THE QUASAR PAIR Q1634+267A,B AND THE BINARY QSO VERSUS DARK LENS HYPOTHESES[1]

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ABSTRACT

Deep *HST*/NICMOS *H*-band (F160W) observations of the $z = 1.96$ quasar pair Q1634+267A and B reveal no signs of a lens galaxy to a 1 σ threshold of $\simeq 22.5$ mag. The minimum luminosity for a normal lens galaxy would be a $6L^*$ galaxy at $z \simeq 0.5$, which is 650 times greater than our detection threshold. Our observation constrains the infrared mass-to-light ratio (M/L) of any putative, early-type, lens galaxy to $(M/L)_H \gtrsim 690 \, h_{65}$ ($1200 \, h_{65}$) for $\Omega_0 = 0.1$ (1.0) and $H_0 = 65 \, h_{65}$ km s^{-1} Mpc^{-1}. We would expect to detect a galaxy somewhere in the field because of the very strong Mg II absorption lines at $z = 1.1262$ in the Q1634+267A spectrum, but the *HST H*-band, *I*-band (F785LP), and *V*-band (F555W) images require that any associated galaxy be very underluminous $\lesssim 0.1 L_H^*$ ($1.0 L_I^*$) if it lies within $\lesssim 40 \, h_{65}^{-1}$ (100 h_{65}^{-1}) kpc from Q1634+267A and B. While the large image separation (3″85) and the lack of a lens galaxy strongly favor interpreting Q1634+267A and B as a binary quasar system, the spectral similarity remains a puzzle. We estimate that, at most, 0.06% of randomly selected quasar pairs would have spectra as similar to each other as the spectra of Q1634+267A and B. Moreover, spectral similarities observed for the 14 known quasar pairs are significantly greater than would be expected for an equivalent sample of randomly selected field quasars. Depending on how strictly we define similarity, we estimate that only 0.01%–3% of randomly drawn samples of 14 quasar pairs would have as many similar pairs as the observational sample.

Subject headings: gravitational lensing — quasars: general — quasars: individual (Q1634+267)

1. INTRODUCTION

The number of strong gravitational lenses has grown tremendously in the last five years, with well over 40 examples of strong gravitational lenses produced by galaxies (e.g., Keeton & Kochanek 1996 and the CASTLES webpage[5]). When the separations are smaller than 3″0, the lens galaxy has now been detected in all but one system: the small-separation, high-luminosity contrast lens Q1208+1011. The lens galaxies have normal photometric properties and their mass-to-light ratios (M/L) are typical of early-type galaxies embedded in dark matter halos (Kochanek et al. 1999b; Keeton, Kochanek, & Falco 1998). For the 18 systems with separations larger than 3″0 and nearly identical redshifts (see Table 1), a normal lens galaxy is detected in only four systems (RXJ 0911+0551, Q0957+561, HE 1104−1805, and MG 2016+112). No lens galaxy has been detected in any of the remaining 14 systems, with typical lower bounds on the M/L of the lens about 10 times higher than those measured for the normal lenses (Jackson et al. 1998). Whether the *quasar pairs*[6] with nearly identical red-

shifts separated by 3″0–10″0 are examples of " dark " gravitational lenses or binary quasars remains largely a mystery. Proving either scenario has very interesting ramifications on the dark mass distribution in the universe or the nature of interacting quasars (Schneider 1993). There are about two such quasar pairs for every 1000 optically selected quasars (Hewett et al. 1998).

Kochanek, Falco, & Muñoz (1999a) used a comparison of the optical and radio properties of the quasar pairs to show that the majority of the systems must be binary quasars. First, five pairs (PKS 1145−071, HS 1216+5032, Q1343+2640, MGC 2214+3550, and FIRST J1643+315) are " O^2R " pairs in which only one of the quasars is a radio source and we can be certain that the system is a binary quasar. Second, even though most of the known lenses were radio selected and the angular completeness of the radio lens surveys is better than that of the optical lens surveys, there is no example of a " dark " radio lens (an " O^2R^2 " pair). These two facts are inconsistent with the dark lens hypothesis. Quantitatively, Kochanek et al. (1999a) set a 2 σ (1 σ) upper limit of 22% (8%) on the fraction of the quasar pairs that could be gravitational lenses, with the most likely scenario being that none is a gravitational lens.

The high incidence and angular separations of the binary quasars can be quantitatively explained in terms of merger induced quasar activity (Kochanek et al. 1999a). The enhancement of the quasar-quasar correlation function by a factor of 10^2 on the angular scales of the pairs is exactly as predicted by the locally observed enhancement by a factor of 10 in the quasar-galaxy correlation function on the same physical scales (Fisher et al. 1996; Yee & Green 1987; French & Gunn 1983). The concentration of the pairs on scales smaller than 10″0 (< 50 kpc) is a natural consequence of the need for a close passage and tidal interactions to trigger renewed quasar activity. The absence of binaries on

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[5] http://cfa-www.harvard.edu/castles/.
[6] The definition of quasar pairs also includes close physical systems proven to be nonlenses but excludes known lenses.

TABLE 1

QUASAR PAIRS WITH SEPARATIONS OF 3″ TO 10″

Name	z_s	$\Delta\theta$ (arcsec)	R (h_{50}^{-1} kpc)	f_O	f_R	F_{20} (mJy)	$\|\Delta v\|$ (km s^{-1})	Lens?	Type	References
Q0151+048[a]	1.91	3.3	28	27.5		<1	520 ± 160	No	O^2	1
PKS 1145−071	1.35	4.2	36	2.1	>500	740	200 ± 110	No	O^2R	2
HS 1216+5032	1.45	9.1	78	5.2	>28	3.9	260 ± 1000	No	O^2R	3
Q1343+2640	2.03	9.5	78	1.1	>57	8.6	120 ± 890	No	O^2R	4
J1643+3156	0.59	2.3	17	1.3	>40	120	80 ± 10	No	O^2R	5
LBQS 2153−2056	1.85	7.8	64	14.5		<1	1100 ± 1500	No	O^2	6
MGC 2214+3550	0.88	3.0	26	1.6	>42	246	148 ± 420	No	O^2R	7
MG 0023+171	0.95	4.8	40	3.0	~10	186	292 ± 260	?—	O^2R^2	8
Q1120+0195[b]	1.46	6.5	56	173.8		<1	628 ± 120	?—	O^2	9
LBQS 1429−008	2.08	5.1	42	17.4		<1	260 ± 300	?—	O^2	10
QJ 0240−343	1.41	6.1	52	2.1		<1	250 ± 180	?	O^2	11
Q1634+267	1.96	3.8	32	4.4		<1	33 ± 86	?	O^2	12
Q2138−431	1.64	4.5	38	3.0			0 ± 115	?	O^2	13
Q2345+007	2.15	7.3	58	4.0	>9	0.035	476 ± 500	?	O^2	14
RXJ 0911.4+0551	2.80	3.1	24	1.9		<1	158 ± 1000	Yes	O^2	15
Q0957+561	1.41	6.1	52	1.4	1.3	552	200 ± 15	Yes	O^2R^2	16
HE 1104−1805	2.32	3.1	24	4.8		<1	300 ± 90	Yes	O^2	17
MG 2016+112	3.27	3.6	26	1.7	~1	191	40 ± 100	Yes	O^2R^2	18

NOTE.—z_s is the source redshift; $\Delta\theta$ is the angular separation; R is the projected separation at the source redshift for $\Omega_0 = 1$, and $H_0 = 50$ h_{50} km s^{-1} Mpc^{-1}, f_O, and f_R are the optical and radio flux ratios or their lower limits; F_λ is the radio flux of the brighter image at wavelength λ (in cm); and $|\Delta v|$ is the velocity difference between the quasars. The entries in the "Lens?" column are: "Yes" if a normal lens (galaxy, group, or cluster) is seen in the correct position to produce the observed system, there is no significant velocity difference, and the radio and optical data are consistent with the lens hypothesis; "No" if we see no lens and either the radio emission or the emission-line velocity difference, confirmed by an absorption-line velocity difference, are inconsistent with the lens hypothesis; and "?" if we see no lensing object but have no objective criterion to decide whether or not the object is lensed. If there is some evidence that the system is actually a binary, we use the label "?—." Type denotes the optical/radio classification of the pair. Note that MG 2016+112 is really a triple system, not a pair.

[a] Q0151+048 is also named PHL 1222 and UM 144.

[b] Q1120+019 is also named UM 425.

REFERENCES.—(1) Meylan et al. 1990; (2) Djorgovski et al. 1987; (3) Hagen et al. 1996; (4) Crampton et al. 1988; (5) Brotherton et al. 1999; (6) Hewett et al. 1998; (7) Muñoz et al. 1998; (8) Hewitt et al. 1987; (9) Meylan & Djorgovski 1989; (10) Hewett et al. 1989; (11) Tinney 1995; (12) Djorgovski & Spinrad 1984; (13) Hawkins et al. 1997; (14) Weedman et al. 1982; (15) Bade et al. 1997; (16) Walsh et al. 1979; (17) Wisotzki et al. 1993; (18) Lawrence et al. 1984.

scales smaller than 3″0 is a natural consequence of the rapid increase in the orbital decay rate caused by dynamical friction as the binaries shrink.

These limits on the existence of dark lenses are, however, statistical. While the maximum likelihood solution is that there are no dark lenses, the statistical limit corresponds to allowing the existence of three dark lenses at the 2 σ limit. The existence of even three dark lenses would mean that the densities of dark lens halos and normal clusters are the same on these mass scales (Maoz et al. 1997; Kochanek 1995; Wambsganss et al. 1995). Moreover, the binary hypothesis must somehow explain the remarkable similarity of the quasar pair spectra in the optical (e.g., Hawkins et al. 1997; Hewett et al. 1989; Steidel & Sargent 1991, hereafter SS91; Michalitsianos et al. 1997).

Q1634+267A and B remains one of the best candidates for exploring the issue of dark lenses and binary quasars. After the discovery by Sramek & Weedman (1978) in a slitless spectroscopy survey, Djorgovski & Spinrad (1984) and Turner et al. (1988) found the optical spectra of the two quasars to be very similar, with an upper limit on the velocity difference of 150 km s^{-1}, at the redshift of $z = 1.961$. The flux ratio of the pair was 4.4 at R band, although in images with seeing comparable to the image separation (Djorgovski & Spinrad 1984). No lens galaxy has been detected down to limits of $K \approx 21.5$ (SS91) and $R = 23.5$ (Djorgovski & Spinrad 1984).

Steidel & Sargent (1991) used the Palomar 5 m telescope to obtain very high signal-to-noise spectra of Q1634+267

that illustrate the striking similarity of the spectra of components A and B, modulo a constant scaling factor of 3.28. They also found a number of absorption lines in the brighter component A, most notably the Mg II doublet $\lambda\lambda2796$, 2803 at $z = 1.1262$, which perhaps hinted at the presence of a lens galaxy. When the emission-line spectra of A and B were compared in detail, there were slight differences in the Lyα + N v, Si IV + O IV], and C IV line profiles, and the line velocities were shifted by as much as 300–500 km s^{-1} (Small, Sargent, & Steidel 1997). The time delay created by the different travel times for the two rays can lead to spectral differences under the lens hypothesis, if the source quasar is variable. The temporal variations of quasar spectra have been examined by Filippenko (1989), Wisotzki et al. (1995), Impey et al. (1996), and Small et al. (1997). In particular, Small et al. (1997) demonstrated that the spectral differences observed in Q1634+267A and B were typical of the differences seen in spectra of the same quasar taken after an interval of several years.

With the advent of a second generation of instruments on the *Hubble Space Telescope* (*HST*), NICMOS has offered unique capabilities to discover and identify missing lens candidates by observing them at rest optical wavelengths where they are bright while providing unprecedented high angular resolution in the infrared necessary for studying these systems in detail. The CfA/Arizona Space Telescope Lens Survey (CASTLES) project is currently conducting a study of roughly 40 gravitational lens systems and candidates using optical/near infrared imaging with the *HST*.

The selection sample consists of "simple" systems in which the strong lensing is believed to be caused predominantly by a single galaxy. Some of the goals are to place tighter constraints on the lens geometry; to study the mass and light distribution of the lens galaxy; to study the evolutionary history and environment of the lens galaxy; to constrain better cosmological parameters through lens modeling and statistics; and, finally, in some cases to discover the missing lens galaxy.

Section 2 presents our observations of Q1634+267A and B, the photometry, and the determination of the magnitude limit at the anticipated lens position. We also present new limits on the radio flux of Q1634+267A and B and two other quasar pairs. Section 3 presents parameters derived for a hypothesized lens galaxy from a simple isothermal sphere model. We discuss the properties of the metal line absorber at $z = 1.1262$ in § 4 and the statistical similarity of quasar spectra in § 5. Conclusions follow in § 6. We adopt $H_0 = 65$ km s^{-1} Mpc^{-1} throughout the paper and display key results for both $\Omega_0 = 0.1$ and $\Omega_0 = 1$.

2. OBSERVATIONS AND ANALYSIS

2.1. Observations

We observed Q1634+267 on 1997 August 15 with *HST* using NICMOS Camera 2 (NIC2) and the *H* (F160W) filter.

We obtained four 690 s integrations in a 10.5 pixel dither pattern, for a total integration time of 2560 s. We reduced the data with our own software package "nicred" (McLeod 1997; Lehár et al. 1999). Figure 1 shows the reduced, combined image of the field of Q1634+267. Q1634+267A and B are approximately centered in the NIC2 field, and a star is visible at the edge of the $\sim 19'' \times 19''$ field of view.

2.2. Astrometry and Photometry

The plate scales of the NICMOS cameras changed as the IR array underwent thermal expansion. The variation was monitored (Cox et al. 1997), and the NIC2 plate scales were $0\rlap{.}''0760926$ and $0\rlap{.}''0754090$ pixel^{-1} in the *x*- and *y*-directions, respectively, for the measurement nearest the date of observation. The difference in the *x* and *y* plate scales is caused by a small tilt of the IR array relative to the focal plane. We adopt a zero point of $M_H = 21.79 \pm 0.02$ for F160W for infinite apertures, based on a comparison of *HST* archival and ground-based observations of the standard star P330E (Persson et al. 1998). It agrees closely with the value of 21.83 mag obtained by the Space Telescope Science Institute.[7] The foreground Galactic extinction in the direction of

[7] http://www.stsci.edu/ftp/instrument_news/NICMOS/NICMOS_phot/keywords.html.
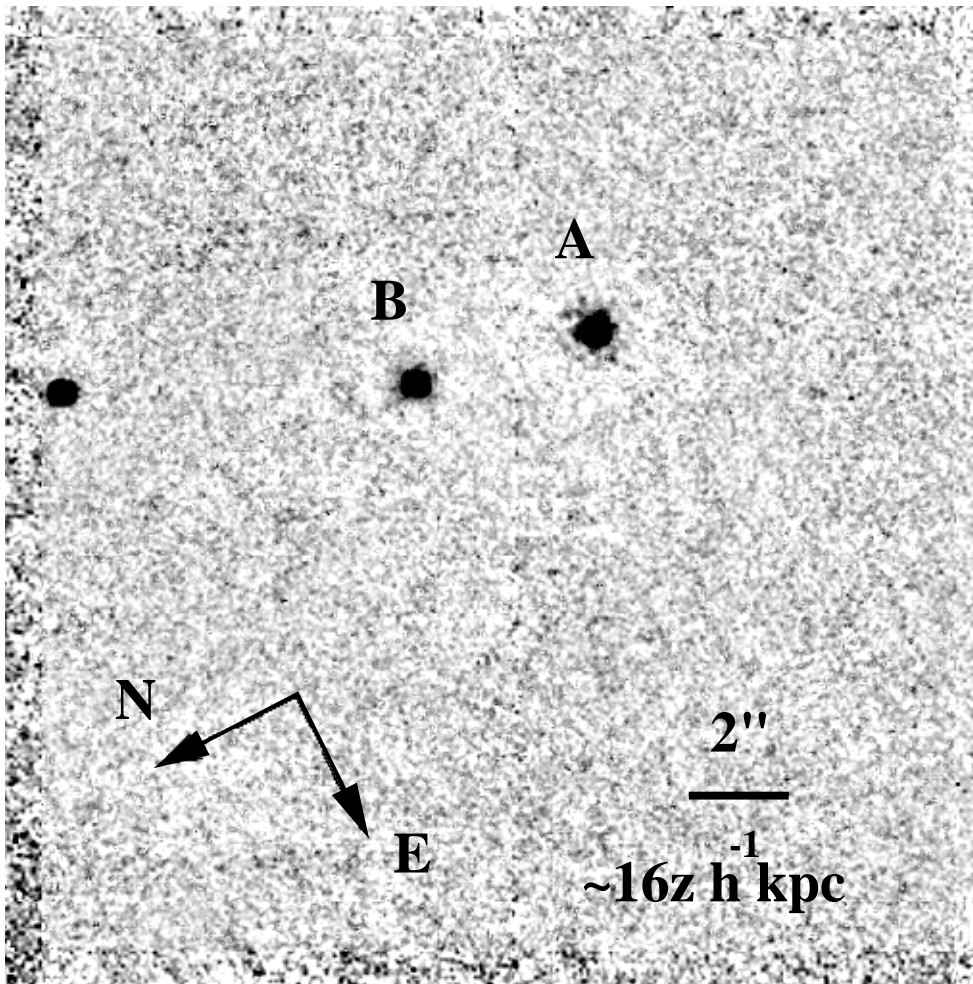

FIG. 1.—Image of Q1634+267A and B. Horizontal bar shown is 2″ in length, which corresponds to roughly 16 $z\,h_{65}^{-1}$ kpc, for an $\Omega = 0.1$ open cosmology.

TABLE 2
OBSERVED PROPERTIES OF Q1634+26A, B

Parameter	Value
Image separation (arcsec)	3.852 ± 0.003
Δ R.A.	-0.673
Δ Decl.	3.793
H-magnitude of component A......	18.26 ± 0.01
H-magnitude of component B......	19.56 ± 0.01
H-magnitude of star	19.67 ± 0.01
Flux ratio (A/B)	3.34 ± 0.06
Power-law slope α[a]	-0.13
$EW_0(Ly\alpha)$ (Å)........................	47.95
$EW_0(Nv\ \lambda1240)$ (Å)	24.18
$EW_0(Si\ IV\ \lambda1400)$ (Å)	11.83
$EW_0(CIv\ \lambda\lambda1548, 1550)$ (Å)	37.44
$EW_0(CIII]\ \lambda1909)$ (Å)	16.91

[a] Power-law slope defined as $F_\nu \propto \nu^\alpha$.

Q1634+267 is only $E(B-V) = 0.072$ for $R_V = 3.1$ (Schlegel, Finkbeiner, & Davis 1998); hence, we applied no extinction corrections to our photometric estimates.

We fitted a point-spread function (PSF) to our combined image to determine the relative coordinates and the magnitudes of Q1634+267A and B. Because A and B are well separated, we derived a PSF estimate from both components with the IRAF[8] DAOPHOT package. Table 2 shows the resulting relative coordinates and H-band magnitudes of A, B, and the star within our field of view. The quasar images are separated by $3\farcs852 \pm 0\farcs003$; the brightness ratio A/B is 3.34 ± 0.06.

We obtained 10 minute snapshots of three quasar pairs, Q1634+267, Q1120+0195, and LBQS 1429−008, on 1998 December 9 with the VLA in the C array at $\lambda = 3.6$ cm. We detected no radio flux to 1 σ limits of 0.028, 0.030, and 0.045 mJy beam^{-1}, respectively. With these low flux limits, there is little hope that further radio observations can shed much light on these systems.

2.3. Magnitude Limit at the Expected Lens Position

Visual inspection of the images revealed no lens candidate near the expected position. To search for a faint lens that might be hidden by A or B, we fitted the PSF derived in § 2.2 to the quasar components. We then subtracted the fitted PSF from these components. The fainter one, B, was marginally broader than A. The difference might be caused by intrinsic PSF differences at different positions on the detector, and similar small PSF mismatches were seen in other NICMOS archival images containing two or more stars. Thus, we cannot conclude that the slight broadening is caused by a faint galaxy underneath quasar B. Such a galaxy would have $m_H \gtrsim 21.8$ mag, which is too faint and at the wrong location to be able to produce lensed images with the observed splitting of $\sim 3\farcs8$.

To determine our detection limit for a lens galaxy, we generated circular galaxies with a de Vaucouleurs profile and an effective radius corresponding to an L^* galaxy (~ 3 h_{65}^{-1} kpc) over the redshift range $0.4 \lesssim z \lesssim 1.8$ and for

[8] IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

$\Omega_0 = 0.1$ and 1.0 cosmologies. We convolved the redshifted galaxies with the PSF derived from A and B and added them to our NIC2 frame on a grid of positions within the frame. The resulting images were smoothed with a Gaussian kernel with $\sigma = 3$ pixels and inspected for signs of the added galaxies. We found a magnitude limit of $m_H = 22.5$ (1 σ) for an early-type lens galaxy. For the sky background in our frame, the standard deviation of the noise level per pixel corresponds to a surface brightness of roughly 23.3 mag arcsec^{-2}.

3. LOWER LIMIT ON A LENS M/L

We compute the expected M/L for a putative lens galaxy for Q1634+267 from our detection threshold. The anticipated mass of the lens can be derived from simple lens theory, assuming it has a singular isothermal sphere (SIS) mass profile. The lens equation relates the angular coordinates β (θ) of the source (images), $\beta = \theta - \alpha(\theta)$, where $\alpha(\theta)$ is the deflection angle for an image at θ, with the lens galaxy at the center of coordinates. The SIS assumption implies: $\alpha(\theta) = (1/2)\Delta\theta = 4\pi(D_{ds}/D_s)(\sigma_v^2/c^2)$, where D_s (D_{ds}) is the distance from the observer (lens) to the source; $\Delta\theta$ is the observed angular separation of the lensed images; and σ_v is the velocity dispersion of the lens galaxy. Therefore, using the observed image separation, one can determine the velocity dispersion σ_v for a lens galaxy as a function of redshift. We show in Figure 2a the velocity dispersion $\sigma_v(z)$ using cosmologies $\Omega_0 = 0.1$ and 1, and $H_0 = 65$ km s^{-1} Mpc^{-1}. For an A/B magnification ratio of μ, the lens galaxy should lie $\Delta\theta[\mu/(\mu+1)]$ from image A along the A-B separation vector.

We translate our magnitude limit of $H = 22.5$ into an upper bound on the luminosity of the missing lens galaxy, placed at various redshifts. We follow the method implemented in Keeton et al. (1998) to derive H-band luminosity of elliptical galaxies at various redshifts using Charlot & Bruzual (1993) models. The models account for k-correction
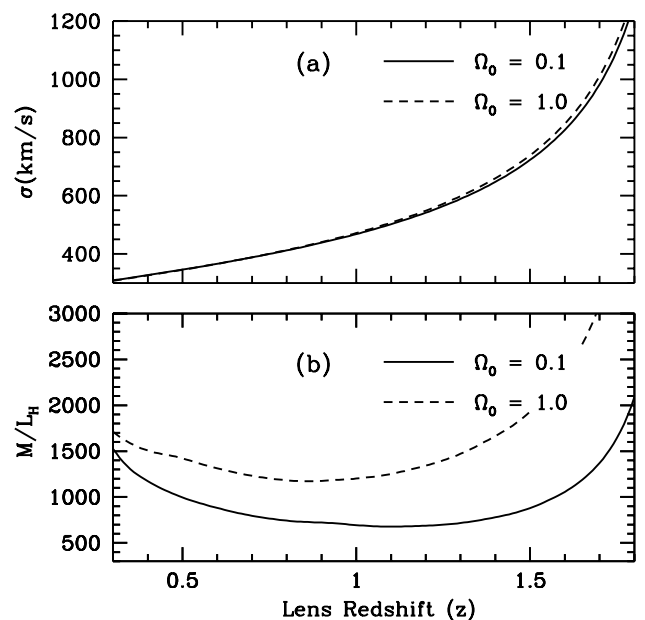

FIG. 2.—(a) Anticipated velocity dispersion of a putative lens galaxy; (b) M/L_H ratio as function of redshift for a putative lens galaxy, assuming properties of an early-type galaxy.

and passive evolution from formation redshift $z = 5$. Coupled with the masses required to produce lensing, determined via the lens equations, the luminosity limits yield the M/L as a function of redshift, shown in Figure 2b for cosmologies of $\Omega_0 = 0.1$ and 1. The most likely (comoving) distance to the lens is half the distance from the observer to the source, where the galaxy has the largest cross section for multiply imaging a source. For Q1634+267 at redshift 1.961, the most probable lens location is therefore at redshift 0.45. An elliptical galaxy at $z = 0.5$ would have $M/L \gtrsim 1000$ in a low-density universe, which is $\gtrsim 50$ times higher than a normal lens galaxy (Keeton et al. 1998; Jackson et al. 1998) and 50 times higher than a limit placed by Turner et al. (1988) in the optical. Therefore, if obscuration is responsible for hiding a lens galaxy with a normal M/L from view, then the dust must cause at least 4 mag of extinction in the H band. If, however, we accept the Mg II absorption lines as evidence for a lens galaxy at $z \approx 1.1$ (SS91), then the detection limit of $H > 22.5$ corresponds to about $0.15 L_H^*$ or $M/L_H \gtrsim 690$ for an E/S0 type galaxy. But if the lens galaxy type is an Sb, at a redshift of $z = 1.1$ it would have a $M/L_H \gtrsim 430$. The minimum M/L_H is 400 for an Sb galaxy at a redshift of $z = 1.3$.

If the lens is an early-type galaxy, we can predict its luminosity from the Faber-Jackson relation (1976) between velocity dispersion σ_v and luminosity, $\sigma_v/\sigma^* = (L/L^*)^{1/4}$, where σ^* and L^* are the velocity dispersion and luminosity of an L^* galaxy. Studies of lens statistics (e.g., Kochanek 1996) show that the velocity dispersion estimated from the image separation should closely match the central velocity dispersion of the stars. Figure 2a shows the velocity dispersion estimated from the lens geometry as a function of the lens redshift. At $z \approx 0.5$, the predicted velocity dispersion is $\sigma \approx 350$ km s^{-1}, considerably higher than the characteristic velocity dispersion of an L^* galaxy of $\sigma^* \simeq 220$ km s^{-1}. A galaxy at $z \approx 0.5$ would be a $L \approx 6 L_H^*$ galaxy, far brighter than normal early-type galaxies, where $1 L_H^*$ would correspond to $H \approx 17.4$ (16.9) mag for a passively evolving stellar population formed at $z_f \approx 5$ using the Charlot & Bruzual (1993) models for $\Omega = 0.1$ (1.0). Such a bright galaxy would be at least 650 (1000) times above our detection limit. At the redshift of the Mg II absorber of $z \approx 1.1$, the required velocity dispersion rises to ≈ 500 km s^{-1}, at the highest end of the range observed for bright galaxies (see, for example, Bender, Ziegler, & Bruzual 1996). It would have an extreme luminosity of $15 L_H^*$ if the scaling relation continued to hold.

We conclude that the absolute lower limit on the M/L of the putative lens is $M/L_H \approx 690$ for an early-type galaxy at a redshift $z \approx 1.1$ and $M/L_H \gtrsim 400$ for an Sb type at a redshift of $z \approx 1.3$. The limit is higher for any other redshift and for $\Omega_0 > 0.1$. For the most probable lens redshift of $z \approx 0.5$ and the cosmology of a high-density universe, the limit is $M/L_H > 1000$. Depending on the redshift of the presumed galaxy, the observed H band corresponds roughly to rest R band ($z \approx 1.5$) or I band ($z \approx 0.4$). Since $(B-H) \approx 5.7$ mag for ellipticals at redshift 0.5, and $(B-H)_\odot = 1.91$ mag, the limit would be about 30 times higher for M/L_B than for M/L_H. If Q1634+267A and B is the split image of a single quasar, the lens must be a galaxy with an unprecedentedly high M/L.

In fact, as we discuss in § 4, there are no galaxies above a detection limit of $\approx 0.1 L_H^*$ within 40 h_{65}^{-1} kpc and no galaxies above a detection limit of $\approx 1 L_I^*$ within 100 h_{65}^{-1} kpc of the quasars. Thus the depth of the imaging also rules out

any normal cluster of galaxies centered near the expected lens position. Moreover, the limit on the optical M/L of $M/L_B \approx 10^4 \, h_{65}$ greatly exceeds even the usual estimates for groups and clusters of galaxies, where $M/L_B \approx 10^3 \, h_{65}$ (Carlberg et al. 1996) is typical.

4. THE NATURE OF THE Mg II ABSORBER

In Q1634+267A and B, metal absorption lines are observed at $z = 1.839$ and $z = 1.126$ (SS91; Djorgovski & Spinrad 1984; Turner et al. 1988). Mg II $\lambda\lambda 2796$, 2803 absorption doublets with equivalent widths like the EW$_0$(Mg II $\lambda 2796$) = 1.51 Å doublet at $z = 1.126$ (SS91) are associated with chemically enriched material in the halos of visible, luminous galaxies along the line of sight (e.g., Steidel 1993, 1995; Steidel et al. 1997). Because quasars show roughly one metal line absorption system per unit redshift down to a typical rest equivalent width limit of ~ 0.3 Å (e.g., Steidel 1993), the mere presence of a metal absorption system is not evidence for the presence of a lens galaxy. In a survey of galaxies selected by the presence of Mg II absorption, Steidel (1993) showed that the absorbers are associated with galaxies of Hubble types from E to Sb. The strength of the absorption is anticorrelated with the distance of the quasar from the nearest luminous galaxy, and it is correlated with the intrinsic brightness of the galaxy (Steidel 1995, 1993). The luminosities of the approximately 70 systems studied by Steidel (1995) and Steidel et al. (1997) range from $0.02 L^*$ to $4 L^*$ with 87% (61/70) having $L > 0.1 L^*$. All but one (i.e., 99%) of the galaxies were found within a projected radius of 40 h_{65}^{-1} kpc.

We searched both the NICMOS H image and existing *HST* WFPC1 optical images (obtained under GTO-1116 by Westphal) for signs of a galaxy associated with the $z = 1.126$ absorption feature. Since the absorbing galaxy could have an exponential disk profile rather than the de Vaucouleurs profile considered in § 2, we rederived the detection limit for an exponential disk galaxy with a scale factor of 4 h_{65}^{-1} kpc. The limit of 22.5 mag (1 σ for $\Omega_0 = 0.1$) was similar to that for a de Vaucouleurs model with a 3 h_{65}^{-1} kpc effective radius. In the evolutionary models of Charlot & Bruzual (1993), a passively evolving L^*, Sb-type galaxy that formed at $z_f = 5$ would have $H_* \approx 19.7$ for $\Omega_0 = 1.0$, and $H_* \approx 20.0$ for $\Omega_0 = 0.1$, at $z = 1.126$. Therefore, our detection limit implies that we could have detected a galaxy with $L > 0.1 L_H^*$ anywhere within an impact parameter at 40 h_{65}^{-1} kpc from Q1634+267A (to the edge of the NICMOS array along the short direction). We derive a weaker detection limit of $L > L_I^*$ from the F785LP (I band) out to 100 h_{65}^{-1} kpc. Thus, any galaxy associated with the $z = 1.126$ Mg II absorption feature is either unusually faint or distant compared with those found in the Steidel (1993, 1995) surveys.

Since the PSF of quasar B is broader than that of quasar A, it is unlikely that the null detection could be explained by a galaxy directly under Q1634+267A, although we cannot exclude a very subluminous, compact dwarf with perfect alignment. Alternatively, a galaxy with a luminosity $\gtrsim 1 L_B^*$ lying outside our field of view might be responsible for the absorption. Distant ($>40 \, h_{65}^{-1}$ kpc), luminous ($L > L^*$) galaxies are associated with absorption, but the Mg II equivalent widths are less than 0.4 Å (Steidel 1995; Steidel et al. 1997), compared with the observed 1.5 Å. For distant absorbers, it is also odd that no equivalent Mg II absorption feature is seen in Q1634+267B. In summary, the absorbing

galaxy falls outside of the parameter space populated by galaxies found in Mg II absorber survey. The absorber must therefore be very underluminous, $\lesssim 0.1 L_H^*$.

5. SIMILARITY OF THE QUASAR SPECTRA

In the absence of a lens galaxy, it is the remarkable spectral similarity of many of the quasar pairs that provides the impetus for the gravitational lens interpretation. The spectra of the Q1634+267A and B pair show some of the greatest similarities of the pair population, and Small et al. (1997) have demonstrated that the observed differences are consistent with the temporal variations of quasar spectra over epochs separated by months to years. No study, however, has examined whether the spectra of the close pairs show a degree of spectral similarity that is statistically greater than that of randomly selected quasars. An affirmative answer increases the credibility of the lens hypothesis, because the lens hypothesis provides a natural explanation for the spectral similarities. While it would not rule out the binary hypothesis, it leaves a serious puzzle as to why the nuclear regions of two separate galaxies have such highly correlated emission properties. We start by defining how we will measure spectral similarities and then estimate the likelihood of finding a single quasar pair with spectra as similar as Q1634+267A and B. In isolation, the significance is hard to interpret because we picked Q1634+267A and B for study because of its spectral similarities. Thus, in our final step we estimate the likelihood of finding a population of quasar pairs with the observed spectral similarities.

5.1. *Sample Definition*

We will compare spectra using the observed differences between the spectral slope α and the rest equivalent widths (EW$_0$) of the Lyα, C IV ($\lambda\lambda$1548, 1550) and C III] (λ1909) emission lines. We selected these features because they are commonly measured in statistical surveys of quasar spectra. For Q1634+267 we computed the indices from the SS91 spectra. These calibrated spectra were taken at the Palomar 5 m telescope, using a double spectrograph that covered the blue (3150–4750 Å) and the red (4600–7000 Å) wavelengths. We used either the Large Bright Quasar Survey (LBQS) or the pair population as a whole for a comparison sample.

The LBQS consists of 1055 optically selected quasars (Foltz et al. 1987, 1989; Hewett et al. 1991). We use the measurements of the spectral indices for the LBQS quasars from Francis (1996), Hewett, Foltz, & Chaffee (1995), Francis (1993a), and Francis et al. (1991). The binned distributions for the LBQS quasars were fitted with analytic functions (composites of Gaussians and Lorentzians) to provide smooth probability distributions. Some of the spectral features are correlated (Francis et al. 1992; Francis 1993a), and we will conduct tests to examine the effects of these correlations on the probability calculations.

Unfortunately we lack a complete spectral database for the pairs, although the uncanny similarity of Q1634+267A and B is not an isolated case. There are 14 quasar pairs with angular separations $3'' \lesssim \theta \lesssim 10''$ and similar redshifts (see Table 1). We will frequently refer to this as our "14 pair sample." Of these 14, we can reject six as lenses. In the cases of PKS 1145−071, HS 1216+5032, Q1343+2640, J 1643+3156, and MGC 2214+3550, only one of the quasars is a radio source, and in the case of Q0151+048, the small emission-line redshift difference is confirmed by an absorption feature in the background quasar. Three of these

binaries (PKS 1141−071, HS 1216+5032, Q0151+048) show fairly similar spectra, although they all have at least one significant spectral difference. Of the eight ambiguous pairs, five (Q2138−431 in Hawkins et al. 1997, Q1429−008 in Hewett et al. 1989, Q1634+267 and Q2345+007 in SS91, Q1120+0195 in Michalitsianos et al. 1997) show remarkably similar optical spectra. For the pair sample, we restrict our comparison to the C IV equivalent width and the power-law slope α because the other two indices are not consistently observed or are impossible to measure without the original data.

5.1.1. *Line and Continuum Slope Measurements*

To determine the spectral slope, we fit a power law (defined as $F_\nu \propto \nu^\alpha$) excluding regions where there are emission or absorption lines. The Fe II in the UV spectra of quasars introduces substantial uncertainty in the measurement of continuum slopes. The power law α is also uncertain in the blue spectrum from contamination caused by the extended wings of the C IV, N V, and Lyα emission lines, as well as the Lyα forest absorption. Because of these complications, the width of the spectral slope distribution remains controversial. Some (e.g., Elvis et al. 1994; Webster et al. 1995) find large dispersions, while others find little or no dispersion in α (Francis 1996; Sanders et al. 1989). In our analysis, we will adopt the narrow α distribution from Francis (1996), as derived from 30 LBQS quasars. The Francis (1996) distribution has a root mean square (rms) width of $\sigma_\alpha = 0.3$, compared with $\sigma_\alpha = 0.5$ for the broader distributions of Francis et al. (1992). In Q1634+267, the mean slopes are $\alpha = -0.17$ in the blue (observed 3150–4734 Å) and $\alpha = -0.12$ in the red (observed 4580–6985 Å) spectra, respectively. In both the blue and the red, the power-law indices between A and B differ by $\Delta\alpha = 0.03 \pm 0.03$.

When comparing equivalent widths, we must be careful to use identical measurement methods because of the difficulties introduced by line blending and continuum definition. Francis (1993a) showed that C IV equivalent widths can vary by a factor of 2 depending on the measurement method and thus broaden the distribution of equivalent widths by the same factor. For Q1634+267A and B we avoid these problems by using the same definitions followed by the LBQS (Francis 1993a). For this method, continuum windows are defined on both sides of a given line. Then the flux is summed above a line adjoining the continuum windows, over a region known as the line window. The continuum windows are chosen to exclude the flux contributed by nearby broad lines, so the line fluxes should be considered a lower limit. The difference in rest equivalent widths (EW$_0$) between A and B are 3 Å for C IV, 8 Å for Lyα, and 3 Å for C III]. Measuring EW$_0$(C IV) requires connecting the red and blue halves of the spectra because the blue side spectrum terminates on the red wing of the C IV emission line, causing the continuum windows to fall on different spectrographs. We calculate a scaling factor of 1.22 using the regions of overlap. But there is some evidence that the same scaling factor might not apply to quasar B because of large fluctuations in the data over that region. Therefore the EW$_0$(C IV) differences of 3 Å should be considered an upper limit. Indeed, restricting ourselves to the blue regions alone and fitting Gaussians to the emission lines we find quasars A and B to differ at most by ΔEW$_0$(C IV) = 1 Å. The two methods yield the same flux. For completeness,

and because the numbers have not been published elsewhere, we also measure other line fluxes and summarize them in Table 2, although some we do not use in our analysis. All of the line fluxes are measured with the technique described in Francis (1993a) except for N V. Because of the blending with Lyα, the measurement for N V lines is done by fitting Gaussians to Lyα simultaneously with N V where we assumed that both lines are similar in shape.

For the other quasar pairs, we estimated bounds on the C IV equivalent width and the spectral index α based on the published spectra. For the five most similar pairs, we estimate that they have spectral differences $\Delta\alpha \lesssim 0.1$ and $\Delta EW_0(C\ IV) \lesssim 6$ Å (see Table 3). For the two pairs whose spectra have the worst noise, Q1120+0195 (Michalitsianos et al. 1997) and Q1429−008 (Hewett et al. 1989), the estimates are rough, while they are more accurate for the other three pairs. Since the estimates of the equivalent widths may be imprecise, we will also quote results by doubling our bound on the differences to $\Delta EW_0(C\ IV) \lesssim 12$ Å. We summarize our parameter estimates for the pairs in Table 3.

5.1.2. Joint Probabilities and Correlations among Spectral Features

To compute the probability that two random quasars have given differences in C III], Lyα, C IV equivalent widths and spectral slope α, we randomly draw the properties of two quasars at a time from the compiled number distributions. If the spectral features are completely uncorrelated, the likelihood that two quasars are similar to each other, i.e., have differences of less than $\Delta EW_0(C\ IV)$, $\Delta EW_0(C\ III])$, etc., is simply the joint product of each individual probability. However, if there are correlations, they could make the alarming similarities of the quasar pairs a trivial selection effect. Therefore, we first explore the extent to which spectral features are correlated.

Through a principal component analysis, Francis et al. (1992) showed that the equivalent widths of quasar emission lines are correlated with the power-law slope α. Francis (1993b) further showed that α is correlated with redshift. Their study was based on correlations with a spectral slope distribution in Francis et al. (1992), which has a large RMS dispersion of about $\sigma_\alpha = 0.5$. The strongest correlation, Al III + C III] with α, has a large scatter; the correlations of this and other lines are very weak. Subsequently, Francis (1996), using more accurate photometry, found that the spectral slope distribution actually has a much narrower dispersion of $\sigma_\alpha = 0.3$. But the newer study does not affect the disper-

sions of the line strengths, which are more accurate as long as they are measured consistently. Because the scatter of the line strengths remains large for a much reduced range in spectral slopes, the correlations are weaker in light of the narrow distribution compared with Francis et al. (1992). Furthermore, plotting spectral slope versus redshift from Francis (1996) shows that there is no correlation between the two parameters. In the analysis below, we will use the narrow power-law distribution found in Francis (1996). Therefore, the correlations between line emission, continuum, slopes, and redshifts can be safely ignored for our purposes.

Nonetheless, to confirm that correlations are unimportant even under extreme scenarios, we conduct the following Monte Carlo experiment to choose quasars from the number distributions found in Francis et al. (1992) and Francis (1993a). We select from the broader spectral slope distribution where correlations were originally found. The correlation between emission line strengths and α, and α with redshift z, means that the process of drawing quasars must proceed in a sequence to account for correlations at each step: first we draw quasars out of the LBQS redshift distribution, then the spectral slope distribution, followed at last by the emission-line distribution. To account for the correlation of α with redshift, we do the following. Having picked a redshift, and given the power-law distribution α, we offset the entire distribution by an amount $d\alpha = 0.79 \times d\log(1+z)$ (see Fig. 2 of Francis 1993b). We can then randomly select a value of α from this new distribution. There is, however, one subtlety. The distribution for α contains no redshift information because it is summed over all redshifts. But because of the correlation, if quasars at *any given* redshift have a small dispersion in their spectral slopes, as one accumulates the distribution over broader redshift ranges, the *net* distribution would also gradually become wider. We account for this effect by arbitrarily shrinking the dispersion and then drawing from this narrower spectral slope distribution instead of the original, broader one. We verified that decreasing the dispersion by 25%, more than one would expect, would not significantly alter our discussions below. Once a value for α has been selected, one can then proceed in the same fashion to select from the number distribution of C III], C IV, or Lyα, accounting for their roughly linear correlations with α by $EW_{line} = m\alpha + b$, where the correlation coefficients m and b are given in Francis et al. (1992). Again, we verified that any correlations would only begin to affect our conclusions if the number distributions were all narrowed by more than 25%.

There may also be weak correlations of quasar spectral properties with luminosity. The pair members share a common redshift and have similar luminosities, so we would underestimate the likelihood of the members possessing similar spectra if the distributions of spectral indices are correlated with either variable. We saw that the spectral index correlation with redshift has little or no role in our analysis. The Baldwin (Baldwin 1977) effect, a correlation between luminosity and C IV equivalent width, has been studied extensively (e.g., more recently, see Kinney et al. 1990; Sargent et al. 1989; Baldwin, Wampler, & Gaskell 1989). Their results show that at a given luminosity the equivalent widths of the C IV emission line have a defined range in strengths, with a scatter of about 20 Å. The strength of the C IV lines decreases with luminosity and the

TABLE 3
QSOs A AND B PARAMETER DIFFERENCE ESTIMATES

	$\Delta\alpha$	$\Delta EW_0(C\ IV)$ Å	Lens?	References
Q1120+0195............	0.1	6	?	1
LBQS 1429−0053......	0.03	6	?	2
Q1634+267.............	0.03	3	?	3
Q2138−431.............	0.02	6	?	4
Q2345+007.............	0.07	3	?	5
LBQS 2153−2056......	0.05	14	No	6
QJ0240−343............	0.2	<20	?	7

NOTE.—Estimated differences between the spectra of QSO pairs A and B spectra are published in the literature.
REFERENCES.—(1) Michalitsianos et al. 1997; (2) Hewett et al. 1989; (3) SS91; (4) Hawkins et al. 1997; (5) SS91; (6) Hewett et al. 1998; (7) Tinney 1995.

relation holds over 7 orders of magnitude in quasar luminosity. The parameterization of the correlation EW(C IV) $\propto L_{1450}^{\beta}$ has β ranging from $\beta = -0.07$ (Francis et al. 1992) to $\beta = -0.45$ (Smetanka et al. 1991). LBQS quasars, being a magnitude limited sample, have only a small spread in absolute luminosity, $-28 \lesssim M_B \lesssim -26$ (Francis et al. 1992). Since at any luminosity there is a considerable scatter in C IV and vice versa (see Osmer & Shields 1999 for summary), we do not expect the luminosity correlations to affect our analysis. Nonetheless, we tested for any effects by deriving the distribution of $\Delta EW_0(C$ IV) both with and without limits on the luminosity difference ΔL of the quasars making up the simulated pairs using the B_J magnitudes and $EW_0(C$ IV) values for the 439 LBQS survey quasars from Francis (1993a). We found no significant differences between the distributions without a luminosity restriction and those where the quasars were required to have absolute luminosities differing by less than a factor of 5 (1.7 mag) or a factor of 2.5 (1 mag).

Because the parameter correlations are very weak, in the discussions that follow, we make the assumption that no two spectral features are correlated.

5.2. The Spectral Similarity of Q1634 + 267A and B

As discussed previously, the spectra of Q1634 + 267A and B have equivalent width differences $\Delta \leq 3$ Å for C IV; 8 Å for Lyα; and 3 Å for C III], as well as 0.03 for α. If we select randomly from the distributions of these features in the LBQS survey, the probability of finding two quasars with smaller differences are 11%, 16%, 30%, and 12%, respectively. Assuming no correlations between the features, the joint probability of the differences being as small as observed is 0.06%.

With such a low joint probability, it would be reasonable to find several quasars with such similar spectra in the total quasar population ($\sim 10^4$ quasars) but highly unlikely to find any in the tiny subpopulation of quasar pairs (14 objects). The strength of this conclusion depends only weakly on the details of the comparison, and the joint probability only rises to 1% if we confine the comparison to the spectral index and C IV equivalent width differences. Adding additional spectral features to the estimate would further reduce the likelihood, but it becomes increasingly important to fully understand the spectral correlations of quasars. Moreover, calculations of a posteriori probabilities can generally yield arbitrarily low likelihoods by overspecifying the problem. Nonetheless, the similarity of the Q1634 + 267A and B spectra extends across the entire rest-UV spectra of the pair.

5.3. The Spectral Similarity of the Pair Population

Because we preselected Q1634 + 267A and B for study because of its spectral similarities, we cannot interpret it in isolation from the rest of the pair population. Moreover, the uncanny similarities of Q1634 + 267A and B are not an isolated example among the pairs. To understand the significance of the spectral similarities of the pairs fully, we must consider the entire pair population.

Under the assumption that the quasars making up the pair sample are drawn from the same parent population as the quasars in the LBQS, we can produce mock samples of quasar pairs by randomly selecting 14 pairs of quasars from the LBQS. We can then compare the distribution of the spectral slope and C IV equivalent width differences, $\Delta \alpha$ and

$\Delta EW_0(C$ IV), with those observed for the pairs. We will estimate the probability of finding at least as many similar pairs as observed in the real sample.

We generated 10^4 mock pair catalogs to determine the fraction of catalogs in which N_{sim} pairs have spectral differences smaller than the specified limits on $\Delta \alpha$ and $\Delta EW_0(C$ IV), and the results are illustrated in Figure 3. The top panel shows the limits on spectral similarity [$\Delta \alpha \lesssim 0.1$ and $\Delta EW_0(C$ IV) $\lesssim 6$ Å], which characterize the differences observed for the five pairs with similar spectra (Q2138−431, LBQS 1429−008, Q1634+267, Q1120+0195, and Q2345+007). The chance of drawing five or more pairs with such similar spectra in the sample of 14 pairs is about 0.2%. If we were to relax the constraints to $\Delta \alpha \lesssim 0.1$ and $\Delta EW_0(C$ IV) $\lesssim 12$ Å to account for possible systematic errors in measuring $\Delta EW_0(C$ IV), the probability for finding five or more such pairs grows only to 3%. We conclude that the likelihood for finding five pairs with such similar spectra in a sample of 14 pairs is low. If we significantly broaden the criterion for similarity [$\Delta \alpha \lesssim 0.2$ and $\Delta EW_0(C$ IV) $\lesssim 20$ Å], the likelihood of finding five or more similar pairs rises to 60%. However, with these weaker criteria, there are now seven observed pairs meeting the criterion for similarity (we should add QJ 0240−343 and LBQS 2153−2056), and the likelihood of finding seven or more similar pairs is then smaller, at 20%. We regard this third case as a significant underestimate of the similarities. The low probability for finding similar quasars randomly, using two parameters, may only be an upper bound. If our pairs sample were partly made up of gravitational lenses, microlensing and time delay might cause some spectral differences in those systems. It is impossible to quantify such a conjecture with our pairs sample.
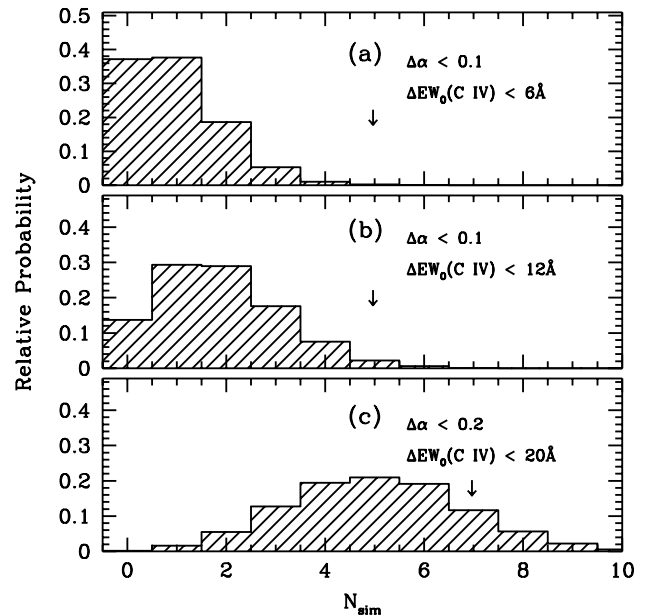

FIG. 3.—Fraction of trials in which N_{sim} pairs from a sample of 14 pairs randomly drawn from the LBQS meet the stated conditions on $\Delta \alpha$ and $\Delta EW_0(C$ IV). We assume the narrow spectral slope distribution from Francis (1996). The arrow marks the number of pairs observed to meet the similarity condition. (a) Representative spectral differences actually observed for the five lens candidates. Probabilities for (b) and (c) have substantially weaker C IV and spectral slope constraints, as indicated in each box.
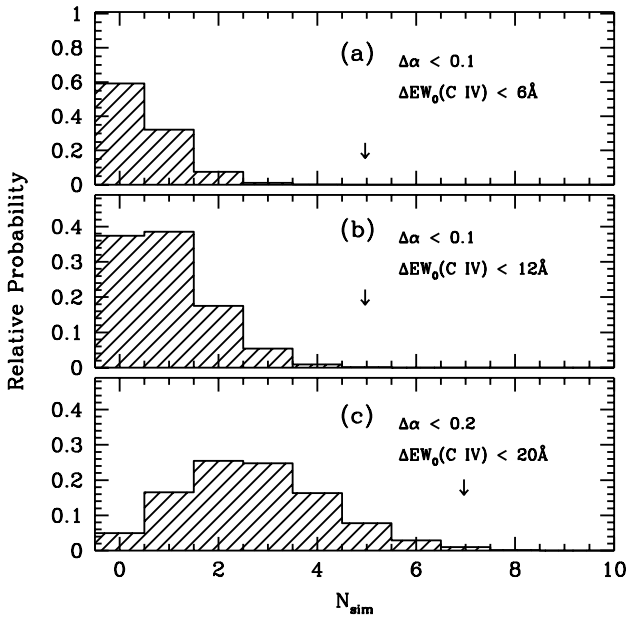
FIG. 4.—Fraction of trials in which N_{sim} pairs from a sample of 14 pairs randomly drawn from the LBQS meet the stated conditions on $\Delta\alpha$ and $\Delta EW_0(C\ IV)$. Here we assume the broad spectral slope distribution from Francis et al. (1992). The arrow marks the number of pairs observed to meet the similarity condition. The similarity conditions for the cases are the same as in Fig. 3.

The probability for finding similar quasars is significantly lower if we use a broad continuum slope distribution (e.g., Francis 1992) rather than the narrow distribution of Francis (1996) used for the estimates in Figure 3. For the broad estimate of the α distribution, the likelihoods for drawing at least five similar pairs under the same three sets of constraints on $\Delta\alpha$ and $\Delta EW_0(C\ IV)$ are 0.01%, 0.2%, and 1.2% instead of 0.2%, 3.0%, and 20% (see Fig. 4). Thus, the debate about the width of the continuum slope distribution does not alter the conclusion that the spectral similarities of the pairs are unlikely to occur by chance unless the distribution is even narrower than that found by Francis (1996). The distribution of C IV equivalent widths, *as long as measured consistently*, does not suffer from the systematic problems of the spectral slope distribution.

6. CONCLUSIONS

We again confirm that there is no sign of a lensing galaxy or a surrounding group or cluster of galaxies near the Q1634+267A and B quasar pair. Our limit on the M/L is $\gtrsim 690\ h_{65}$ in the H band, which is tighter than previous estimates. We also lack a candidate galaxy within $100\ h_{65}^{-1}$ kpc for producing the $z = 1.126$ Mg II absorption feature in the spectrum of A. Since the existence of even one large separation lens produced by a "dark" mass distribution has profound implications, confirming or disproving the lens hypothesis is highly desirable. It appears from the data in the literature that the flux ratio of the quasars is significantly time variable, changing from 4.4 (Djorgovski & Spinrad 1984) to 2.83 (Turner et al. 1988) to 3.28 (SS91) and 3.34 (this work). With its large angular separation, regular photometric monitoring of the system to search for a time delay would be simple on modest-sized, ground-based telescopes. Although we found that the pairs Q1634+267, Q1120+0195, and LBQS 1429−008 are, at best, weak

radio sources, with upper limits on their fluxes of 0.028, 0.030, and 0.045 mJy beam^{-1} at $\lambda = 3.6$ cm, deeper observations may still detect the sources or demonstrate that both members are at the extremes of the radio to optical flux ratio distribution. Deep X-ray observations would also be useful, both to measure the flux ratio of the quasars and to search for hot X-ray–emitting gas associated with any lensing potential. Deep IR imaging should detect the quasar host galaxies, whose shapes must show tangential arc distortions under the lens hypothesis.

The spectral similarities of some of the quasar pairs has always been the major impetus for the "dark" lens interpretation of the systems. To date, these arguments have been based on the similarities of individual pairs rather than the overall pair population. Using the distribution of continuum slopes and C IV equivalent widths, we demonstrated that it was improbable to find as many similar pairs as observed in the existing sample of 14 pairs. The probability estimates range from 0.01% to 3%, depending on how strictly similarity is defined and depending on whether a broad or narrow distribution was used for the continuum slope distribution. A better quantitative analysis needs a uniform spectral survey of the pairs.

The effects of binary quasar interaction on spectral similarity have been surmised, for example, by Schneider (1993). Kochanek et al. (1999a) demonstrated that most of the quasar pairs are binary quasars rather than "dark lenses." The binary quasar hypothesis is a successful quantitative interpretation of both the number of quasar pairs and the distribution of their separations. If they are all binary quasars, then there must be a physical explanation for the spectral similarities. Binary quasars are examples of quasar activity triggered by mergers, which represent a small fraction of all quasar activity (about 5% in simple models—see Kochanek et al. 1999a). We present two hypotheses for how binary quasars can have such similar spectra. First, if the physical properties of quasars triggered by major mergers (e.g., mass, accretion rate, surrounding gas density) were confined to a limited range of values compared with the overall quasar population, then the observable properties of the binaries would be more similar than those of randomly selected quasars. This hypothesis has a definite, testable prediction—the spectra of the different pairs should be more similar to each other than for randomly selected quasars. It would also be expected that the quasar host galaxies have properties commensurate with being the products of major mergers, which can be tested by deep imaging. Second, if quasar spectra have a significant dependence on the age of the activity, then the binary spectra are more similar than for random quasars because the merger provides a common triggering event for the activity in the two systems. Here we would not expect the spectra of the different pairs to show any more similarity than randomly selected quasars. In either case, the binary quasar population becomes a very important probe of the physics of quasars because it provides evidence for correlations between events on large scales and the detailed operation of the central engine.

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