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DISCOVERY OF A PAIR OF $z = 4.25$ QUASARS FROM THE SLOAN DIGITAL SKY SURVEY[1,2]

Donald P. Schneider,[3] Xiaohui Fan,[4] Michael A. Strauss,[4] James E. Gunn,[4] Gordon T. Richards,[3,5] G. R. Knapp,[4] Robert H. Lupton,[4] David H. Saxe,[6] John E. Anderson, Jr.,[7] Neta A. Bahcall,[4] J. Brinkmann,[8] Robert Brunner,[9] István Csabai,[10,11] Masataka Fukugita,[12,6] G. S. Hennessy,[13] Robert B. Hindsley,[14] Željko Ivezić,[4] R. C. Nichol,[15] Jeffrey R. Pier,[16] and Donald G. York[5]
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ABSTRACT

We report the discovery of a pair of $z = 4.25$ quasars with a separation of 33″. The brighter of the two objects was identified as a high-redshift quasar candidate from Sloan Digital Sky Survey multicolor imaging data, and the redshift was measured from a spectrum obtained with the Hobby-Eberly Telescope. The slit orientation of this observation *by chance* included another quasar, approximately 1 mag fainter and having the same redshift as the target. This is the third serendipitous discovery of a $z > 4$ quasar. The differences in the relative strengths and profiles of the emission lines suggest that this is a quasar pair and not a gravitational lens. The two objects are likely to be physically associated; the projected physical separation is approximately 210 h_{50}^{-1} kpc and the redshifts are identical to ≈ 0.01, implying a radial physical separation of 950 h_{50}^{-1} kpc or less. The existence of this pair is strong circumstantial evidence that $z \sim 4$ quasars are clustered.

Key words: early universe — quasars: individual

1. INTRODUCTION

One of the first observations of the $z > 4$ universe was also one of the most startling: the serendipitous discovery of the $z = 4.4$ quasar Q2203+29 by McCarthy et al. (1988). While obtaining a spectrum of the $z = 0.707$ radio galaxy 3C 441, the spectrograph slit was aligned along the radio jet. The data included the spectrum of a faint red source 51″ from the nucleus; the secondary source's redshift of 4.41 made it the second most distant known object at the time! The authors showed that this was a very low probability event unless the number density of high-redshift quasars had been underestimated by orders of magnitude (a slight possibility at the time, given that only a few $z > 4$ quasars were known and thus the number density was poorly constrained).

Several years later, PC 0027+0521, a faint $z = 4.21$ quasar, was found by chance in a high-redshift quasar survey (Schneider, Schmidt, & Gunn 1994). The object happened to lie in the slit (i.e., the slit was placed at the parallactic angle, not rotated to acquire additional objects) while the spectrum of a high-redshift quasar candidate (which turned out to be a star!) was obtained.

Post facto calculations showed that the chance of either event occurring was on the order of 0.1%. In this paper, we describe the third serendipitous discovery of a $z > 4$ quasar; it was discovered, as PC 0027+0521 was, when by chance it was included in a spectroscopic observation of a high-redshift quasar candidate. In this case, however, the candidate was indeed a quasar, and it has the same redshift as the serendipitous source.

2. OBSERVATIONS

2.1. *Sloan Digital Sky Survey*

The Sloan Digital Sky Survey (SDSS; York et al. 2000) uses a CCD camera (Gunn et al. 1998) on a dedicated 2.5 m telescope (Siegmund et al. 2000) at Apache Point Observatory, New Mexico, to obtain images in five broad optical bands over 10,000 deg^2 of the high Galactic latitude sky centered approximately on the north Galactic pole. The five filters (designated u', g', r', i', and z') cover the entire wavelength range of the CCD response (Fukugita et al. 1996). Photometric calibration is provided by simultaneous observations with a 20 inch (0.5 m) telescope at the same site. The survey data-processing software measures the properties of each detected object in the imaging data and determines and applies astrometric and photometric calibrations (Pier et al. 2000; Lupton et al. 2000).

The high photometric accuracy of the SDSS images and the information provided by the z' filter (central wavelength 9130 Å) make the SDSS data an excellent source for identifi-

[1] Based on observations obtained with the Sloan Digital Sky Survey, which is owned and operated by the Astrophysical Research Consortium.
[2] Based on observations obtained with the Hobby-Eberly Telescope, which is a joint project of the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig-Maximillians-Universität München, and Georg-August-Universität Göttingen.
[3] Department of Astronomy and Astrophysics, 525 Davey Laboratory, Pennsylvania State University, University Park, PA 16802; dps@astro.psu.edu.
[4] Princeton University Observatory, Peyton Hall, Princeton, NJ 08544-1001; fan@astro.princeton.edu, strauss@astro.princeton.edu.
[5] Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637.
[6] Institute for Advanced Study, Olden Lane, Princeton, NJ 08540.
[7] Fermi National Accelerator Laboratory, P.O. Box 500, 500 Wilson Road, Batavia, IL 60510.
[8] Apache Point Observatory, P.O. Box 59, Sunspot, NM 88349-0059.
[9] Department of Astronomy, 105-24, California Institute of Technology, 1201 East California Boulevard, Pasadena, CA 91125.
[10] Department of Physics and Astronomy, Johns Hopkins University, 3701 University Drive, Baltimore, MD 21218.
[11] Department of Physics of Complex Systems, Eötvös University, Pázmáy Péter sétány 1/A, H-1117, Budapest, Hungary.
[12] Institute for Cosmic Ray Research, University of Tokyo, 3-2-1, Midori, Tanashi, Tokyo 188-8588, Japan.
[13] US Naval Observatory, 3450 Massachusetts Avenue, NW, Washington, DC 20392-5420.
[14] Remote Sensing Division, Code 7215, Naval Research Laboratory, 4555 Overlook Avenue, SW, Washington, DC 20375.
[15] Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15232.
[16] US Naval Observatory, Flagstaff Station, P.O. Box 1149, Flagstaff, AZ 86002.

cation of high-redshift quasar candidates. In the past two years the SDSS has identified many $z > 3.5$ quasars (Fan et al. 1999b, 2000a, 2000c; Schneider et al. 2000; Zheng et al. 2000), culminating in the discovery of a $z = 5.80$ quasar (Fan et al. 2000d).

We have started a survey of faint, high-redshift quasars using the SDSS imaging data. This survey uses a multicolor selection technique similar to that of Fan et al. (1999b, 2000a); the major modification is a change from $i^* = 20.0$ to $i^* = 21.0$ for the limiting magnitude. The $i^* \approx 20.6$ object SDSSp J143952.58−003359.2 was flagged as a probable $z \approx 4.3$ quasar, primarily based on its location in the $(g^* - r^*, r^* - i^*)$ diagram, from imaging data taken on 1999 March 22 (SDSS imaging run 756). For brevity, we will sometimes refer to this object as "A" in this paper.

The area containing the quasar had also been observed on 1999 March 20 (SDSS imaging run 745). The SDSS photometric measurements of the quasar on both nights are presented in Table 1, which shows that the photometry and errors are internally consistent.

In SDSS nomenclature, the names for sources have the format SDSSp Jhhmmss.ss+ddmmss.s, where the coordinate equinox is J2000.0, and the "p" refers to "preliminary." The reported magnitudes are based on a preliminary photometric calibration; to indicate this the filters have an asterisk instead of a prime as the superscript. The estimated astrometric accuracy for each coordinate is 0.″1 and the calibration of the photometric measurements is accurate to 0.05 mag. Note that the u^* measurements indicate essentially zero flux in this band.

2.2. *Spectroscopy of Quasar Candidates*

A spectrum of SDSSp J143952.58−003359.2 was obtained on 2000 June 2 with the Marcario Low-Resolution Spectrograph (LRS; Hill et al. 1998a, 1998b) of the Hobby-Eberly Telescope[17] (HET; Ramsey et al. 1998). The LRS is mounted in the Prime Focus Instrument Package, which rides on the HET tracker. The 900 s observation was acquired with the 2″-wide slit, rotated to the parallactic angle. The dispersive element was a 300 line mm^{-1} grism blazed at 5500 Å. An OG515 blocking filter was installed to permit calibration of the spectra out to 1 μm. The detector is a thinned, antireflection-coated 3072 × 1024 Ford Aerospace CCD and was binned 2 × 2 during readout; this produced an image scale of 0.″50 pixel^{-1} and a dispersion of ≈4.5 Å pixel^{-1}. The spectra covered the range from 5100 to 10,200 Å at a resolution of approximately 20 Å.

The wavelength calibration was provided by Ne, Cd, and Ar comparison lamps, and the relative flux and atmospheric band absorption calibration was provided by the observation of the spectrophotometric standard BD +26°2606 (Oke & Gunn 1983). The observing conditions were marginal; the seeing was 2″ with moderate cloud cover (the signal from the standard indicated more than 1 mag of extinction). Absolute spectrophotometric calibration was carried out by scaling each spectrum so that i^* magnitudes synthesized from the spectra matched the SDSS photometric measurements.

Figure 1 shows the SDSS i' image of the field of SDSSp J143952.58−003359.2, which is denoted by "A" in the figure; this object was placed in the center of the slit. The slit was oriented at position angle 26°; the spectra of the bright star and object B, both located southwest of A, were obtained as they fell into the slit. A single 900 s exposure was made.

Figure 2 displays the region centered at 6680 Å of the spectroscopic exposure. The spectra run vertically from 5790 Å, at the bottom of the figure, to 7575 Å, at the top. The data are dominated by the spectrum of the star slightly to the right of center. The spectrum of A is clearly visible in the center of the frame, and the spectrum possesses the characteristic signal of a high-redshift quasar (strong, broad emission line and a significant drop in the continuum as one moves from red to blue across the line). The initial visual inspection of the frame revealed that the spectrum of B, located midway between the star and the right of the frame in Figure 2, appeared to have a spectrum very similar to A.

The flux and wavelength-calibrated spectra of the two objects are presented in Figure 3 (the brighter object, A, is in the top panel). Although the signal-to-noise ratio is not large (6 per binned pixel at 7000 Å in A and a factor of 2 lower in B), there is little doubt that both objects are $z \approx 4.25$ quasars: the broad, strong, asymmetric Lyman α emission line and the continuum depression due to Lyman α forest absorption are the most obvious features. The Lyman α forest absorption appears to be significantly different in the two quasars; both the photometry and the spectroscopy indicate that the spectrum of A undergoes considerably less absorption than B. We are unable to search for any Lyman limit absorption because the OG515 filter does not transmit light below wavelengths of ≈980 Å in the rest frame of the quasars.

The redshifts, determined from the Si + O and C IV emission lines in A and the C IV line in B, are identical to within

[17] A summary of the commissioning of the LRS is given in Schneider et al. (2000).

TABLE 1

SDSS PHOTOMETRY

SDSS Run	u^*	g^*	r^*	i^*	z^*
SDSSp J143952.58−003359.2[a]:					
745......	23.17 ± 0.51	23.41 ± 0.24	20.98 ± 0.05	20.56 ± 0.06	20.20 ± 0.16
756......	24.20 ± 0.59	23.35 ± 0.20	20.95 ± 0.04	20.57 ± 0.05	20.27 ± 0.12
SDSSp J143951.60−003429.2[a]:					
745......	23.58 ± 0.61	23.11 ± 0.19	21.69 ± 0.09	21.67 ± 0.15	21.39 ± 0.42
756......	22.95 ± 0.38	23.48 ± 0.22	21.89 ± 0.10	21.46 ± 0.10	20.95 ± 0.21

NOTES.—Photometry is reported in terms of asinh magnitudes; see Lupton, Gunn, & Szalay (1999) for details. In this system, zero flux corresponds to 23.24, 24.91, 24.53, 23.89, and 22.47 in u^*, g^*, r^*, i^*, and z^*, respectively.

[a] Coordinate equinox is J2000.0.

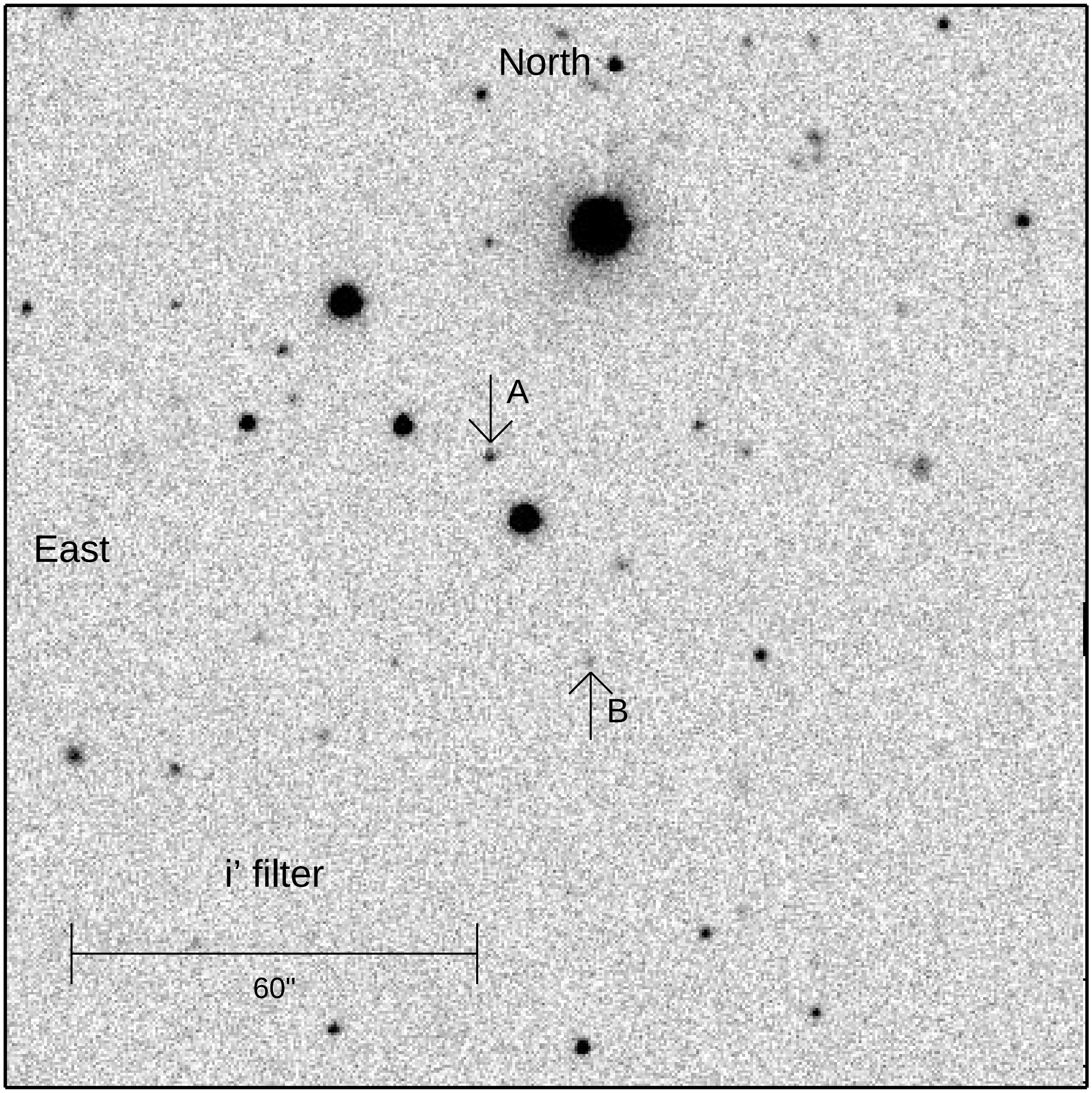

FIG. 1.—Finding chart for the field. North is up and east to the left, and the chart is 160″ on a side. This is the i' image taken with the SDSS camera. The brighter quasar (the target of the spectroscopic observation), SDSSp J143952.58−003359.2, is denoted by the letter A; B identifies the fainter quasar. The HET LRS observation had the slit oriented at the parallactic angle and included spectra of A, B, and the star between the quasars.

the measurement errors. The two objects, however, are almost certainly a pair of quasars and not a lens, given the relatively large separation and markedly different profiles of the Lyman α emission line and the contrast in the strengths of the S i + O feature.

3. DISCUSSION

Object B was identified with SDSSp J143951.60−003429.2 in the SDSS database; its photometric measurements are presented in Table 1. Figure 4 shows the locations of B and A in the (g^*-r^*, r^*-i^*) diagram, the SDSS color-color plot in which $z \approx 4$ are most clearly separated from the stellar locus (the Lyman α emission line falls in r' and the Lyman forest occurs in g'; see Fan 1999). Object A satisfies the high-redshift selection criteria in this diagram (*shaded area*) and is approximately 0.4 mag brighter than the $i^* = 21.0$ limit. Object B lies in the same direction as A from the stellar locus, but is slightly outside the selection region and is also nearly half a magnitude too faint in i^* to be included in the sample. For both objects the g' measurement has a very low signal-to-noise ratio.

A summary of the properties of the two quasars is given in Table 2; the absolute magnitudes were calculated assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$. (We will use this cosmological model throughout this section.) We do not quote a continuum depression value (D_A) because of the limited signal-to-noise ratio of the data. The quasars are

TABLE 2

PROPERTIES OF QUASARS

Object	z	AB_{1450}	M_B
SDSSp J143952.58−003359.2......	4.255 ± 0.010	20.67	−25.8
SDSSp J143951.60−003429.2......	4.258 ± 0.010	22.03	−24.4

NOTE.—Properties calculated assuming $H_0 = 50$, $q_0 = 0.5$, $\alpha = -0.5$, and a standard Galactic reddening law with $E(B-V) = 0.039$ (Schlegel, Finkbeiner, & Davis 1998).

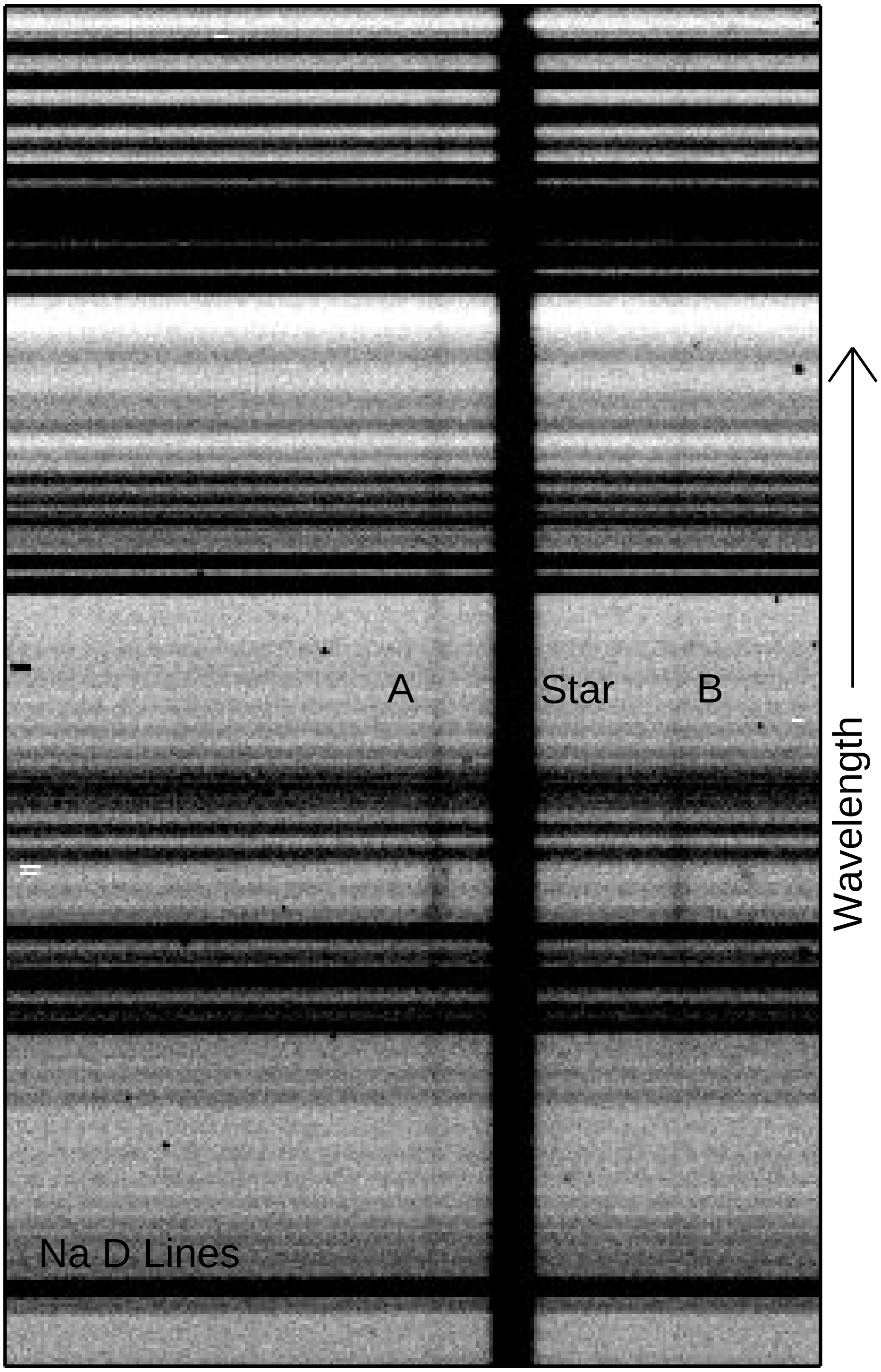

FIG. 2.—Section of the flattened LRS frame that contains the Lyman α emission lines of the two quasars. Blue is toward the bottom of the frame (the bright skyline near the bottom is Na D) and the slit width is 2″ (18 Å). The width of the figure is 125″. The spectrum of the brighter quasar (A) is in the center of the frame, the star's spectrum is just to the right of this, and the spectrum of the fainter quasar (B) lies approximately midway between the star's spectrum and the right edge of the figure.

relatively faint (indeed, the fainter of the pair is quite similar in redshift and luminosity to the second serendipitous $z > 4$ object, PC 0027+0521), but the luminosity of each is well above the canonical quasar/Seyfert dividing line, $M_B = -23$. The observed radio emission from each quasar must be less than 1 mJy, based on the lack of detection in the FIRST survey (Becker, White, & Helfand 1995) data; the quasars are radio-quiet, as are the vast majority of $z > 4$ quasars (Schneider et al. 1992; Schmidt et al. 1995b; Stern et al. 2000; Carilli et al. 2000).

The quasars are separated by 33″.4, and B is at position angle 206° relative to A. In our adopted cosmology, this corresponds to a projected spatial separation of 208 kpc (1.1 Mpc comoving), much closer than any other published pair of $z > 4$ quasars. We have measured the redshift difference in the spectra both from individual line redshifts and cross-

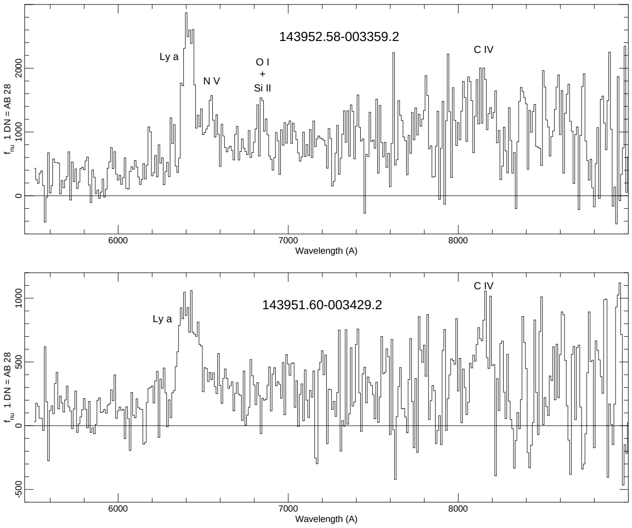

FIG. 3.—Spectra of the two quasars taken with the Low-Resolution Spectrograph on the Hobby-Eberly Telescope. The exposure time was 900 s; the data were taken through moderate cloud cover. The data have been rebinned to 10 Å pixel^{-1}. The spectral resolution is 20 Å; the unit of flux is $AB = 28.0$ or 2.29×10^{-31} ergs cm^{-2} s^{-1} Hz^{-1}. Prominent emission lines are marked.

correlating the spectra; both techniques yield a redshift difference consistent with zero but with an uncertainty of 0.01.

If the redshift difference is 0.01 and this is due to cosmological expansion rather than peculiar velocities, then the radial separation is 950 kpc (5 Mpc comoving). It is quite possible, however, that the redshift difference is much smaller, in which case assigning a distance to the redshift difference is suspect. If we assume that we have no radial information and are viewing the pair at a random angle, the mean deprojected separation is 327 kpc (1.7 Mpc comoving).

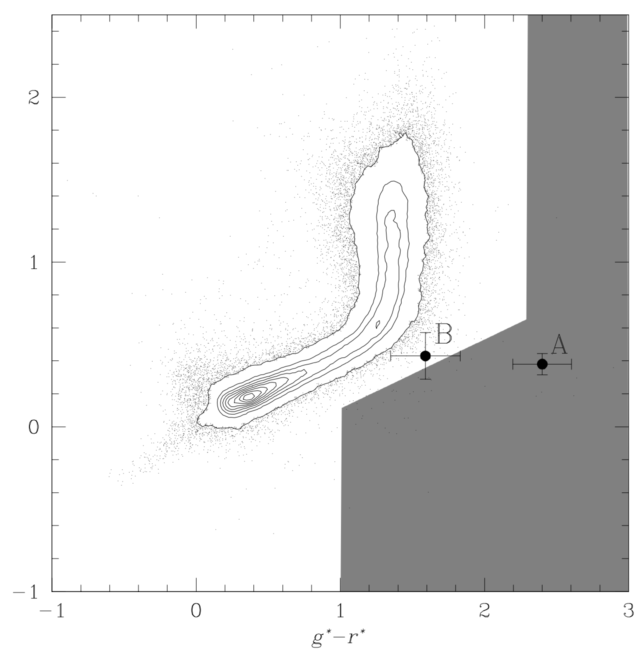

FIG. 4.—Location of the two quasars in the (g^*-r^*, r^*-i^*) diagram. The shaded area is the selection region for high-redshift quasars. The points and contours indicate the distribution of stars brighter than $i^* = 21$ selected from an area of 25 deg^2.

The only other known pair of $z > 4$ quasars with a comoving separation of less than 100 Mpc was found in observations for the Palomar Scan Grism Survey (PSGS; Schneider, Schmidt, & Gunn 1999): PC 0027+0525 ($z = 4.099$, $M_B = -24.8$) and the previously mentioned serendipitously discovered PC 0027+0521 ($z = 4.210$, $M_B = -24.0$). This pair is separated on the sky by 319″ and has a comoving separation of approximately 58 Mpc.

Both these pairs are chance discoveries, so calculation of the probability of finding them will necessarily involve post facto arguments. With this caveat in mind, we investigate this probability, first assuming that quasars are unclustered, then taking clustering into account. What are the chances of finding pairs of quasars of a given spatial separation between redshifts 4.0 and 4.5 in which both members have $M_B < -24.0$? In the following discussion, we will examine three examples: a "minimum" separation model (330 kpc; 1.7 Mpc comoving) and a "maximum" separation model (1 Mpc; 5.3 Mpc comoving) for the SDSS pair and a 58 Mpc separation for the PSGS objects.

Fan et al. (2000b) have investigated the luminosity function of high-redshift quasars from a sample of 39 $z > 3.6$ objects identified by the SDSS (including 18 quasars with redshifts larger than 4). They find the comoving number density of quasars more luminous than $M_B \le -26$ at redshift 4.25 to be 2.8×10^{-8} Mpc^{-3}, and an $n \propto L^{-2.5}$ differential luminosity function. These numbers are in excellent agreement with the previous studies by Schmidt, Schneider, & Gunn (1995a) and Kennefick, Djorgovski, & de Carvalho (1995), which were based on samples that contained nine and 10 $z > 4$ quasars, respectively. This luminosity function produces a number density of 4.4×10^{-7} Mpc^{-3} for quasars with $M_B < -24.0$. This calculation requires an extrapolation of more than 1.5 mag from the Schmidt et al. and Fan et al. data and should be viewed as an upper limit on the number density, given the evidence (e.g., the PSGS) that the quasar luminosity function flattens at luminosities below $M_B = -26$.

For the three examples mentioned above, the volumes enclosed by spheres whose radii are equal to the separations are 20.6, 624, and 8.2×10^5 Mpc^3, respectively; the chances of more than one quasar occurring in each volume are 4.1×10^{-11}, 3.9×10^{-8}, and 0.051, respectively. The volume enclosed by the shell bounded by redshifts 4.0 and 4.5 is 1.4×10^{11} Mpc^3 so one would expect 0.28, 8.9, and 8700 such pairs, respectively, over the entire sky. Given that the PSGS and SDSS have examined only 1% of the celestial sphere for high-redshift quasars, the likelihood of finding a 1.7 Mpc pair is approximately 1 in 350 and there is only a 9% chance of identifying a 5.3 Mpc pair. The existence of only two, not 87, known pairs with separation smaller than 58 Mpc is merely a reflection of the fact that the current sample of $z > 4$ quasars is woefully incomplete to $M_B = -24$, which comes as no surprise. This implied incompleteness, much more than a factor of 10, makes the discovery of the SDSS pair even more striking.

This calculation suggests that given the existence of the SDSS pair it is very unlikely that high-redshift quasars are not clustered. Kundić (1997) and Stephens et al. (1997) found that luminous $z > 2.7$ quasars are clustered, based on the three pairs with less than 30 Mpc (comoving) separation found in the 90 high-redshift quasars of the Palomar Grism Transit Survey (Schneider et al. 1994). Their estimate of the comoving correlation length was 35 Mpc, with a relatively large uncertainty. Bahcall & Chokshi (1991) discussed the origin of low-redshift quasar correlations, and two recent papers (Martini & Weinberg 2000; Haiman & Hui 2000) predict that high-redshift quasars should be clustered, based on theoretical arguments.

How strong must the quasar-quasar correlation function be to produce the observed SDSS pair in only 1% of the sky? If we assume a correlation function of the form seen in the local universe and that for $z \approx 3$ galaxies

$$\xi(r) = (r/r_0)^{-\gamma}$$

(Giavalisco et al. 1998), the ratio of the number of objects in the clustered case to that in the unclustered case within a sphere of radius R is

$$\left.\frac{n_{\rm corr}}{n_{\rm field}}\right|_R = \frac{\int_0^R 4\pi r^2 \xi(r) dr}{\int_0^R 4\pi r^2 dr} = \frac{3}{3-\gamma}\left(\frac{R}{r_0}\right)^{-\gamma} .$$

By adopting the representative value $\gamma = 1.8$, this expression becomes

$$\left.\frac{n_{\rm corr}}{n_{\rm field}}\right|_R = 2.5(R/r_0)^{-1.8} .$$

If this expression describes the high-redshift quasar-quasar correlation function, then the scale length r_0 must approach 30 Mpc for the minimum model and 12 Mpc for the maximum model for there to be a reasonable chance of finding a pair in the SDSS database to date. (Remember that this calculation assumes that the quasar sample is complete to $M_B = -24$!)

One could argue that the above discussion is invalid because current surveys are failing to find most of the quasars at this redshift because of effects such as reddening (e.g., Ostriker & Heisler 1984); therefore the estimate of the mean number density of quasars is grossly underestimated and hence "chance" pairs are much more prevalent than the calculation suggests. This may indeed be the state of affairs, but even if true it would not invalidate the above reasoning. The quasar surveys mentioned above have detection algorithms that rely on the strength of the Lyman α absorption and strong Lyman α emission (although the SDSS has demonstrated the ability to find high-redshift objects without Lyman α emission; see Fan et al. 1999a). Perhaps we can identify but a tiny fraction of the luminous objects at redshift greater than 4, but we can state that luminous objects with strong Lyman α emission are clearly strongly clustered.

These numbers indicate that it is highly likely that a significant number of $z > 4$ quasar pairs will be discovered in current large-area surveys. Recent investigations of the environments of high-redshift quasars (e.g., Djorgovski 1999) demonstrate that these distant beacons do not occur in isolation. The SDSS spectroscopic survey should discover several thousand quasars with redshifts larger than 4, and the SDSS image database will contain useful color information for objects brighter than $i' \approx 21.5$, similar to the brightness of the fainter of the SDSS pair in this study, in all the fields. While the efficiency of identification of high-redshift quasars in the primary SDSS survey at this limit falls well below the 50%–70% levels seen in the SDSS to date (e.g., Fan et al. 1999b, 2000a), the number of such candidates within an arcminute or two of known high-redshift quasars should be sufficiently small for spectroscopic investigation. The southern SDSS survey, consisting of an area of 225 deg^2 that will reach a magnitude or more deeper than the primary SDSS survey, should be ideal for studies of the high-redshift quasar correlation function.

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The Hobby-Eberly Telescope (HET) is a joint project of the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig-Maximillians-Universität München, and Georg-August-Universität Göttingen. The HET is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly. The Marcario LRS is named for Mike Marcario of High Lonesome Optics, who fabricated several optics for the instrument but died before its completion.

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[18] For the SDSS Web site, see http://www.sdss.org/.

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