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THE SEARCH FOR GALAXY CLUSTERING AROUND A QUASAR PAIR AT $z = 4.25$ FOUND IN THE SLOAN DIGITAL SKY SURVEY[1]

Masataka Fukugita,[2] Osamu Nakamura,[2] Donald P. Schneider,[3]
Mamoru Doi,[4] and Nobunari Kashikawa[5]

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ABSTRACT

We present an investigation of the environment (≈600 kpc radius) of a pair of luminous $z = 4.25$ quasars, SDSS J1439−0034A and B, separated by 33″. An analysis of high-quality Subaru spectra of the quasars suggests that this configuration is indeed a physical pair and not a gravitational lens; the redshifts are slightly different (although marginally consistent with being the same), and the two spectra have strikingly different features. We search for bright galaxies ($L \gtrsim 0.4L^*$) having similar redshifts using the V dropout technique and semi-narrowband imaging looking for strong Lyα emission. We find no enhancement in the galaxy density around the quasar pair; its environment differs very little from a general field, with the upper limit of the density enhancement being about 3.5 at a 90% confidence. We infer that bright quasars happened to appear in two normal galaxies in a general field.

Subject headings: large-scale structure of universe — quasars: individual (SDSS J1439−0034)

1. INTRODUCTION

Luminous quasars are rare phenomena in the universe. When the density of luminous quasars reaches a maximum at $z \approx 2$, its comoving density is about 10^{-7} times the density of galaxies (e.g., Schmidt, Schneider, & Gunn 1995). High-redshift quasars are often used as signposts to search for accompanying galaxies, as one expects a rich environment around quasars (e.g., Hall & Green 1998; Djorgovski 1998, 1999 and references therein). Pairs of quasars may be taken as particularly promising markers of high-density regions, since the probability that two quasars exist in a small volume is very small, unless they are embedded in a special environment such as rich clusters or protoclusters of galaxies. Therefore, the search for physical pairs of quasars, especially at high redshifts, is particularly interesting from the point of view that they may permit exploration of an unusually rich environment in the early universe. Taking advantage of wide-field multicolor CCD imaging of the Sloan Digital Sky Survey (SDSS; York et al. 2000), Schneider et al. (2000) discovered a pair of luminous quasars at $z = 4.25$ separated by 33″ in their follow-up spectroscopy. In this Letter the two quasars are designated as SDSS J1439−0034A and B, with A being the brighter component. Spectroscopic features indicated that this pair is most likely to be a physical association, not a gravitational lens, although the spectra were of limited signal-to-noise ratio (S/N). The projected distance is 0.16 h^{-1} Mpc with a nonzero lambda ($\Omega_0 = 0.3$, $\lambda = 0.7$) cosmology. This system's separation is among the smallest known at high redshifts. No comparable high-redshift quasar pairs have been found among the 16,713 quasars in the 1360 deg^2 given in the SDSS First Data Release (Schneider et al. 2003).

The widely accepted model of galaxy formation based on the cold dark matter (CDM) dominance suggests that luminous quasars may be embedded in a rich environment (Martini & Weinberg 2001; Haiman & Hui 2001). In CDM models, quasars are usually ascribed to a phenomenon associated with very rare high peaks of Gaussian fluctuations (Efstathiou & Rees 1988). Such fluctuations preferentially reside in the region where one expects rich clusters as the universe evolves. This is particularly true if the lifetime of individual quasars is long and only very rare peaks are associated with luminous quasars.

To collect empirical information about the environment of two luminous quasars at $z \sim 4.25$, we investigate the distribution of galaxies around the SDSS quasar pair to determine whether this system is embedded in a rich protocluster of galaxies. We have carried out deep V, R, and I imaging and narrowband imaging with the $N642$ filter, which was available at the observatory, for the 6′ field around the SDSS quasar pair using the Subaru Telescope at Mauna Kea. Our prime purpose is to study the spatial distribution of galaxies that show Lyman break features (Steidel, Pettini, & Hamilton 1995) in the V passband (Madau et al. 1996), which indicate $z \approx 4$, and those that show Lyα emission around the same redshift. Additional high-quality spectroscopic observation was made to study whether the two quasars are lensed images or two distinct objects with the same redshift.

2. REDSHIFTS OF THE PAIR OF QUASARS

Schneider et al. (2000) concluded from the large separation and the apparent differences in the spectra that SDSS J1439−0034A and B is a pair of quasars and not a gravitational lens. Given the limited S/N of the spectra, however, this conclusion can only be regarded as tentative.

To improve on the spectra obtained by Schneider et al., spectroscopic observations of the quasar pair were made on 2001 June 20 using the Faint Object Classification and Analysis System (FOCAS) at the Subaru Telescope (Kashikawa et al. 2002). The instrument configuration was a 0″.4 long slit, a 300 line mm^{-1} grism blazed at 5500 Å (B300 grism), and an SY 47 blocking filter. The 3600 s exposure was made with the slit rotated to include the two quasars. FOCAS CCD detectors produce an image scale of 0″.104 pixel^{-1} and a dispersion of 1.40 Å pixel^{-1}. The pixels are binned 3 × 2 (spatial × spec-

[1] Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

[2] Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan; fukugita@icrr.u-tokyo.ac.jp, nakamura@sdss1.icrr.u-tokyo.ac.jp.

[3] Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802; dps@astro.psu.edu.

[4] Institute for Astronomy, University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan.

[5] National Astronomical Observatory, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan.

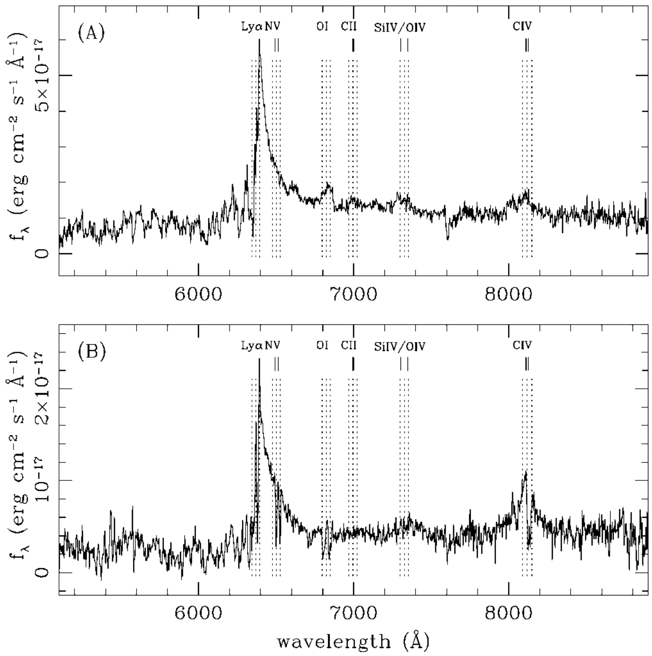

FIG. 1.—Subaru spectra of a pair of quasars SDSS J1439−0034A and B. The spectral resolution is approximately 1000. The positions of typical emission lines are drawn for assumed redshifts of $z = 4.22$, 4.24, and 4.26. Short slabs at the top of dotted lines indicate the position of doublets N V, C II, Si V, and C IV for $z = 4.24$.

tral) during readout. The spectrum covered 4700–9400 Å at a resolution of approximately $\lambda/\Delta\lambda \simeq 1000$. Observing conditions were reasonable, although some cirrus was recognized; the seeing was 0.″95 FWHM. The spectrophotometric calibration was made with BD +28°4211. Absolute spectrophotometry was obtained by adjusting the scale to the broadband *R* magnitude for each quasar.

The Subaru spectra of SDSS J1439−0034A and B are displayed in Figure 1. Both spectra show the standard features of high-redshift quasars: a significant Lyα forest, a strong, highly absorbed Lyα emission line, prominent C IV emission line, and other weaker features. The redshifts of the quasars, as measured from a weighted value of the emission lines other than Lyα, are 4.228 ± 0.005 (A) and 4.243 ± 0.009 (B). The redshifts are marginally consistent with a single value. The velocity difference is 860 km s^{-1}, with an uncertainty of comparable size.

The spectra show a number of striking differences, in particular in the strength of the C IV line (the equivalent width in B is nearly twice that in A) and the presence of a strong N V/O I/Si II/C IV associated absorption system in the spectrum of B. The redshift of the absorption system, 4.249 ± 0.002, is slightly larger (340 km s^{-1}) than the emission-line redshift of B; this is consistent with the appearance of the C IV line profile. We conclude that all of the available data support the interpretation of SDSS J1439−0034A and B as a physical pair separated by several hundred kiloparsecs.

3. IMAGING OBSERVATION AND DATA REDUCTION

The imaging observation was made on 2001 June 19 and 20 also using FOCAS at the Subaru Telescope. The circular field of view has a radius of 3.′0, and the image scale is 0.″104 pixel^{-1} on two 2k × 4k CCD. A small fraction of the field is obscured by the autoguider. The conditions were photometric when the *VRI* photometry was acquired on the first night, but light cirrus was present on the second night when the narrowband imaging was obtained. The image quality was approximately 0.″7 FWHM for both nights. The total exposure times were 6000, 3600, and 2340 s for *V* (5500), *R* (6600), and *I* (8050) and 3600 s for N642, whose passband extends from 6364 to 6492 Å. Data were processed using an IRAF photometry package, and objects were identified with SExtractor version 2.2.1. The objects are cataloged if they meet a 2 σ threshold after Gaussian smoothing with the width of $\sigma = 3$ pixels in the *R*-band frame. This detection threshold corresponds to $R_{AB} \approx 26$ or roughly $I_{AB} \approx 25.5$. (All magnitudes reported in this Letter are on the AB magnitude scale, and throughout the rest of this Letter we drop the AB subscript.) The characteristic magnitude of $z \approx 4$ Lyman break galaxies is $I^* \simeq 25$ derived by Steidel et al. (1999). Our observations are sufficiently deep to detect significant numbers of bright galaxies at $z \approx 4$, as our simulation (described later) indicates. The photometric zero points determined from standard stars agree with those of SDSS photometry to within 0.1 mag. The FOCAS field that contains quasars will be referred to as field Q. The basic properties of the quasars are listed in Table 1. Extra *VRI* imaging observations were made with slightly shorter exposure times for a "blank" field centered at $\alpha_{2000} = 23^h24^m36^s$ and $\delta_{2000} = 0°04'30''$; this is designated as field B. Note that the FOCAS field is sufficiently wide that the majority of field Q can also be used as a background field.

4. DISTRIBUTION OF HIGH-REDSHIFT GALAXIES AROUND THE QUASAR PAIR

The catalog contains 1181 objects fainter than $I = 23.0$ in field Q (effective area after excising the masked area for bright stars and a satellite track is 21.6 arcmin^2) and 954 objects in field B (21.6 arcmin^2). We apply the *V* dropout technique to select candidates of $z \sim 4$ galaxies. We use the population synthesis model of Kodama & Arimoto (1997) to calculate the evolution tracks in color space, but we have checked that the tracks of GISSEL95 (see Bruzual & Charlot 1993) differ little for the redshift of interest here. The effects of Lyα absorbers are incorporated according to Madau (1995; see also Steidel et al. 1999). A variety of star formation histories, from single burst ($\tau = 0.1$ Gyr) to continuous star formation, is adopted to calculate the location for $z \approx 4$ galaxies with internal reddening varying from $E(B-V) = 0$ to 0.3, and the region in $V-R$ versus $R-I$ space is optimized using a Monte Carlo simulation that we describe in what follows. The formation redshift is assumed to be $z = 10$, but tracks with lower formation redshift pass through

TABLE 1
PAIR QUASARS SDSS J1439−0034

Quasar	R.A. (J2000.0)	Decl. (J2000.0)	V_{AB}	R_{AB}	I_{AB}	$N642_{AB}$	Redshift
A	14 39 52.58	−00 33 59.2	21.65	20.47	...[a]	19.88	4.228 ± 0.005
B	14 39 51.60	−00 34 29.2	22.76	21.77	21.61	20.95	4.243 ± 0.009

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] The *I*-band signal of quasar A is saturated in our image.

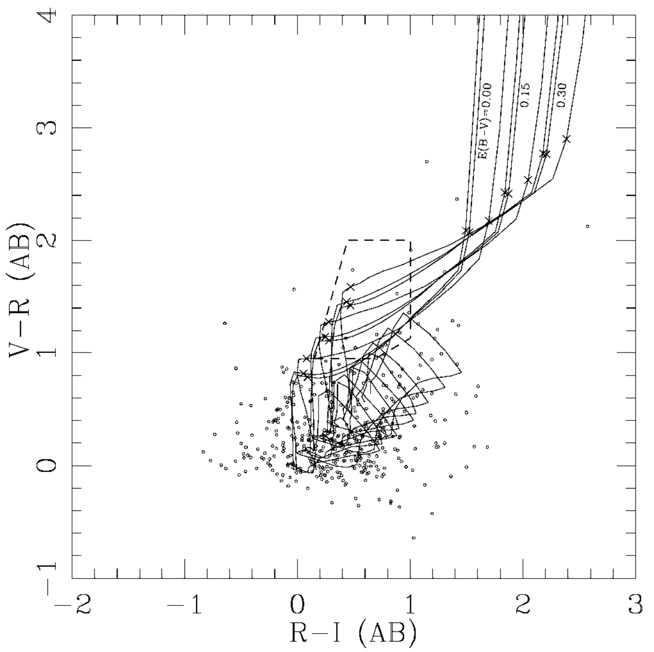

FIG. 2.—Galaxies in the $(V-R)_{AB}$ vs. $(R-I)_{AB}$ plane (the galaxies are taken from a subsample of field Q). The evolution tracks shown correspond to the range of models with a short burst at a high redshift to those with continuous star formation, including extinction $E(B-V) = 0$–0.3. The crosses on the tracks show the position at $z = 4$ and 5. The area delineated by the dashed line is condition (1) to select $z \approx 4.24$ galaxies.

the same region in color space. The condition that we adopt to select galaxies centered at $z \approx 4.24$ is

$$0.95 < V-R < 2.0,$$
$$0.59(R-I) + 0.54 < V-R < 3.6(R-I) + 0.4,$$
$$23.5 < I,\ R-I < 1.0. \qquad (1)$$

This color-color region (delineated with the dashed line) and typical evolution tracks are shown in Figure 2, together with the galaxies that we detected on one of the 2k × 4k CCD exposed for field Q (we omitted data points with large photometric errors, $\delta I > 0.07$ mag: largely scattered data points in the $R-I < 0$ region are ascribed mostly to poor I photometry).

With condition (1) we obtain 26 galaxies in field Q and 18 in field B. Those galaxies that satisfy condition (1) in field Q are plotted by large circles, together with all others with $23.5 < I$ that are denoted by dots in Figure 3.

A Monte Carlo simulation is carried out using the color, magnitude, and redshift distribution of galaxies in the Hubble Deep Field–North (HDF-N; Fernández-Soto, Lanzetta, & Yahil 1999) to find the selection criterion and to estimate the contamination and completeness of the sample, as was done in Ouchi et al. (2001). Figure 4 presents an example of Monte Carlo simulation, showing the redshift distribution of the galaxies selected with condition (1). Taking our window to be in the range $4.0 < z < 4.6$, the contamination from low-redshift objects and those just below or above the window is 60% for $I = 24$–25.5. Almost all objects with $I < 23.5$ are of low redshifts. The completeness is about 75% for $I = 23.5$–25 but drops to 60% for $I \approx 25$.

It is already clear in Figure 3 that there is no recognizable clustering of galaxies around the quasar pair. To make this statement more precise, we show in Figure 5 number counts

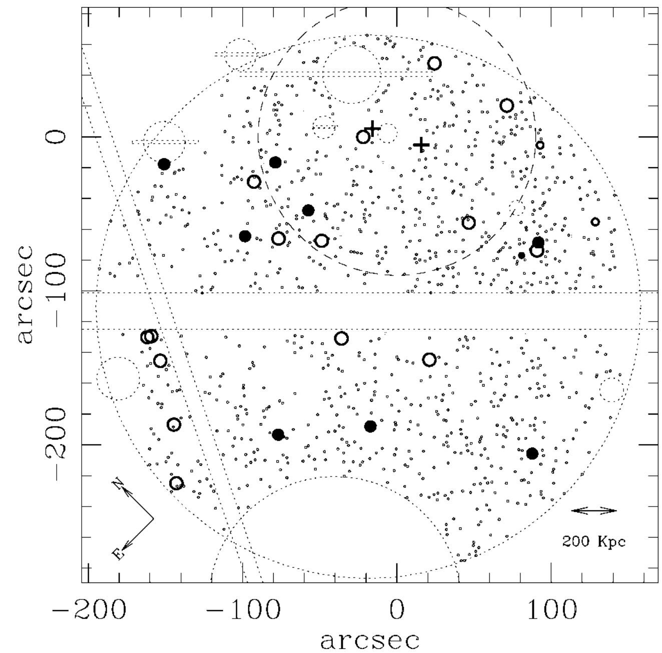

FIG. 3.—Distribution of galaxies detected with the 2 σ threshold in field Q. Large circles show the galaxies that satisfy condition (1) yet are brighter than $I_{AB} = 26$ (those fainter than $I_{AB} = 26$ are shown with smaller circles). Among them N642-passband bright galaxies are shown with filled circles. The two plus signs denote the pair of quasars SDSS J1439−0034A and B (A is at the left). Dotted boundaries show the masked region and a gap between the two CCDs. The dashed circle is 90″ (0.61 Mpc for $h = 0.7$) from the center of the quasar pair, which is also taken to be the origin of the coordinates.

of galaxies in the I band for those in a circular region (indicated in Fig. 4) of the radius 90″ (physical distance: 0.61 Mpc for $h = 0.7$) from the center of the quasar pair and those in other parts of field Q plus field B. The choice of a 90″ radius was made to maximize the number of galaxies encircled to derive a conservative limit on the surface density of galaxies around the quasars. The area for the quasar field is 5.8 arcmin^2 and that of the background totals 37.3 arcmin^2. We applied the

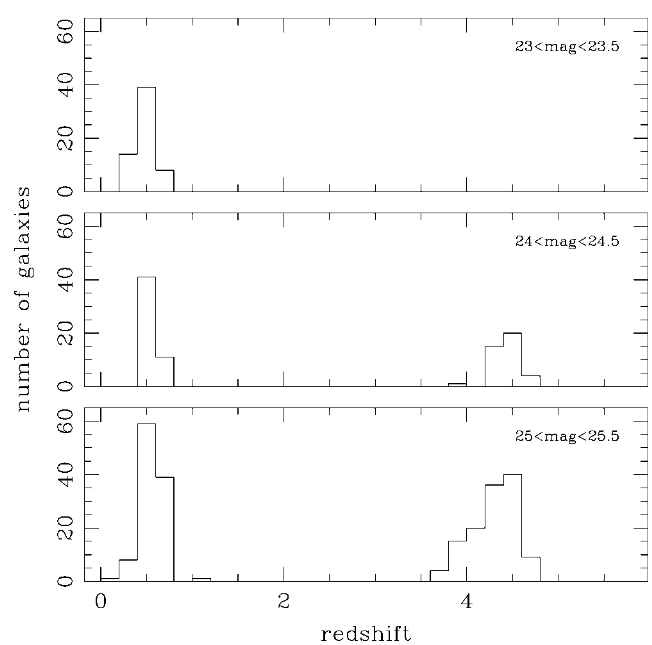

FIG. 4.—Redshift distribution of galaxies that satisfy condition (1) expected from a Monte Carlo simulation using the empirical galaxy data from HDF-N (Fernández-Soto et al. 1999).

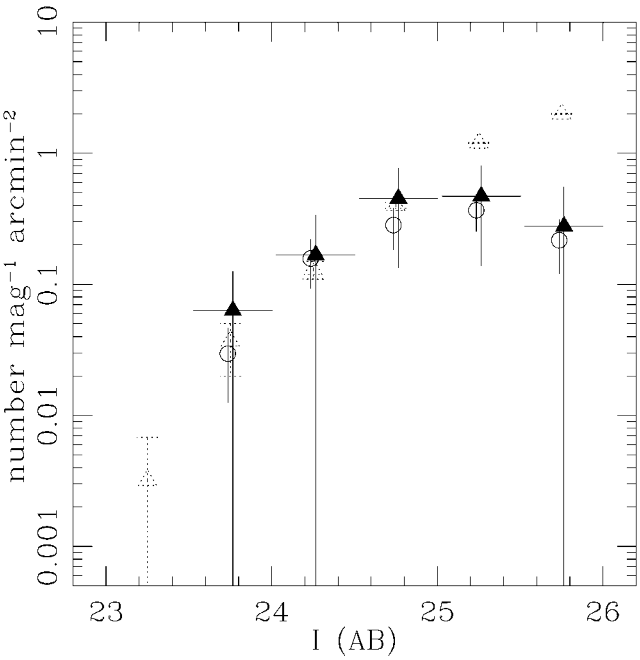

FIG. 5.—Number counts of galaxies in the I_{AB} band expected for $4.0 < z < 4.6$ after the corrections for completeness and contamination as described in the text. Those in the QSO field (90″ from the center of the quasar pair) are represented by filled triangles, and those in the background field (field Q excluding the QSO field and field B combined) are indicated by open circles. The dotted triangles show number counts of Ouchi et al. (2001).

corrections for incompleteness and contamination. The dotted triangles are number counts for $z \approx 4$ galaxies obtained by Ouchi et al. (which agree with those of Steidel et al. 1999). The number counts in both regions agree for all magnitudes brighter than $I = 26$ and with Ouchi et al. counts for $I < 25$. The disagreement beyond $I > 25$ indicates incompleteness of our catalog, but this completeness is not important for our purpose. This figure confirms no enhancement of galaxies with the luminosity $L > 0.4L^*$ in the vicinity of the quasar pair. From the field values and our Monte Carlo simulation we expect 2.1 $z \approx 4.25$ objects (3.0 if corrected for incompleteness) and 3.4 contaminants in the QSO field. Taking the completeness as the success probability of Bernoulli trials, we derive from the observed number of galaxies the density enhancement around the quasars to be $\rho_{\rm qso}/\bar{\rho} < 3.5$ (10.5 $z \approx 4.25$ objects) at the 90% confidence level in the QSO field. This calculation includes two quasars as $z \approx 4.25$ galaxies.

Our final discussion concerns N642 semi-narrowband imaging. The passband of the filter covers Lyα emission for $4.23 < z < 4.33$, but the bandwidth is not narrow enough for a sensitive search for Ly emission. So, we adopt a criterion $N - I < 1.0$ to select "N bright" galaxies. Among the high-z galaxy candidates that meet condition (1), those that satisfy this criterion are shown by filled circles in Figure 3. The distribution of these N bright galaxies is scattered; no clustering is seen around quasars. Incidentally, we have confirmed by removing the $I > 23$ mag condition that there are no quasars in field Q that fall in this redshift range other than the two that are already known.

5. CONCLUSIONS

We have shown that the field in the vicinity of the quasar pair SDSS J1439−0034 at $z = 4.24$ hardly differs from the general field regarding the surface density of bright galaxies at around $z \approx 4$. A density enhancement, if present, is no more than 3.5 times the field density at a 90% confidence.

Although this is but one example (although the pair of quasars makes it a particularly attractive one), our null results suggest that luminous quasars are not always signposts for high-density regions. This is perhaps an example of a case in which two normal galaxies happened by chance to simultaneously display the quasar phenomenon. The scarcity of luminous high-redshift quasars is not solely (or even primarily) due to the requirement that they reside in the rare high-density perturbations; a relatively short lifetime of the quasar phenomenon at high redshift could play an important role.

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