
Chapter 9

An overdensity of galaxies near the most distant radio-loud quasar

Abstract. A 5 arcmin² region around the luminous radio-loud quasar SDSS J0836+0054 ($z = 5.8$) hosts a wealth of associated galaxies, characterized by very red ($1.3 < i_{775} - z_{850} < 2.0$) color. The surface density of these $z \sim 5.8$ candidates is approximately 6 times higher than the number expected from deep ACS fields. This is one of the highest galaxy overdensities at high redshifts, which may develop into a group or cluster. We also find evidence for a substructure associated with one of the candidates. It has two very faint companion objects within $2''$, which are likely to merge. The finding supports the results of a recent simulation, which finds that luminous quasars at high redshifts lie on the most prominent dark-matter filaments and are surrounded by many fainter galaxies. The quasar activity from these regions may signal the buildup of a massive system.

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9.1 Introduction

The fluctuations in the cosmic microwave background temperature observed by the Wilkinson Microwave Anisotropy Probe (WMAP; Bennett et al. 2003) are believed to be the seeds for the first generation of baryonic objects, which eventually evolved into the stars, galaxies, and clusters seen in the current epoch. Several hundred galaxy candidates at $z \gtrsim 6$ have been found as i_{775} -dropout objects (Stanway et al. 2003; Yan & Windhorst 2004; Bouwens et al. 2003, 2005), characterized by a large color difference between the i_{775} - and z_{850} -band and faint magnitudes of approximately 26. The current best estimate of the average surface density of these galaxies is from the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004), approximately 0.25 arcmin^{-2} to a z_{850} -band magnitude of 26.5 (Dickinson et al. 2004; Bouwens et al. 2005). In addition, at least a dozen of quasars have also been discovered at redshift $z \gtrsim 5.7$ (Fan et al. 2004), and their high luminosities suggest the presence of massive black holes of mass $> 10^9 M_{\odot}$. The formation of such black holes at epochs less than one billion years after the big bang requires an extremely high accretion rate (Haiman & Loeb 2001).

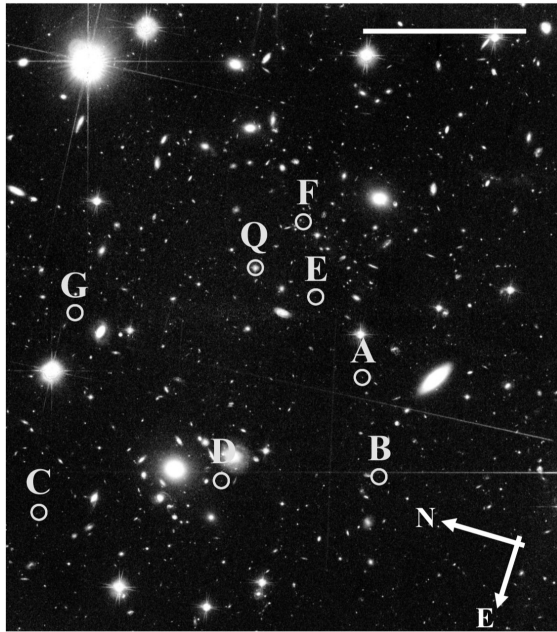
According to the hierarchical model of galaxy formation (Press & Schechter 1974), massive baryonic objects are formed in the densest halos. The latest simulations of CDM growth (Springel et al. 2005) predict that $z \sim 6$ quasars may lie in the center of very massive dark matter halos of $\sim 4 \times 10^{12} M_{\odot}$, which will grow into the most massive clusters of $\sim 4 \times 10^{15} M_{\odot}$ at $z = 0$. Studying the clustering properties of young galaxies and quasars may provide insights into their formation history. Reports of clustering of galaxies at redshift $z \sim 6$ (Ouchi et al. 2005; Wang et al. 2005; Malhotra et al. 2005) suggest that the formation of large structures in the early universe may be more significant than the cold dark matter (CDM) models have predicted. Recently Stiavelli et al. (2005) reported that one of the most distant quasars, SDSS J1030+0524 at $z = 6.28$, exhibits an excess of associated galaxies. It has also been found that some radio

galaxies harbor an enhanced number of associated galaxies. Venemans et al. (2002) and Miley et al. (2004) found a potential protocluster around TN J1338–1942, a radio galaxy at $z = 4.1$. Venemans et al. (2004) and Overzier et al. (2005) observed an excess of Ly α emitters (LAEs) and Lyman break galaxies (LBGs) in the field of TN J0924–2201, the most distant radio galaxy at $z = 5.2$. These reports confirm an empirical result that powerful, high-redshift radio galaxies are associated with massive forming galaxies (van Breugel et al. 1999). To explore the possibility that radio-loud quasars may also be a signpost of galaxy clustering at high redshifts, we initiated a project with the *Hubble Space Telescope* (HST) Advanced Camera for Surveys (ACS) to image the fields around some of the most distant radio-loud quasars.

The quasar SDSS J0836+0054 ($z = 5.82$; Fan et al. 2001) is the most distant radio-loud quasar known to date and is one of the most luminous. The object is detected in the Faint Images of the Radio Sky at 20 cm (FIRST) radio survey, with a total flux density at 1.4 GHz of 1.11 mJy. Very Large Array (VLA) and Max Planck Millimeter Bolometer Array (MPMBA)-IRAM observations (Petric et al. 2003) yield flux densities of 1.75 mJy at 1.4 GHz, 0.58 mJy at 5 GHz, and a non-detection at 250 GHz, with a 3σ upper limit of 2.9 mJy. It is a compact steep-spectrum radio source with a radio spectral index of -0.8 . VLBI observations at ~ 10 mas angular resolution (Frey et al. 2003) show an apparent core-jet morphology, with no indication of multiple images produced by gravitational lensing. The quasar's enormous power at $M \sim -27.8$ in the rest-frame UV band implies a mass of the central black hole of $5 \times 10^9 M_{\odot}$, posing a challenge to the theoretical models on how such massive objects are formed in the very early universe.

Throughout the paper, we use AB magnitudes and assume the common values of cosmological parameters, $\Omega_m = 0.3$, $\Omega_{\lambda} = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Figure 9.1 — Composite *HST* ACS image of the field of the quasar SDSS J0836+0054. The quasar (Q) and the i_{775} -dropout candidates (A–G) are marked with open circles. The scale bar measures $50''$ (~ 300 kpc of proper distance).



9.2 Data

The *HST* ACS observations of SDSS J0836+0054 were carried out on 2004 October 8 and November 17, with a total exposure of 10,778 s in the z_{850} -band and 4676 s in the i_{775} -band, at two different position angles. They were processed with the standard pipeline CALACS (Pavlovsky et al. 2005), then with APSIS (Blakeslee et al. 2003). These procedures carried out flat-fielding, removing bias, dark current, and cosmic ray events, correcting for geometrical distortion of the detectors, and drizzling the dithered images. The final images cover approximately 11.4 arcmin^2 . The APSIS tasks determine the Galactic extinction of $E(B-V)=0.05$ from the dust maps of Schlegel et al. (1998) and applied 0.1 and 0.07 to i_{775} - and z_{850} -band magnitudes, respectively.

We used SExtractor (Bertin & Arnouts 1996) to find and parameterize sources from the science images and their rms counterparts. We first

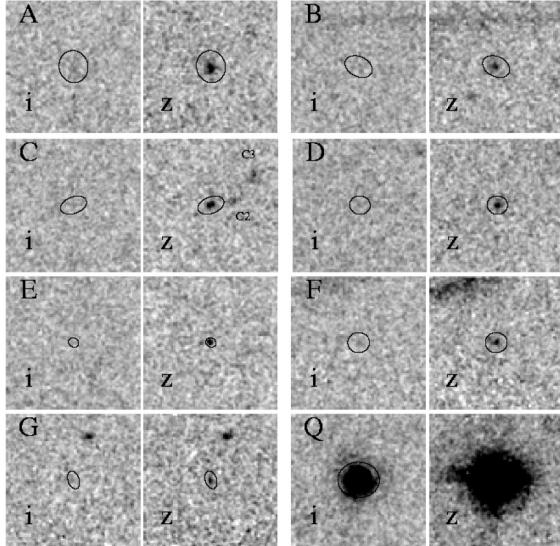
used the z_{850} -band as the detection image and then reran the task in a dual mode, namely to use the profile information in the z_{850} -band to link and constrain the parameter counterparts in the i_{775} -band image. The limiting magnitudes are similar to those of the GOODS fields, 26.5 mag in the z_{850} -band, for a 10σ detection of a source of $0''.2$ in diameter. As shown in Table 1, we selected objects with a color $i_{775} - z_{850} > 1.3$ (MAG_ISO). Only sources with a star-galaxy index of < 0.8 were considered (0 for galaxy and 1 for star). To further avoid contaminations from cosmic ray events, we only considered sources in the sky region that is covered by all six exposures in each band, which is approximately 10 arcmin^2 . The limiting z_{850} magnitudes are MAG_AUTO as they allow us to collect most of the source flux, but the colors are determined with MAG_ISO, in order to maximize the signal-to-noise ratio (S/N). Extensive tests by Benítez et al. (2004) suggest that the colors of faint galaxies are more robust with MAG_ISO. The color selection threshold of 1.3 is chosen to avoid the contamination from low-redshift interlopers. Seven sources are listed, and five of them are i_{775} -faint objects, enabling us to separate them from objects at $z > 6$. Ly α emission at $6 < z < 7$ is at wavelengths redward of the i_{775} -band, and the $i_{775} - z_{850}$ color is at least 2.5 mag. No detection in the i_{775} -band is therefore anticipated. There are nine objects with $1.0 < i_{775} - z_{850} < 1.3$, which may be LAEs at $z \sim 5.8$ or galaxies at $z \sim 1$.

At a redshift of 5.8, $1''$ corresponds to approximately 5.7 kpc, and the transverse dimension of the ACS field is approximately 1.1 Mpc. Along the line of sight, the proper distance between $z = 5.7$ and 5.9 is approximately 13 Mpc.

9.3 Results

We identified seven galaxy candidates with $z > 5.5$ in the field of this quasar. Table 1 lists the properties of the candidates, along with that of the quasar, and Fig. 1 displays their positions. Object D is near a foreground cluster approximately $1'$ south of the quasar. The cutout images of each candidate are shown in Fig. 2. We

Figure 9.2 — Cutout i_{775} - and z_{850} -band images of candidates. The image sizes are $2''$. The objects are named alphabetically (see Table 1) as marked at the top left corner of each panel of paired images. The images of the quasar, at the bottom right panel, are marked as “Q.” The band name is marked at the bottom left corner of each image. The contour at the center of each image marks the area where flux is collected for MAG_AUTO. The source color was calculated from MAG_ISO, which were derived from a compact core within the contour.

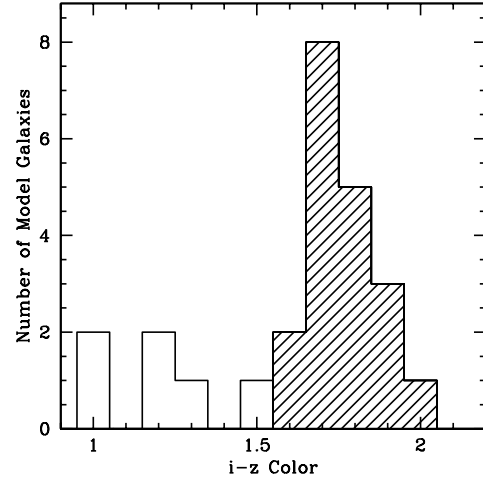


carried out a test on negative images (Dickinson et al. 2004) as spurious sources may be present even at $S/N > 5$. The i_{775} - and z_{850} -band images were multiplied by -1 , and SExtractor tasks were carried out using the same detection parameters. No candidate was detected with the same selection criteria.

The Bayesian photometric redshifts (BPZ; Benítez 2000) were calculated with a calibrated template set of Benítez et al. (2004) supplemented by a very blue starburst template. These templates significantly improve the photometric redshift estimation for faint, high- z galaxies. The new features in BPZ identify multiple peaks of redshifts and assigns a probability to each of them. The values of the first-peak redshifts are listed in column (8) of Table 1.

While it is common to refer to objects with large $i_{775} - z_{850}$ color as “ i_{775} dropouts”, we can

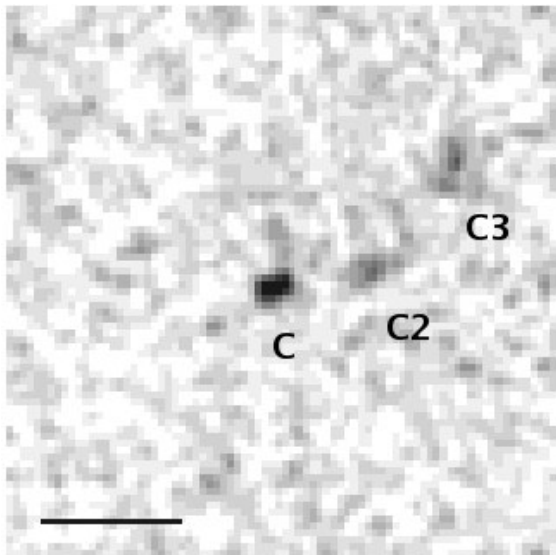
Figure 9.3 — Distribution of $i_{775} - z_{850}$ color for simulated galaxy spectra at redshift $z = 5.8$. The open region represents LAEs, and the hatched region LBGs. Our selection of $1.3 < i_{775} - z_{850} < 2.0$ is expected to include most LBGs but only about 1/3 of the LAEs.



obtain a better redshift discrimination by selecting objects with strong $i_{775} - z_{850}$ breaks, but that are still detected in the i_{775} -band. At $z \sim 5.8$, the redshifted $\text{Ly}\alpha$ feature straddles both the i_{775} - and z_{850} -band. Because of the high throughput of ACS, most candidates at this redshift are expected to be detected in the i_{775} -band. As the redshift increases from 5.8 to 6.0, $\text{Ly}\alpha$ emission rapidly moves out of the i_{775} -band, and therefore, the $i_{775} - z_{850}$ color increases rapidly from magnitude ~ 1.5 to $\gtrsim 2.0$. Having set a detection limit of $z_{850} < 26.5$, we are able to secure a 2σ detection of sources with $i_{775} - z_{850} < 2.0$. We tested the reality of i_{775} -band detections by deliberately shifting the i_{775} -band image by ± 20 pixels along its row and column and then reran SExtractor. The source apertures defined by the z_{850} -band images would point to a nearby sky field, and in all the cases, the aperture source fluxes in the i_{775} -band were below $S/N=1.4$. We therefore conclude that an i_{775} -band detection at $S/N > 2$ is unlikely to be the result of random fluctuations. The detection in both bands

significantly enhances the confidence level and also enables us to exclude background galaxies at $z > 6$ (i_{775} - or i -dropouts). Objects B and G in Table 1 are not detected in the i_{775} band. They are likely background galaxies at $z > 6$ and not physically associated with the quasar.

Figure 9.4 — Field around object C in the z_{850} band. Two additional red objects are marked. The angular scale of $1''$ (~ 5.7 kpc of proper distance) is marked.



9.4 Discussion

The GOODS results (Dickinson et al. 2004; Bouwens et al. 2005) suggest that the surface density of i_{775} -dropouts and i_{775} -faint objects is approximately 0.25 arcmin^{-2} , to a limiting magnitude of $z_{850} \sim 26.5$. These objects are believed to be at redshifts $5.5 < z < 6.5$. Since we only select i_{775} -faint objects, the photometric redshifts of these objects only cover the range of $5.5 < z < 6$. From previous studies (Dickinson et al. 2004; Stiavelli et al. 2005; Bouwens et al. 2005) we estimate that approximately 60% of these objects are i_{775} -faint and the rest are i_{775} -dropouts. The surface density of i_{775} -faint objects is only $\sim 0.15 \text{ arcmin}^{-2}$, or 1–2 in the ACS field of view. Since the chance of finding seven i_{775} -dropouts (including i_{775} -faint ob-

jects) in GOODS in a random ACS WFC-size cell ($\sim 11 \text{ arcmin}^2$) amounts to a few percent (Stiavelli et al. 2005), our finding of five i_{775} -faint objects (and two i_{775} -dropouts) in one ACS field suggests a significant source overdensity. Since all our candidates lie in a region of five arcmin^2 the actual factor of overdensity is approximately six with respect to GOODS, with no random cells drawn from GOODS containing seven objects (four being the highest using the sample of Bouwens et al. 2005). Although cosmic variance is expected to be nonnegligible even on scales as large as those probed by GOODS (Somerville et al. 2004), field to field variations cannot be determined empirically until larger surveys become available.

Our results provide new evidence for an excess of galaxies associated with quasars at $z \gtrsim 5.8$. Stiavelli et al. (2005) find seven candidates at $z \gtrsim 6$ in the field of a radio-quiet quasar at $z = 6.28$. Four out of these seven candidates are detected in the i_{775} -band, and are likely to be foreground galaxies at redshift $5.5 < z < 6$. The number of galaxies associated with the $z = 6.28$ quasar is at most three. We therefore believe that the five $z \sim 5.8$ candidates in the vicinity of quasar SDSS J0836+0054 represent a significant overdensity. Such an overdensity is consistent with the prediction of the Millennium Simulation (Springel et al. 2005) that a “first quasar” candidate at $z = 6.2$ lies on one of the most prominent dark matter filaments and is surrounded by a large number of other, much fainter galaxies. The quasar itself exhibits an $i_{775} - z_{850}$ color of 1.2, which is considerably smaller than that in the SDSS (2.2). This is because the i_{775} -band sensitivity of ACS detectors extends further to the red than that of the SDSS. The bulk of redshifted $\text{Ly}\alpha$ emission falls into that extended wavelength region beyond 8000 \AA and boosts the i_{775} -band flux. We carried out color simulations of galaxies at $z \sim 5.8$, using the spectral evolution library of Bruzual & Charlot (2003). Among the 39 representative model templates, we chose 21 at age of 1.4 Gyr and younger, which included starburst models. We also added $\text{Ly}\alpha$ emission lines to the models

Table 9.1 — Objects with Large $i_{775} - z_{850}$ Color.

Object	R.A. (J2000)	Decl. (J2000)	z_{850}	S/N (i_{775}) ^a	$i_{775} - z_{850}$	FWHM ($''$)	z_B^b
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
A	08 36 45.248	00 54 10.99	25.54 ± 0.10	3.2	1.91 ± 0.36	0.46	$5.8^{+1.4}_{-0.2}$
B ^c	08 36 47.053	00 53 55.90	26.00 ± 0.17	1.5	2.40 ± 0.97	0.39	$5.9^{+1.0}_{-1.0}$
C	08 36 50.099	00 55 31.16	26.24 ± 0.15	2.4	1.92 ± 0.60	0.29	$5.9^{+1.1}_{-0.5}$
C2	08 36 50.058	00 55 30.54	27.26 ± 0.39	1.5	2.42 ± 1.23	0.29	$5.9^{+1.1}_{-1.5}$
C3	08 36 50.010	00 55 30.27	26.82 ± 0.18	0.7	3.41 ± 3.43^d	0.20	$7.0^{+0.0}_{-0.7}$
D	08 36 48.211	00 54 41.19	26.42 ± 0.14	2.2	1.84 ± 0.49	0.29	$5.8^{+1.2}_{-0.7}$
E	08 36 44.029	00 54 32.79	26.39 ± 0.16	2.3	1.61 ± 0.42	0.19	$5.2^{+1.7}_{-0.7}$
F	08 36 42.666	00 54 44.00	26.03 ± 0.17	2.6	1.64 ± 0.42	0.46	$5.7^{+1.2}_{-0.7}$
G ^c	08 36 45.962	00 55 40.53	26.36 ± 0.25	1.7	1.91 ± 0.63	0.43	$5.8^{+1.2}_{-0.8}$
Quasar	08 36 43.871	00 54 53.15	18.85 ± 0.02	22	1.19 ± 0.03	0.11	$5.7^{+0.1}_{-0.1}$

^a Calculated using FLUX_ISO and MAG_ISO.

^b Bayesian photometric redshift, at a 67% confidence level. First-peak redshifts are estimated with a preset upper limit of $z = 7.0$.

^c i_{775} -dropout. Not considered as being associated with the quasar.

^d Calculated using MAG_AUTO, as MAG_ISO yields no detection.

with ages of 25 Myr. The $\text{Ly}\alpha$ emission is assumed to have a line width $\text{FWHM} = 1000 \text{ km s}^{-1}$ and varying equivalent widths 100 or 200 Å in the rest frame. All the model spectra are redshifted and corrected for intergalactic absorption. As shown in Fig. 3, the $i_{775} - z_{850}$ color peaks around 1.7 for LBGs and falls in the range $1.0 < i_{775} - z_{850} < 1.6$ for LAEs. Approximately 90% of the LBGs are selected by our criteria but only a fraction of LAEs.

The field around source “C” is interesting. The source seems to be a multiple system, as shown in Fig. 4. In its vicinity there are two red objects that are slightly fainter and are marked as “C2” and “C3”. The two companion objects of source C are not among our initial sample, as they do not meet our selection criteria. However, they are in the vicinity of source C and share similarly red colors suggesting that they may be physically associated. The angular separation between these three sources is only $\sim 1''.7$ or $\sim 10 \text{ kpc}$, suggestive of merging.

There is a slight chance that some of the candidates are reddened objects at lower red-

shifts. Red galaxies at $z \sim 1$ display a color of $0.9 \lesssim i_{775} - z_{850} \lesssim 1.1$ (Mei et al. 2006). Uncertainties in the $i_{775} - z_{850}$ color in our sample may introduce contaminations from red galaxies at $z \sim 1$. While it is possible that large uncertainties in magnitudes may lead to contamination from these galaxies, such an effect should also apply to the ACS images of the GOODS fields, because they used the same instrument and had comparable exposure times. As the GOODS fields exhibit a considerably lower surface density of i_{775} -faint objects than our field, the contamination level is low at $\sim 8\%$ (Bouwens et al. 2003). The so-called extremely red objects (ERO) can display sharply rising fluxes toward longer wavelengths in several adjacent bands. The lack of deep infrared images does not allow us to exclude such objects, but since the sizes and morphologies of our candidates do not fit either type, having neither pointlike nor rather diffuse profiles, we conclude that they are unlikely to be EROs. Malhotra et al. (2005) suggest that $\sim 90\%$ of sources with $i_{775} - z_{850} > 1.3$ and $z_{850} < 27$ are spectroscopically confirmed at red-

shift $z > 5.5$. The actual contamination rate is even lower when starlike objects are excluded.

Our finding complements a number of recent reports of overdensities of associated galaxies in the vicinities of radio galaxies at $z > 4$ (although not exclusively) and suggests a possibility of enhanced activities of clustering in the fields of radio sources at high redshifts. The galaxy candidates are more than a 100 times fainter than the quasar itself, and they form a good example of a hierarchical evolution. The detection of radio emission signals an environment that is rich in dark matter, thus harboring the formation of massive black holes.

9.5 Summary

The region around the radio-loud quasar SDSS J0836+0054 is rich in i_{775} -faint objects, which are candidates for galaxies at $z \sim 5.8$. The surface density of these objects is approximately 4–6 times higher than that of the GOODS fields, yielding one of the highest overdensities at $z \sim 6$ known to date. Our finding supports a hierarchical structure, as predicted by a recent simulation, in which luminous quasars are surrounded by fainter galaxies. Spectroscopic observations are needed to further confirm the association and enable us to estimate the volume density occupied by these sources. Future observations of this field in infrared bands will also provide information about the spectral energy distribution of these distant sources.

The observations add fresh evidence that quasars and radio galaxies are good beacons for finding protoclusters of young galaxies at high redshifts. Our measurements could provide the first constraint on the halo occupation number for LBGs in one of the most massive halos at high redshift, which will provide interesting a comparison to numerical simulations.

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