem, we have observed the most distant QSO at $z = 6.43$ using the large field of view of the Suprime-Cam (34′ × 27′). Newly installed red-sensitive fully depleted CCDs allowed us to select Lyman break galaxies (LBGs) at $z \sim 6.4$ more efficiently. We found seven LBGs in the QSO field, whereas only one exists in a comparison field. The Poisson probability to find seven objects when one expects four is $\sim 10\%$, while the probability to find seven objects in one field and only one in the other is less than 0.4%, suggesting that the QSO field is significantly overdense relative to the control field. These conclusions are supported by a comparison with a cosmological smoothed particle hydrodynamics simulation which includes the higher order clustering of galaxies. We find some evidence that the LBGs are distributed in a ring-like shape centered on the QSO with a radius of $\sim 3$ Mpc. There are no candidate LBGs within 2 Mpc from the QSO, i.e., galaxies are clustered around the QSO but appear to avoid the very center. These results suggest that the QSO is embedded in an overdense region when defined on a sufficiently large scale (i.e., larger than an HST/ACS pointing). This suggests that the QSO was indeed born in a massive halo. The central deficit of galaxies may indicate that (1) the strong UV radiation from the QSO suppressed galaxy formation in its vicinity or (2) that star formation closest to the QSO occurs mostly in an obscured mode that is missed by our UV selection.

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

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1. INTRODUCTION

At $2 < z < 5$, strong overdensities of star-forming galaxies have been found around QSOs and radio galaxies, and thus, QSOs have been thought to trace highly biased regions in which the present-day massive galaxy clusters formed (e.g., Djorgovski et al. 2003; Miley et al. 2004; Kashikawa et al. 2007). It is expected that this extends to the most luminous $z \sim 6$ QSOs as well, as this rare population hosts supermassive black holes of several billion solar masses that are presumed to reside in the most massive galaxies and dark matter halos present at this redshift.

However, observational results to date have been puzzling; five $z \sim 6$ QSO fields observed by the Hubble Space Telescope (HST)/Advanced Camera for Surveys (ACS) show no major enhancements in the galaxy density (Kim et al. 2009). Even though a few QSO fields have shown an apparent overdensity (Stiavelli et al. 2005; Zheng et al. 2006), none of them were among the richest structures discovered to date at $z \sim 6$, as evidenced by much larger overdensities found in random fields (e.g., Ouchi et al. 2004b; Kashikawa et al. 2007; Ota et al. 2008, see Overzier et al. 2009 for a discussion).

Why do QSOs suddenly appear to stop being at the center of the overdensity at $z \sim 6$? One hypothesis is that the higher dark matter densities near the QSOs, the strong ionizing UV radiation from the central QSOs may prohibit the condensation of gas thereby suppressing galaxy formation around the QSOs (Barkana & Loeb 1999). An alternative and perhaps more likely explanation is that the lack of overdensities identified is related to the fact that it is currently technically challenging to perform a survey deep enough to detect faint $z \sim 6$ galaxies and cover an area large enough to probe the large-scale structure surrounding the QSOs.

In this work, we aim to study the large-scale structure around the currently most distant QSO at $z = 6.43$, taking advantage of the large aperture of the 8.2 m telescope “Subaru” located on Maunakea Observatory and the wide field prime focus camera “Suprime-Cam” (34′ × 27′) (Miyazaki et al. 2002b). In addition, we have recently installed new red-sensitive fully depleted CCDs on the Suprime-Cam (Kamata et al. 2008), allowing us to reach necessary depths in much shorter exposure time. Improved sensitivity is a factor of about 1.4 and 2 better in the $z^\prime$ band and at $\sim 1 \mu m$, respectively.

Throughout the paper, we use $H_0 = 70 h_{70}$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. Magnitudes are given in the AB system.
2. DATA AND ANALYSIS

2.1. Observation

We observed the field surrounding the most distant QSO, CFHQS J2329−0301 at $z = 6.43$, $M_{1450} = −25.23$ (Willott et al. 2007) using Suprime-Cam with the filters $i′, z′, z_R$ during an engineering run in 2008 August and UH time in 2009 June. We used the special $z_R$-band filter constructed by Shimasaku et al. (2005). This filter covers the redder side of the $z'$ band and has a central wavelength of 9900 Å (Figure 1). The seeing was stable throughout the runs, with an FWHM $≈ 0.5$ arcsec in $i′$, $0.4 \sim 0.7$ arcsec in $z'$, and $0.5 \sim 0.7$ arcsec in $z_R$. The exposure times were 360 and 500 s in $i′$ and $z_R$, respectively. The exposure times in the $z'$ band varied; we obtained three exposures of 100 s, two of 300 s, 3 of 400 s, six of 500, and two of 700 s resulting in more than 10,000 ADU of sky counts. The total exposure times in $i′$, $z'$, and $z_R$ were 3600 s on 2008 August 28, 6900 s on 2008 August 27, and 12,532 s on 2008 August 27 and 2009 June 18, respectively, under good seeing conditions (less than 0.6 arcsec FWHM). Our dither strategy consisted of five or more pointings on a circle of 1 arcmin radius.

2.2. Data Reduction

Our reduction procedure follows Miyazaki et al. (2002a), with small adjustments made related to the new CCD. A major difference between the old and new Suprime-Cam is that the latter has four-channel readout circuits for faster readout. As a result, overscan subtraction and background sky-subtraction should be performed on each channel individually for each CCD. An overscan value is evaluated by taking the mean along the columns of the overscan region of each channel and then subtracted from the science region. A flat field image is created by taking the median of all science images after masking objects. The background sky is subtracted on each channel after flat fielding. To estimate the background, we first reject data points having two times larger or four times lower sigma value than the sky value. The upper cut prevents astronomical objects from contaminating the sky, while the lower cut removes residuals from the flat fielding. Then, we estimate the modes in 64 pixel $\times$ 64 pixel boxes. A background of each pixel is estimated by interpolating these mode values at vertexes of a triangle centered on the pixel.

Before combining all the science frames, the images need to be corrected for (1) geometric distortion, (2) displacement and rotation of each CCD from the fiducial position, and (3) pointing offsets between exposures. We corrected for these effects by minimizing the positional differences of common control stars identified on each CCD in all exposures relative to the first exposure. The resulting positional error of the control stars from the fiducial point is approximately 0.5 pixel (rms). We solve the transformation among the three bands, aligning each frame with the first exposure of the $z_R$ band in order to perform multi-band photometry using an aperture as small as possible to obtain a high S/N ratio. Flux offsets are also calculated during this procedure. Since we want to determine the transformation among the bands as accurately as possible, an image warping procedure was performed only once, and a second order bilinear interpolation was used for rebinning. For stacking, we adopted the clipped mean in order to eliminate cosmic rays. The implementation of these reduction steps was performed using the software suite imcat.

2.3. Photometric Calibration

Photometric calibration is performed by comparing stars in a reference field 2 deg away to the north ($\alpha, \delta_{2000} = (23:29, −01:01)$ with those in the SDSS/DR7 star catalog (Abazajian & Sloan Digital Sky Survey 2009) and using the following equations:

$$i_{\text{Subaru}}' = 0.125(i' - r')_{\text{SDSS}} + 0.003 + i_{\text{SDSS}}'$$

$$z_{\text{Subaru}}' = −1.091(i' - z')_{\text{SDSS}} - 0.004 + i_{\text{SDSS}}'$$

$$z_R, \text{Subaru} = −1.414(i' - z')_{\text{SDSS}} + 0.021 + i_{\text{SDSS}}'$$ (3)

These equations are determined from Gunn & Stryker (1983) and convolved with response curves that include both optics and the atmosphere. We measured the efficiency of the new CCDs in Kamata et al. (2008). Since the calibration field was observed soon after the completion of our science exposure, no airmass/ atmospheric corrections were needed to obtain the photometric zero point. After the correction, the rms of the magnitude differences between our catalog and the SDSS catalog is 0.06, 0.07, and 0.07 in $i'$, $z'$, and $z_R$, respectively.

We have checked the colors of a sample of star-like objects selected according to CLASS_STAR $> 0.9$, by comparing the color of the stars from Gunn & Stryker (1983) to the observed ones, confirming a good internal consistency of colors in our catalog. The template and observed colors were consistent within an accuracy of 0.05 mag. Since the seeing in the final images is 0.58, 0.54, and 0.50 arcsec (FWHM), we use a small aperture to perform photometry to obtain a better S/N ratio. Following Shimasaku et al. (2005), who used an aperture size twice that of point-spread function (PSF), we adopt a 1.2 arcsec aperture to perform photometry. The $3\sigma$ limiting magnitudes within this 1.2 arcsec aperture are $i' = 26.95$, $z' = 26.13$, and $z_R = 25.46$ (AB) mag. Here, $1\sigma$ sky magnitudes are computed by randomly placing a 1.2 arcsec aperture in the blank (sky) part of each image (Yagi et al. 2002; Ouchi et al. 2004a).

2.4. Astrometric Calibration

We obtain an astrometric solution by comparing our catalog with the USNO-B1.0 catalog (see scamp; Bertin 2006). The
resulting accuracy of the astrometric solution is 0.5 arcsec (rms). Note that we did not use this astrometric solution to stack individual raw images, but only to obtain the final absolute positions of the objects.

2.5. Object Detection

The object detection is performed by SExtractor 2.3.2 (Bertin & Arnouts 1996). We constructed a detection image, the “all”- $z_R$ image, by combining all science frames, including those with slightly poorer seeing conditions. The object detection reliability using this “all”- $z_R$ image is higher than when only using the $z_R$ image for detection given that $\approx 3\sigma$ sources in the $z_R$ image are detected at $\approx 3.7\sigma$ in the “all”- $z_R$ image. Using the “all”- $z_R$ image, we consider an object detected if it has more than five connected pixels with each exceeding the local sky rms by a factor of 2. To reduce contamination by false detections, we only use the “detected cleanly” and “no blending” objects that have FLGS=0 in SExtractor. We measure the magnitudes in 1.2 arcsec apertures for each passband to derive colors of the detected objects and adopted MAG_AUT0 as our estimate for the total $z_R$ magnitude. Objects in the $i'$ band fainter than $2\sigma$ were replaced by the $2\sigma$ limiting magnitude as an upper limit. In addition, all objects having detections in the $z'$ band of less than $2\sigma$ were rejected in order to keep spurious detection at a minimum.

Some lower S/N regions, such as the “blooming regions” (the halos and horizontal spikes surrounding bright stars), as well as the outer edge of the image, are masked manually. The resulting effective field of view (FOV) is $0.219 \text{deg}^2$. We detect 48,632 objects after masking (to a limiting magnitude of 25.46, or $3.7\sigma$ detections on the “all”- $z_R$ image). The number of detections is comparable to that in our comparison field, the Subaru Deep Field (SDF), which contains 45,405 objects in a single FOV of the Suprime-Cam (Shimasaku et al. 2005).

2.6. SED Modeling

We have upgraded the CCDs of the Suprime-Cam to red-sensitive ones, which have 1.4 and 2 times better sensitivity in $z'$ and $z_R$ compared to the previous detectors. Thus, we can reach the necessary depth in a much shorter exposure time. This improved sensitivity allows us to efficiently use the $z'-z_R$ color to select Lyman break galaxies (LBGs) at $z > 6.4$. At the QSO redshift of $z = 6.43$, the $z'-z_R$ color selection is more effective in selecting galaxies than the $i'-z'$ color selection (the so-called $i'$-dropout technique), which has been used in previous works to select 5.5 $< z < 6.5$ galaxies (Figure 1).

In order to predict the colors of galaxies as a function of their redshift, we computed $z'-z_R$ colors of model galaxies (0.05, 0.1, and 0.2 Gyr of age, using Bruzual & Charlot 2003) and added the absorption effects from the neutral hydrogen in the intergalactic medium (IGM; Fan et al. 2006a). According to our modeling, colors of $i'-z' > 1.9$ and $z'-z_R > 0.3$ can be used to identify galaxies at $z > 5.8$ (Figure 2).

2.7. Object Selection

Here, we will select LBGs at $z > 6.4$ using our $i', z', z_R$ catalog. The model colors shown in Figure 2 predict that galaxies at $z = 6.4$ should have a large color difference of about $i'-z' \simeq 3.5$. However, for an object having $z' \simeq 25$ this would require $i' \simeq 28.5$ mag, much fainter than our detection limits. Therefore, we slightly loosen the color cut and require $i'-z' > 1.9$ and $z'-z_R > 0.3$. These relaxed criteria are still appropriate for selecting LBGs at $z > 6.4$, although we must be somewhat cautious of potential galaxies at $z \simeq 1.8$ having colors of $i'-z' \simeq 1.9$ that could make it into the sample as well. In order to assess the impact of this effect on our conclusions, in Section 3.3 below we will try to statistically estimate the number of such $z \simeq 1.8$ interlopers expected.

In our control field (the SDF), only a single object was found that satisfied our color criteria, and this object was classified as a genuine $z \simeq 6$ galaxy by Shimasaku et al. (2005). Because the SDF data are deeper than ours, we adjusted the depth of that field by replacing the magnitudes of all objects fainter than our limits with the limiting magnitudes as computed for our field. We also removed two objects brighter than $z_R,Auto = 24.0$ since such objects are too bright to be at $z = 6.4$ (according to a $z \sim 6$ LBG study in the SDF, there is no $z > 6$ galaxy brighter than $z_R = 24.8$; see Shimasaku et al. 2005). These two objects may be contaminating stars since they have SExtractor CLASS_STAR values greater than 0.95, meaning that they are likely to be unresolved.

As a result, to the magnitude limit of $z' < 25.46$, we have detected seven objects that are good candidates for being $z \sim 6$ LBGs. These objects are shown as red squares in Figure 2. Note that (the lower limits on) their $i-z$ colors are bluer than expected from the models, due to the relatively shallow limiting magnitude in $i'$.

3. SOURCES OF CONTAMINATION

3.1. False Detections

Because we are selecting very faint objects, our sample may be contaminated by false detections due to background fluctuations. To evaluate the number of such contaminations, we created a negative of the “all”- $z_R$ image and repeated our detection, photometry, and masking routines on each of the filter images. No detections were obtained based on this negative image. We conclude that our catalog is not affected by spurious detection.
3.2. Contamination by Faint Dwarf Stars

As we can see in Figure 2, L/T dwarf stars also satisfy our adopted color cut ($i' - z' > 1.9$ and $z' - z_R > 0.3$). In this subsection, we estimate the expected number of L and T dwarfs, given the size, depth, and Galactic position of the field.

As a first test, when we applied our color criteria to the SDF only one object was found and classified as a genuine $z \sim 6$ object (see above). The second reddest object in the field has $i - z \sim 1.65$, i.e., there are no stellar-like objects in the SDF with colors red enough to make it into our selection.

However, we need to take into account the different galactic latitudes of our field and the SDF. Unfortunately, the late-type star counts as a function of Galactic position are not accurately known at the faint magnitudes we are probing. Late-type stars having similar colors to high-$z$ galaxies can only be distinguished by using deep spectroscopic observations. The latest estimate was performed by Caballero et al. (2008), who studied the contamination from L and T dwarfs by modeling the spatial distribution of late-type stars in the Galactic thin disc described using an exponential law $n_i = n_{A_i} e^{-\frac{d}{h_i}}$, where $n_{A_i}$ is the number density of $i$-type stars, $h_i$ and $h_2$ are the scale length and the scale height of the exponential disc, and $d$ is the distance to us in galactic coordinates, $d = (R_0 + d^2 \cos^2 b - 2 R_0 \cos b \cos l)^{\frac{1}{2}}$. The adopted parameters are $R = 8.6$ kpc, $h_R = 2.25$ kpc, and $h_Z = 0.3$ kpc. Local spatial densities of late-type stars are adopted from Knapp et al. (2004). According to this model calculation, we expect 1.5 times as many L/T dwarfs as in the SDF for $z_R < 25.25$ mag, corresponding to the faintest bin of the magnitude of our selected objects.

We have seen that there were no stars in our $z \sim 6.4$ color-selection in the SDF. Here, we try to scale that null detection in the SDF to our field. If we assume that stars follow a Poisson selection in the SDF to our field. If we assume that stars follow a Poisson distribution, we can find the number of stars within a certain magnitude range by integrating the Poisson distribution. For example, if we want to find the number of stars in the $i$-band brighter than a magnitude $i = 27.39$, we can use the Poisson distribution to estimate the number of stars brighter than this magnitude. The Poisson distribution is given by $P(n;\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$, where $\lambda$ is the expected number of stars and $n$ is the observed number of stars.

We note, however, that the object with id 1 could be a dwarf star since its $i' - z'$ color is not large enough. We will include this object in the following discussion.

3.3. Contamination by Red Galaxies at $z \sim 1.8$

As mentioned earlier, we found only one object when applying our adopted color criteria for $z \sim 6.4$ galaxies to the SDF catalog (after adjusting the limiting magnitudes to ours), and this object was identified as a $z \sim 6$ object given that its $B, V, R$ magnitudes were too faint for a low-$z$ interloper. Based on this, the expected number of $z \sim 1.8$ galaxies found according to our criteria should be close to zero with an upper limit of 1.83 at a confidence level of 84% (Gehrels 1986). Although cosmic variance should ideally be taken into account as well, we do not have any other suitable comparison fields that are as deep in $z_R$ as the SDF.

However, we use the publicly available SXDS DR1 catalog (Furusawa et al. 2008) to obtain a rough estimate of the expected contamination using only an $i - z > 1.9$ color cut. The SXDS covers five pointings with the Suprime-Cam, and thus, the cosmic variance is less of a concern. We first applied the observational limits as given by our field by replacing all magnitudes that are fainter than our limiting magnitudes ($i'_{\lim} = 27.39, z'_{\lim} = 26.57$) by our 2$\sigma$ upper limits. We used FLAG=0 in order to select only cleanly detected objects and trimmed a region of lower S/N (500 pixels from the edge of the field). Only three objects were found which passed the selection criteria in all five pointings of the SXDF. These objects are detected in the $B$ band (brighter than 28.4, 3$\sigma$ mag), indicating that they are most likely low redshift interlopers at a redshift of $z \sim 1.8$. If we scale this number to the area of our single pointing field, only 0.6 of such interlopers are expected in our galaxies.

This rough estimate is consistent with the estimate derived above based on the SDF, suggesting that the contamination from $z \sim 1.8$ galaxies is negligible.

4. RESULTS

4.1. Number Counts

Figure 3 shows the number counts of all detected objects, as well as those of the $z \sim 6$ galaxies. The number of all objects in this field is slightly lower, by about 20%, than those detected in the SDF field at $z_R < 24$. This could be due to a small difference in the absolute photometric calibrations between the two catalogs or due to cosmic variance. If it were due to a difference in photometric calibration, a shift of 0.2 mag would be required to explain the difference. Note that such an offset, if real, would not affect the colors used in our color selection of the $z \sim 6$ galaxies, as the colors were checked for internal consistency using a catalog of stars. We next consider the possibility of cosmic variance. Furusawa et al. (2008) observed five Suprime-Cam pointings and derived the number counts. The variance in the number counts was found to amount to a factor of 1.7 among the individual pointings in the $z'$ band. Thus, we conclude that the differences in the number counts found between our field and the SDF are consistent with being due to cosmic variance. Finally, we note that at magnitudes fainter than $z_R = 25$ the difference in number counts becomes larger again, but this is simply because our data are slightly shallower than the SDF.
counts) is less than 0.01%. However, this is not a fair statistic is. If we assume a Poissonian distribution, the probability of
the QSO field, implying that even with the standard field (SDF), we still find 4 objects although 16 objects found in Table 1, and we show the filter thumbnail images in Figure 4.

We speculate that we are seeing the most distant protocluster centered on a massive QSO at $z = 6.4$. The simulated galaxies have appropriate colors and magnitudes, allowing us to make a direct comparison to our observation. In order to simulate galaxies at $z = 7$, we have applied (1) a bright magnitude cut at $z_R > 24$ and (2) a detection completeness. Then, we count how many galaxies would be found in the FOV of Suprime-Cam. To evaluate the completeness of our detection procedure as a function of magnitude, we add artificial objects to the $z_R$ image with all detected objects masked. The artificial objects are modeled by a Moffat function with a half light radius of 0.9 arcsec in the magnitude range of 24–25.46. We used the IRAF task “noao.aridata.mkobjects” for this procedure. Then, we repeat the object detection and measure the success rate.

After applying the completeness and magnitude cuts to the simulated data, we have a realistic sample that can be compared to our observational data. By randomly sampling the Suprime-Cam size FOV from the simulation, we measured the galaxy frequency distribution (Figure 5). Based on this simulation, we found that the probability to find one pointing with seven galaxies and another with one is less than 0.4%, in good agreement with the results from the Poissonian statistics detailed above. Our results suggest that it is hard to explain the overdensity by a chance coincidence of galaxies due to cosmic variance.

4.4. Spatial Distribution of the LBGs

In this subsection, we discuss the peculiar spatial distribution of the LBGs.

Figure 6 shows the spatial distribution of the $z \sim 6.4$ galaxies. The cross located at the center indicates the position of CFHQS

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### Table 1

| id          | $\alpha_{2000}$ | $\delta_{2000}$ | $z_R$ | $i' - z'$ | $z' - z_R$ | FWHM |
|-------------|-----------------|-----------------|-------|----------|-----------|------|
| 1           | 23:29:20.56     | −02:54:29.5     | 24.62 | 2.03     | 0.44      | 0.63 |
| 2           | 23:29:24.10     | −03:07:34.3     | 24.64 | >1.93    | 0.54      | 1.15 |
| 3           | 23:29:28.56     | −02:57:38.4     | 24.69 | >1.98    | 0.52      | 0.55 |
| 4           | 23:28:48.69     | −03:06:23.3     | 24.88 | >2.08    | 0.48      | 0.58 |
| 5           | 23:28:58.68     | −03:12:11.6     | 24.98 | >2.02    | 0.41      | 0.64 |
| 6           | 23:30:04.24     | −02:56:54.6     | 25.00 | >1.97    | 0.38      | 0.69 |
| 7           | 23:29:31.52     | −03:11:05.0     | 25.11 | >1.93    | 0.32      | 1.02 |

**Figure 4.** Thumbnail images of the LBG candidates in the QSO field. The properties of the individual sources are listed in Table 1.

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4.2. Comparing the LBG Number Density in the QSO Field with that in the SDF

We detect seven objects as $z \sim 6.4$ galaxy candidates using the color criteria in Section 2.7, while nine objects are rejected as lower redshift objects at $z < 5.5$ based on a $z' - z_R$ color cut (it would have been difficult to eliminate these objects using only $i' - z'$). For comparison, we apply the same color criteria to the SDF catalog after applying our magnitude limits and find only one candidate. Thus, the number of $z \sim 6.4$ galaxies in the QSO field is 7 times larger than that the SDF field. We note that if we apply a more relaxed cut based on a single color of $i' - z > 1.9$ (the standard i-dropout technique) to the reference field (SDF), we still find 4 objects although 16 objects found in the QSO field, implying that even with the standard i-dropout technique we find an overdensity in the QSO field.

The properties of the objects identified are summarized in Table 1, and we show the filter thumbnail images in Figure 4. Although our data are shallower than the SDF, we have detected more LBGs than in the SDF. The result suggests that the number density of $z \sim 6.4$ galaxies in this QSO field is larger than that in the SDF field. Such an overdensity would be consistent with the predictions from cosmological simulations (e.g., Springel et al. 2005) that suggest that the first QSOs are situated in the most prominent dark matter halos and are surrounded by a large number of fainter galaxies. Although the redshift discrimination offered by our photometric selection is not very accurate, the number of fainter galaxies. Although the redshift discrimination

4.3. Assessing the Significance of the Overdensity

In this subsection, we assess how significant the overdensity is. If we assume a Poissonian distribution, the probability of finding seven objects when one expects one (based on the SDF counts) is less than 0.01%. However, this is not a fair statistic since we have only one comparison field (the SDF) which has a similar size as the QSO field. If we naively calculate the average number of counts expected from the two fields combined, $(7+1)/2$, we expect four counts on average. The Poissonian probability to find seven objects is thus $\sim 11\%$. However, the chance of finding one object in one field and seven in the other is much lower. This can be quantified by calculating the expected number of counts that maximizes the probability of finding seven objects in one field and one in the other. Out of 10,000 Monte Carlo realizations, we find 0.40% of such cases, i.e., the significance of this overdensity is 99.6%.

The above estimates are based on the oversimplification that galaxies are not clustered. Here, we evaluate our results based on the cosmic variance determined from a cosmological simulation. The estimated number of galaxies is predicted from the cosmological smoothed particle hydrodynamics (SPH) simulation of a concordance $\Lambda$ cold dark matter model of Choi & Nagamine (2009, 2010). The simulated galaxies have appropriate colors and magnitudes, allowing us to make a direct comparison to our observation. In order to simulate galaxies at $z = 7$, we have applied (1) a bright magnitude cut at $z_R > 24$ and (2) a detection completeness. Then, we count how many galaxies would be found in the FOV of Suprime-Cam. To evaluate the completeness of our detection procedure as a function of magnitude, we add artificial objects to the $z_R$ image with all detected objects masked. The artificial objects are modeled by a Moffat function with a half light radius of 0.9 arcsec in the magnitude range of 24–25.46. We used the IRAF task “noao.aridata.mkobjects” for this procedure. Then, we repeat the object detection and measure the success rate.

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4.4. Spatial Distribution of the LBGs

In this subsection, we discuss the peculiar spatial distribution of the LBGs.

Figure 6 shows the spatial distribution of the $z \sim 6.4$ galaxies. The cross located at the center indicates the position of CFHQS...
Active galactic nuclei (AGNs) have been extensively studied. At lower redshift, the environments of QSOs and fainter active galactic nuclei (AGNs) have been extensively studied. At 0.05 < z < 0.095, Miller et al. (2003) found that the fraction of galaxies with an AGN is independent of the local galaxy density, indicating strong AGN activity is twice as high in low-density regions compared to high-density regions at 0.05 < z < 0.095. However, the situation is different at higher redshifts. A Keck survey of fields centered on known z > 4 QSOs found excesses in the number of companion galaxies (Djorgovski et al. 2007, 2002). In Overzier et al. (2006, 2008), it was shown that the environments of some radio galaxies at 0.04 < z < 0.06 appear richer than the average field at z = 4–5. In Overzier et al. (2006, 2008), it was shown that the environments of some radio galaxies at z = 4–5 appear richer than the average field at z = 4–5.

J2329–0301, and circles represent the z ∼ 6.4 galaxies. It appears that while these galaxies are clustered around the QSO, none are in its direct vicinity (the closest galaxy being already at a (projected) distance of ∼2 Mpc from the QSO). To quantify the significance of this effect, we show a histogram of the angular distances from the QSO to each of the galaxies in Figure 7 (red solid histogram). The distribution indeed suggests that there is a deficit of galaxies at <2 Mpc, while typical clustered distributions are expected to peak at the center. The blue dotted line in Figure 7 is based on the positions of randomly distributed objects (but avoiding the masked regions just as in the real data). Comparing the two histograms suggests that in the QSO field the number of galaxies at the projected distance from 2 to 4 (physical) Mpc/h is indeed larger than that expected from a random distribution.

We perform a Kolmogorov–Smirnov (K-S) test by calculating the following value:

\[
D = \max_i |R_i - M_i|, \tag{4}
\]

where \( R_i \) is the number of galaxies in the \( i \)th bin and \( M_i \) is the number in the same bin as given by the randomly distributed galaxies. We construct a histogram of the \( D \) statistic using 10,000 times realizations, finding that the distribution in the QSO field differs from the random distribution at a 97% confidence level. If we just compare the peak at 3 Mpc, it has a 1.7σ excess over the random distribution.

5. DISCUSSION

We found an overdensity of LBGs around the QSO with a 99.6% significance. We furthermore found evidence for a ring-shaped distribution, albeit at the <2σ level. Although the physical interpretation must await verification using deeper data or spectroscopic follow-up, below we will discuss possible physical interpretations under the assumption that our results are significant and represent real structure surrounding the QSO.

5.1. Comparison with Previous Work

At lower redshift, the environments of QSOs and fainter active galactic nuclei (AGNs) have been extensively studied. At 0.05 < z < 0.095, Miller et al. (2003) found that the fraction of galaxies with an AGN is independent of the local galaxy density, in a stark contrast to both star-forming and passive galaxies that show an environmental dependence (e.g., Goto et al. 2003). Lietzen et al. (2009) found an underdensity of bright galaxies at a few Mpc scale from nearby QSOs at 0.078 < z < 0.172. Kauffmann et al. (2004) found that at fixed stellar mass the number of galaxies that host AGNs with strong [O iii] emission indicating strong AGN activity is twice as high in low-density regions compared to high-density regions at 0.04 < z < 0.06.

However, the situation is different at higher redshifts. A Keck survey of fields centered on known z > 4 QSOs found excesses in the number of companion galaxies (Djorgovski 1999). Kashikawa et al. (2007) found that LBGs without Lyα emission form a filamentary structure near a QSO at z ∼ 5, while Lyα emitters are distributed around it but avoid it within a distance of ∼4.5 Mpc. Miley et al. (2004) also found that LBGs are concentrated around a luminous radio galaxy at z ∼ 0.5. Interestingly, this is similar to the size of the H II region around z ∼ 6 QSO (Wyithe et al. 2005).

(A color version of this figure is available in the online journal.)
The difference between the low-$z$ and high-$z$ environments of AGNs perhaps stems from the different halo masses that host them. Due to the flux-limited nature of observational surveys, high-$z$ QSOs are much more luminous than local AGNs, and thus, presumably embedded in a more massive halo. Indeed, a generic expectation in most models of galaxy formation is that the most massive density peaks in the early universe (such as QSOs and massive galaxies) are likely to be strongly clustered (Kaiser 1984; Efstathiou & Rees 1988). In the hierarchical formation and evolution scenario of galaxies and QSOs (Haehnelt & Kauffmann 2000), luminous QSOs are located in rare overdense regions. This is why high-$z$ QSOs have been used as beacons to search for high-density regions (Coldwell & Lambas 2006). Croom et al. (2005) and Shen et al. (2007) found an increasing clustering of QSOs with redshift.

Surprisingly, at $z > 6$ the situation appears to change again; luminous QSOs are not necessarily found in strong density peaks. Kim et al. (2009) studied the number densities of $i$-dropout objects around five SDSS $z \sim 6$ QSOs using HST/ACS. They found an overdensity in two fields and underdensity in two fields. Zheng et al. (2006) and Stiavelli et al. (2005) found an overdensities around the QSOs SDSSJ0836+0054 ($z = 5.82$) and SDSS J1030+0524 ($z = 6.28$). However, these overdensities do not appear to be as magniﬁcent structures as were found at lower redshift, or even in some random regions at $z \sim 5$–6 (e.g., Ouchi et al. 2004b; Kashikawa et al. 2007; Ota et al. 2008).

One of the major problems of previous work at $z \sim 6$ is the relatively small FOV of the HST/ACS. The $200' \times 200'$ field can only probe a region of $1$ Mpc $\times 1$ Mpc at $z \sim 6$ and thus may easily miss any larger structures such as found in this work. Computer simulations also predict that the largest structures present at $z \sim 6$ span several tens of megaparsecs (Overzier et al. 2009), while luminosity functions of LBGs show a large field-to-field variation (Hu et al. 2004; Ouchi et al. 2009). These results suggest that previous non-detections of overdensities around QSOs may need to be re-examined using a larger FOV or deeper observations. The diﬀerence in the FOV is perhaps the primary reason why no previous work has detected a highly signiﬁcant overdensity around any of the $z \sim 6$ QSOs. Our positive detection may have been facilitated by the large FOV that allowed us to investigate the structure at scale of $\sim 3$ Mpc.

For an illustration of what such a region at $z \gtrsim 6$ might look like, we show an example of a large protocluster selected from the Millennium-II cosmological N-body simulation (Boylan-Kolchin et al. 2009). Figure 8 shows the (projected) spatial distribution of strongly clustered dark matter halos associated with a protocluster at $z = 6.2$. This protocluster is the progenitor of the most massive cluster found in the Millennium-II simulations and corresponds to an $M \sim 10^{15} M_\odot$ cluster when evolved to $z = 0$. Figure 8 shows, at least qualitatively, that we may expect significant enhancements in the density of the galaxies that are hosted by the dark matter halos shown, provided that QSOs indeed trace protoclusters. A more quantitative analysis of the surface density of $z$-dropout galaxies near QSOs expected in the simulations is needed for a proper comparison.

5.2. Size of the H II Region

Next, we compare our finding of an overdensity of LBGs around a QSO at a characteristic scale of 3 Mpc to spectroscopic measurements of H II regions around QSOs.

It has been demonstrated through spectroscopic observations that there exist large, ionized regions around luminous QSOs. These are sometimes called H II regions, Stromgren spheres, or highly ionized near zones. In this work, we will refer to them as H II regions. In order to deﬁne the size of the H II region, Fan et al. (2006b) proposed a deﬁnition as a point in the spectra where the Ly$\alpha$ transmission ﬁrst drops to $T < 0.1$ for spectra binned in 20 Å pixels. The CFHQS J2329−0301 transmission drops at $T < 0.1$ first at 3.6 Mpc and then again at 6.3 Mpc (Willott et al. 2007). Interestingly, the size of this spectroscopically measured H II region is comparable to the possible ring shape distribution of LBGs around CFHQS J2329−0301 (Figure 6). Note that the size of the spectroscopic H II region is expected to be larger ($\sim 10$ Mpc) for the SDSS QSOs due to their higher luminosities (they are brighter by $\sim 2$ mag). In addition to the small FOV of HST/ACS, this may be an additional reason why no significant overdensity of LBGs has been found around SDSS QSOs. To observe an overdensity of galaxies at a scale of $\sim 10$ Mpc (such as expected around the luminous SDSS QSOs at $z \sim 6$), one needs multiple FOVs even with the Suprime-Cam. We conclude that the size of the H II region is consistent with the apparent lack of LBG candidates closest to the QSO.

5.3. Possible Physical Mechanisms

If our detection of the lack of LBGs near the QSO is real, then what created the observed paucity of galaxies within 3 Mpc from the QSO? One possibility is that the intense emission of ionizing radiation associated with QSOs ionizes the surrounding IGM and may even photoevaporate the gas in neighboring dark halos before it has the opportunity to cool and form stars. In this scenario, QSOs would suppress galaxy formation in their vicinity. One would then observe a paucity of galaxies near a QSO despite the underlying excess of dark matter halos. Shapiro et al. (2004) presented the first theoretical simulations of the gas dynamics coupled with radiative transfer, showing that an ionizing source that emits $10^{56}$ photons s$^{-1}$ (appropriate...
for a QSO) can indeed photoevaporize minihalos of $\sim 10^7 M_\odot$ (that would have been able to form small galaxies) on 100–150 Myr timescales (but see Barkana & Loeb 1999; Wyithe et al. 2005). Compared with our observational results of finding a “ring”-shaped distribution of LBGs, the central QSO may have suppressed the formation of surrounding galaxies thereby creating a paucity of galaxies in its vicinity but still having an overdense region beyond the inner, ionized region. This may explain the observed results, at least qualitatively.

However, Kashikawa et al. (2007) quantitatively estimated that such UV radiation from QSO can suppress galaxy formation or not. According to their simulation, QSO UV radiation can suppress star formation in a halo with $M_{\text{vir}} < 10^9 M_\odot$, while a halo with $M_{\text{vir}} > 10^{10} M_\odot$ is unaffected. Although mass estimate of our $z \sim 6.4$ LBGs is uncertain because we do not have deep near-infrared data, considering bright magnitude, they are likely to be massive galaxies with $M_{\text{vir}} \sim 10^{11–12} M_\odot$. If so, QSO UV radiation is not strong enough to create the central deficit we observed.

Can we find other theoretical predictions that could explain the observations? The simulation of Kashikawa et al. (2007) assumed star formation in spherical dark matter halos. They found that the impact of photoionization is greater if that star formation is taking place in a disk or in substructures (which is perhaps likely to be the case). If the QSO formed at a much earlier time than the surrounding galaxies, this scenario might be able to suppress the formation of galaxy seeds at the time when their masses were still sufficiently small.

Another plausible scenario is that the IGM surrounding the QSO may have been ionized by galaxies long before the QSO turned on. It has been suggested that because luminous QSOs are expected to form in rare overdense regions, the surrounding IGM had already been pre-ionized by galaxies (Yu & Lu 2005). According to the simulation of Bolton & Haehnelt (2007), the neutral hydrogen fraction, $f_{\text{HI}}$, near a QSO is estimated to be $f_{\text{HI}} < 0.3$. Therefore, QSO radiation is emitted into a substantially pre-ionized IGM. In this case, galaxies that formed before the QSO started emitting its strong UV radiation may still be present in the vicinity of the QSO. Because such galaxies are likely to have ceased their star formation, they would not be detected by our LBG technique.

Another overdense region, the QSO host galaxy is likely to be the most massive galaxy that formed the earliest. According to Yu & Lu (2005), QSO host galaxies experiencing rapid star formation at a rate of $\sim 3000 M_\odot$ yr$^{-1}$ combined with the radiation field emitted by the QSO itself can produce enough photons to ionize a large $\text{H}_\text{II}$ region. In order to check whether we see any evidence for the presence of such a massive host galaxy, we have performed a careful PSF subtraction on our images. The residuals indicate the detection of a large host galaxy by spectral energy distribution fitting ($R_e = 11$ kpc, $\lesssim 10^{10} M_\odot$) associated with the QSO CFHQS J2329−0301 (Goto et al. 2009) with evidence of extensive star formation based on its extended rest-frame UV flux. The presence of a massive host galaxy may thus support a scenario in which the QSO and its host galaxy evolve together, suppressing galaxy formation in their vicinity.

Last, it has been suggested that a $z \sim 6$ QSO is likely to have experienced multiple mergers in order for its black hole to grow to a mass of $\sim 10^9 M_\odot$. An example of this scenario is given by the simulation of Li et al. (2007), which predicts that the host galaxy of a $z \sim 6$ QSO may have experienced seven mergers with mass ratios of 4:1 or greater (see their Figure 3). The QSO in our field may thus have merged with all the galaxies in its direct vicinity, explaining the peculiar spatial distribution that we find. This is also consistent with the discovery of the large host galaxy associated with the QSO (Goto et al. 2009).

In summary, although our detection of substructure in the LBG distribution near the QSO is rather weak ($\lesssim 2\sigma$), studies of the spatial distribution of LBGs around QSOs at $z \sim 6$ are very important for testing numerous of the interesting physical scenarios related to the co-evolution of QSOs and galaxies as discussed above. Therefore, it is important that our conclusions are verified using deeper, multi-wavelength imaging and spectroscopic observations that may detect additional galaxies missed by our current selection, such as galaxies that are below our (UV) detection limits, star-forming galaxies that are heavily obscured, or galaxies in which star formation has ceased. Also, it will be important to extend the analysis performed here to other fields to obtain good statistics on the typical structures associated with QSOs at this extreme redshift.

6. CONCLUSIONS

Taking advantage of the large FOV ($34' \times 27'$) and the new red-sensitive fully depleted CCDs recently installed on the Subaru/Suprime-Cam, we have investigated the large-scale environment around the most distant QSO studied to date.

Our findings are as follows. The number of candidate LBGs at $z \sim 6.4$ is 7 times larger than that in a comparison field (the SDF), suggesting that the QSO field hosts an overdense region. We estimate that the probability that this overdensity is a chance coincidence is less than 0.4% based on either using simple Poissonian statistics or on a comparison with a cosmological SPH simulation of $z \sim 7$ galaxies.

We find evidence for a non-uniform distribution of the LBGs in a “ring-like” shape surrounding the QSO at a radius of $\sim 3$ physical Mpc, i.e., galaxies are overdense around the QSO, but at the same time they avoid the very center near the QSO (see Figures 6 and 7). A K-S test shows that the radial distribution of LBGs in Figure 7 is different from random at a 98% significance level. The distance of 3 Mpc is comparable to the size of the $\text{H}_\text{II}$ region around QSOs at $z \sim 6$ (Wyithe et al. 2005). Possible physical explanations of such a central deficit of galaxies include the suppression of galaxy formation due to the strong UV radiation field of the QSO. However, because the significance of our detection of a non-uniform distribution of LBGs around the QSO is low, it is important to verify these results with deeper imaging data and/or spectroscopy.

Our findings show that QSOs at $z \sim 6$ may indeed be embedded in the densest regions of the early universe, provided that they are observed on significantly larger scales compared to previous studies that used the relatively small FOV provided by HST.

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