SPECTRAL DIFFERENCES IN THE QSO PAIRS Q1634+267A,B AND Q2345+007A,B AND THE GRAVITATIONAL LENS INTERPRETATION

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ABSTRACT

We present new high signal-to-noise ratio, moderate dispersion spectra over the wavelength range 3150–7000 Å of two of the widest separation, unconfirmed gravitational lens candidates, Q1634 + 267 A,B (separation = 3.77″) and Q2345 + 007A,B (separation = 7.03″). Aside from the obvious interest in establishing whether or not these pairs are gravitationally lensed images, both of these pairs are capable of setting extremely interesting limits on the sizes of intervening Lyman α and heavy-element absorption systems. For Q1634 + 267A,B, the detailed line profile and continuum shapes strongly support the gravitational lensing hypothesis; however, we find that the Ly α, N V, C IV, Si IV emission lines of the two images exhibit as much as a 1000 km s^{-1} relative shift in velocity, whereas the C III] and Mg II lines are consistent with no velocity shift, as found by previous workers. While the emission line profiles and redshifts of Q2345 + 007A and B are remarkably similar ($\Delta v_{\rm B-A} = 15 \pm 20$ km s^{-1}), the line-to-continuum ratios for various lines differ markedly; the intensity ratios for C IV, Si IV, and Mg II appear to scale roughly with the continuum ratio of the two spectra, whereas the Lyman α and especially C III] intensity ratios differ significantly from the observed continuum ratio. *We conclude that both of the pairs in question are gravitationally lensed*; however, the peculiarities of the emission line properties are puzzling, and may be providing information on the structure of QSO broad line regions. We discuss several possible origins for the differing emission line spectra under the gravitational lensing hypothesis. We favor the notion that there must be large temporal variations, occurring on timescales of about a year or less, in the relative redshifts (and strengths) of emission lines formed in different parts of the QSO emitting regions; *we predict that such variations will be found if the spectra of single QSOs are monitored*. For Q2345 + 007A,B, we report the discovery of at least three, and possibly four, new heavy element absorption systems in the spectra. Thus, several of the lines which have been assumed to be "Lyman α forest" lines are probably associated with heavy element systems. Contamination of the "Lyman α forest" sample with heavy element lines may have significantly affected previous inferred limits on the sizes of the intergalactic clouds. A possible Mg II absorption system at $z = 0.7545$ in the spectrum of Q2345 + 007B may arise in material associated with a lens, and may have been detected as a resolved component of B in high resolution imaging studies of the pair. The possibility of using spectra of Q2345 + 007A,B to set useful limits on the characteristic sizes of, and structures within, the heavy-element absorbing regions is explored.

1. INTRODUCTION

While theoretical predictions all indicate that the bulk of gravitational lensing events should produce images with separations which are difficult to resolve using optical, ground-based observations (e.g., Turner *et al.* 1984), there is a rather large body of already-discovered lens *candidates* many of which have image separations large enough that they stretch the parameters of lens models and are therefore viewed with some skepticism (e.g., Kochanek 1991; Phinney & Blandford 1987). By virtue of the fact that the light traverses two slightly different paths, these same QSO pairs (whether or not they are lensed images of the same QSO) offer the unique possibility of probing the gas in intervening galaxies and intergalactic clouds through the absorption lines recorded in the QSO spectra. This fact has been exploited to set very important limits on the size scales associated with the Lyman α forest clouds (Foltz *et al.* 1984; Smette *et al.* 1991; Duncan 1991) and on the structure of heavy element absorbing clouds (e.g., Crotts 1988; Smette *et al.* 1991); however, as emphasized by Steidel & Sargent (1990), it is important to establish whether the QSO pair in question is in fact lensed or whether it is simply a "binary" QSO because the same angular scale can correspond to very different *physical* scales depending on the nature of the system. In principle, using lenses or binary QSOs with a range of image separations, one can learn about the structure of objects along the line of sight from subgalactic to supercluster scales.

In the present paper, we reexamine two of these questionable wide-separation lens candidates which have received considerable recent attention in the literature, Q1634 + 267A,B[3] and Q2345 + 007A,B. The primary motivation for our investigation was to establish the nature of the pairs so that the interpretation of their absorption spectra would be unambiguous. Of course, along the way, one hopes that in establishing a pair as a lens (or not, as the case may be), new light can be shed on the nature of the lensing

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[3] This pair has been extensively referred to as Q1635 + 267A,B in the literature; however, by the convention adopted by the IAU, it should be correctly designated as Q1634 + 267 based on its epoch 1950 coordinates.

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itself. By obtaining spectra of moderate resolution and high signal-to-noise ratio, we hoped to analyze the properties of a number of broad emission lines, the QSO continua, and the properties of intervening absorption, simultaneously. In particular, we seek idiosyncracies in the emission line/continuum properties which might provide strong arguments as to the nature of the pairs, and evidence for intervening or lensing galaxies which might be expected to be recorded in absorption in one or both of the QSO images. Both of the QSO pairs which we discuss in this paper are extremely faint for high-resolution spectroscopic studies necessary to explore the details of the absorption spectra; however, with the imminent commission of much larger telescope apertures coupled with low-noise CCD detectors, both of these pairs will be accessible to high-resolution spectroscopy in the very near future.

2. OBSERVATIONS AND DATA REDUCTION

2.1 Observations

Spectra of both Q1634 + 267A,B and Q2345 + 007A,B were obtained during the course of a four night observing run, 20–23 July 1990 (UT). All spectra were taken using the Double Spectrograph attached to the Palomar 5.08 m Hale telescope. The instrumental configuration was such that the blue camera recorded the wavelength range 3150–4700 Å (using a 300 l/mm grating blazed at 4000 Å in first order) and the red camera the range 4700–6980 Å (using a 316 l/mm grating blazed at 7000 Å in first order), using 800 by 800 Texas Instruments CCDs as detectors. In order to maximize the spectral resolution, a 1″ slit was used throughout, resulting in spectral resolution of ~ 4 Å in the blue and ~ 6 Å in the red. A minor problem with the CCD in the red camera on one of the nights (22 July) meant that only the data from the blue camera were considered useful; thus, total integration times were generally longer in the blue than in the red.

2.1.1 Q1634+276A,B

The spectrograph slit was rotated to a position angle of 170.4° in order to record spectra of both objects simultaneously. The corresponding optimum (parallactic) position angle was nearly orthogonal to this P.A., but the observations were made within 1.5 hr of the meridian (and the field passes very close to the zenith at Palomar) so that differential light losses due to atmospheric dispersion were not severe despite the narrow slit. The seeing was estimated to be subarcsecond for most of the individual exposures, so that the two objects, separated by 3.77″, do not contaminate one another on the CCD. Total integrations of 21 000 and 17 400 s were obtained in the blue and red, respectively.

2.1.2 Q2345+007A,B

A position angle of 57° was used to record both A and B simultaneously; the separation of the two objects, 7.03″, is sufficiently large that the objects were easily separable given the typical seeing of $\sim 1.0''$. unfortunately, however, the observations were made at airmasses ranging from 1.65–1.2 (1–3 hr east of the meridian) and the optimum P.A. was again nearly orthogonal to the P.A. used. In this case, substantial light losses in the blue were experienced due to differential atmospheric refraction and a guide probe television which is sensitive to red light. We will discuss the procedure used to correct for those losses in Sec. *2.2*. Total integration times were 27 600 and 18 000 s for the blue and red, respectively.

2.2 Data Reduction

The spectra were reduced using procedures similar to those described by Steidel & Sargent (1991), with the following exception: because of the importance of differential atmospheric refraction to the spectral energy distribution of the reduced spectra, we have used the exposures recorded at the smallest zenith distances to "normalize" each individual exposure. That is, the resultant spectrum is corrected to conform to the spectrum for which the minimum light losses were experienced. Because we maintained an "error array" for each individual exposure throughout the reduction process, the corrected spectra wee weighted according to the inverse variance when they were coadded, so that the highest quality data at a given wavelength were always weighted most heavily. In the case of Q1634 + 267A,B, the resulting spectra should be very accurate in terms of relative spectrophotometry, since differential refraction is negligible for the best exposures of the objects. For Q2345 + 007A,B, on the other hand, the spectra are essentially normalized to reflect light losses appropriate to an airmass of 1.2 (the total differential refraction between 3500 and 6500 Å is then about 0.8″); thus, the relative spectrophotometry for the spectra is considerably less reliable. However, we should emphasize for the purpose of later analysis and discussion that, because of the small separation of the A and B images in both cases, any spectrophotometric errors in the spectra should be *equivalent* for both images assuming that the adopted P.A. was indeed correct (this assertion is corroborated by the consistency of the ratios A/B for individual exposures). Thus, for example, the correct *ratio* of A to B at a given wavelength should be preserved.

The final blue and red spectra of Q1634 + 267A,B and Q2345 + 007A,B are plotted in separate panels of Figs. 1a and 1b.

3. EMISSION LINES AND CONTINUA

3.1 Q1634+267A,B

Q1634 + 267A,B were originally discovered by Sramek & Weedman (1978), who suggested that the QSOs, separated by 3.8″, had slightly different emission redshifts. Subsequently, Djorgovski & Spinrad (1984) obtained deep images and improved spectra of the objects, concluding that the pair is a gravitational lens on the basis of the fact that the 2σ upper limit on the velocity difference between the spectra of A and B, based upon comparison of the C III] λ 1909 emission lines, was ~ 200 km s^{-1}. Turner *et al.* (1988) obtained higher signal-to-noise ratio spectra covering a wider wavelength range; based upon the cross correlation of the spectral regions containing C III] and Mg II λ 2800, they obtained an improved 2σ upper limit on the velocity difference of ~ 150 km s^{-1}. Furthermore, the actual profile shape of these two lines was found to be quite consistent between the two objects, providing further evidence for the gravitational lens interpretation.

Turner *et al.* (1988) also found that A and B had clearly different continuum shapes, in the sense that the spectrum of A is significantly "redder" than that of B. This difference prompted Turner *et al.* to fit polynomials to the continua in order to subtract them and leave only the emission line spectra for comparison; however, this method may not be com-

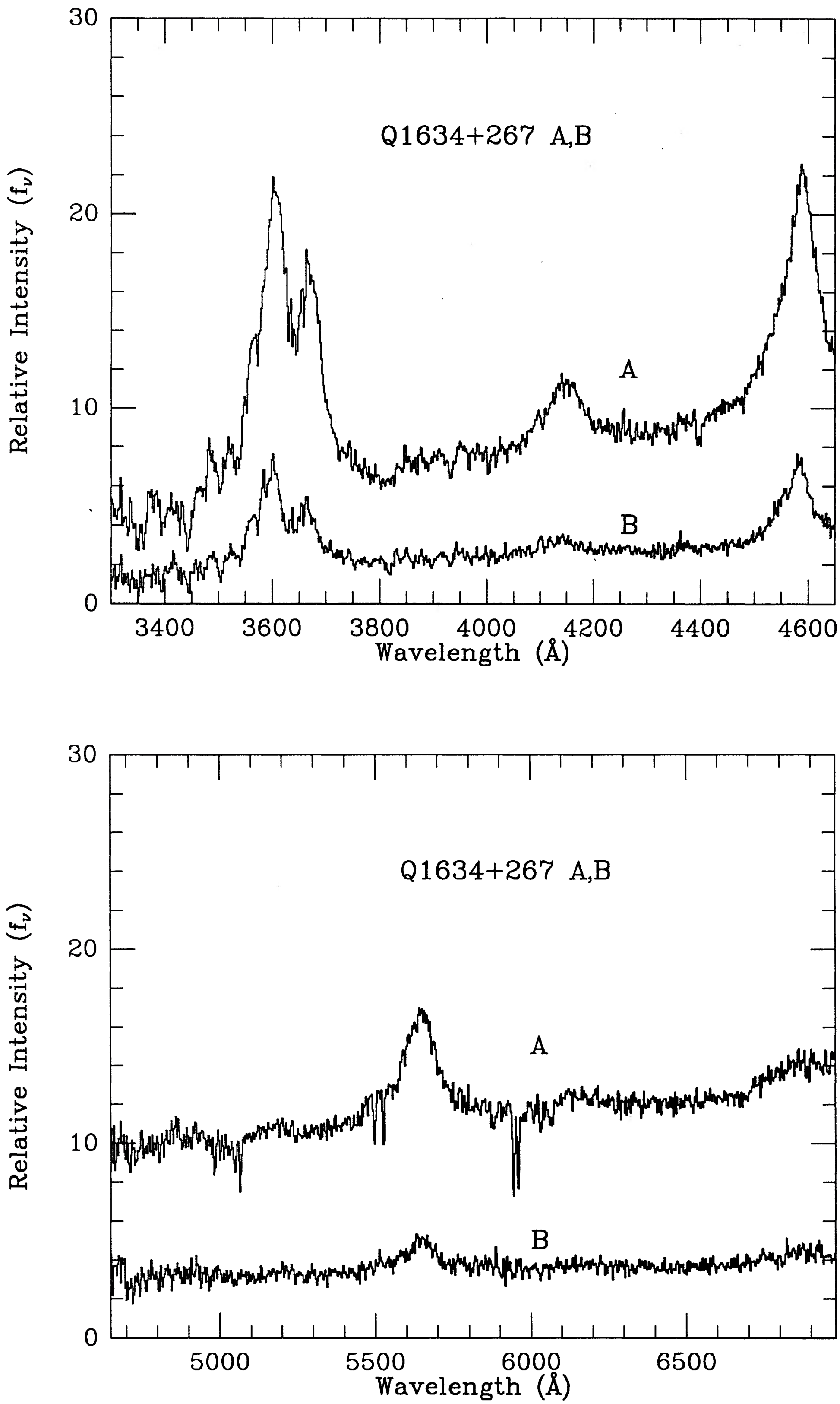
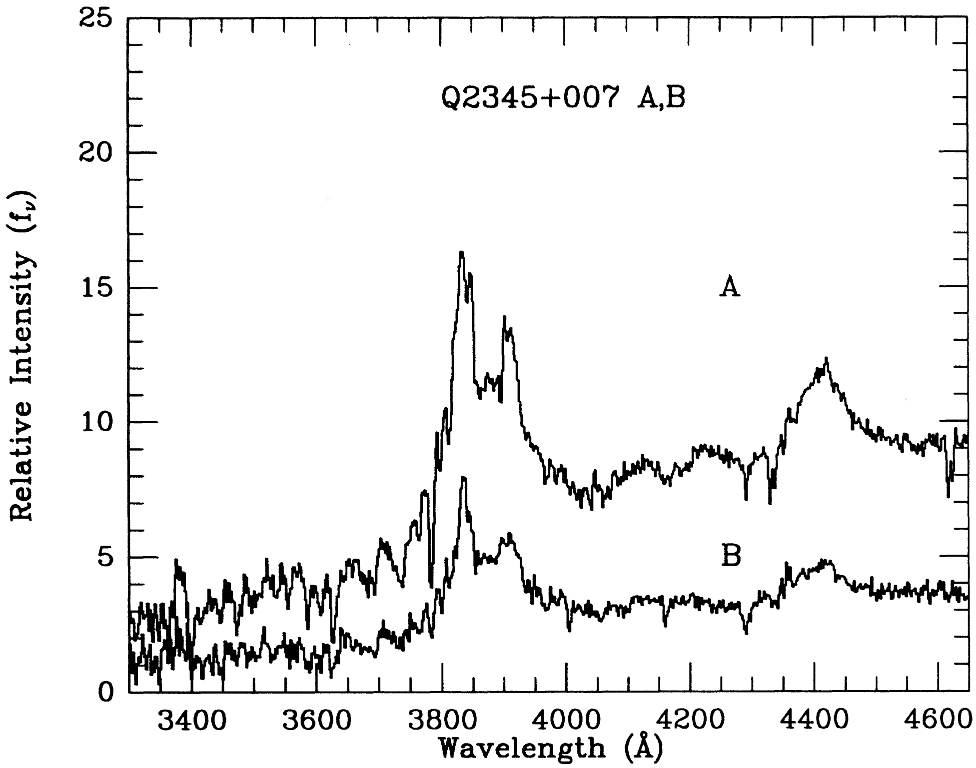


FIG. 1. Spectra of Q1634 + 267A and B, and Q2345 + 007A,B. No scaling has been applied to the spectra. The data have a spectral resolution of ~4 Å shortward of 4650 Å, and ~6 Å longward of 4650 Å.



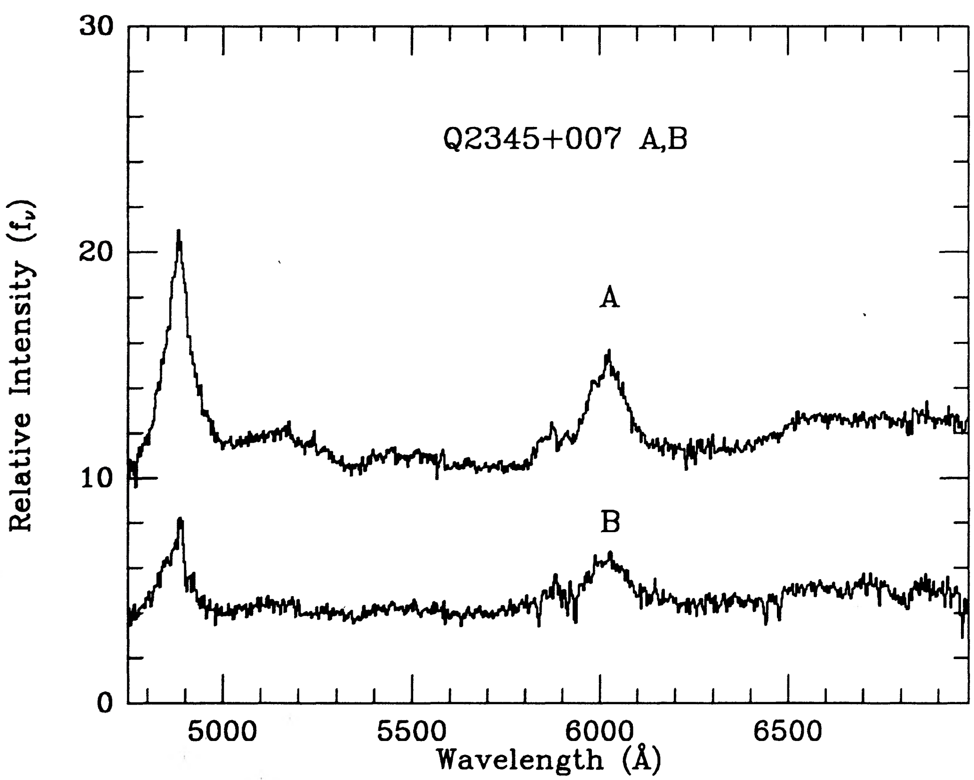


FIG. 1. (continued)

pletely justified, as there is really next to no "true" continuum region over the rest wavelength covered by their spectra (see, e.g., Boyle 1990; Francis *et al.* 1991). Thus, the polynomial fits to the continua may have been strongly influenced by the strength of blended emission lines, particularly the many multiplets of Fe II which occur between C III] and Mg II emission in QSO spectra. In view of this, we have simply calculated the best value of the constant scaling factor between our new spectra of Q1634 + 267A and B, without any continuum subtraction. We find that both the continuum and the strength of the emission lines of the spectra of A and B are very similar when a constant of proportionality A/B = 3.28 is applied. In Fig. 2, we have plotted the red camera spectrum of Q1634 + 267A, with the scaled spectrum of Q1634 + 267B superposed. We note that there is no evidence for residual flux at any wavelength (aside from the positions of the strong absorption lines which appear in the spectrum of Q1634 + 267A but not in B) in the observed range. In particular, we do not find any evidence for the presence of a possible 20th magnitude galaxy contaminating the spectrum of A, as was found by Turner *et al.* 1988. However, it should be pointed out that our new spectra were obtained using a 1″ slit, whereas those of Turner *et al.* (1988) were obtained with a slit width of 2.5″; the possibility remains that their effective aperture did contain a galaxy, whereas ours did not, although Djorgovski & Spinrad (1984) claimed to rule out any significant ($r<23.5$) lensing galaxy more than 1″ from the QSO images.

Also plotted in Fig. 2 is a similar comparison of the blue spectra of Q1634 + 267A and B; here the overall agreement of Q1634 + 267A and the scaled version of Q1634 + 267B is very good, except for highly significant residuals in the vicinity of the Lyman α + N II, Si IV + O IV], and C IV emission lines. The character of the residuals suggests very real differences in the velocities and/or profile shapes of these lines between the two objects. Thus, we now turn to a detailed comparison of the emission line profiles for the lines within our observed spectral range. Because even a casual inspection of the emission line profiles or of the "difference" spectra in Fig. 2 reveals shifts or profile differences which depend on the particular emission line, we do not consider cross correlation of the spectra to be quite the correct way to proceed; instead, in Fig. 3, we have plotted each emission line profile according to the velocity of the line relative to a fiducial redshift defined by the peak of the C IV λ 1549 emission line in the spectrum of Q1634 + 267A. We measure $z_A = 1.961 \pm 0.001$ on the basis of the C IV line, a redshift in excellent agreement with the value previously determined by Djorgovski & Spinrad (1984). Note that, while the profiles of the C III] λ 1909 line are consistent with no significant difference in either profile shape or velocity (this could have been inferred from the lack of any significant residual feature in the difference spectrum shown in Fig. 2), in agreement with Turner *et al.* (1988), there appear to be velocity shifts which approach 1000 km s^{-1} or even exceed this value in the case of N V λ 1240. A shift of ~ 600 km s^{-1} is evident for the C IV and Lyman α emission lines. While the contrast of the Si IV + O IV] line to the continuum is relatively low, a velocity offset in the same sense [i.e., $z(\mathrm{A}) > z(\mathrm{B})$] appears to be present. We emphasize that these velocity differences *cannot* be ascribed to any instrumental calibration problem, as the spectra were recorded simultaneously and the wavelength calibration was achieved by extracting arc spectra from the same CCD columns as the actual QSO spectra. Moreover, we note that the positions of the absorption lines in the Lyman α forest of Q1634 + 267A and B are coincident in wavelength to within the formal accuracy of our spectra [see, e.g., the feature at a velocity of -3000 km s^{-1} with respect to Lyman α in Fig. 3(a)].

Finally, we note that despite the clear differences in velocity, which appear to depend on the ionization level of the ionic species, the profile *shapes* and the relative intensities of the emission lines and the continuum shapes of Q1634 + 267A and B are remarkably similar. Thus, we favor the interpretation that these objects are indeed gravitationally lensed images of the same QSO; however, the velocity shifts may be telling us something interesting about the structure of the QSO broad line emitting region; we will return to a discussion of this possibility in Sec. 5. We note in passing that the spectra of these objects exhibit a somewhat unusual strength of the high ionization N V and C IV lines relative to Lyman α; at present, we are unable to judge the significance of this fact.

3.2 Q2345+007A,B

Q2345 + 007A,B has received much recent attention in the literature, principally because it is the widest-separation lens candidate and because it represents the "cornerstone" of limits on the sizes of the intervening Lyman α forest clouds based on the work of Foltz *et al.* (1984). Most recently, Nieto *et al.* (1988) have presented evidence that image B is resolved into two components with approximately the orientation expected on the basis of lens models; Weir & Djorgovski (1991) have also found that B is marginally resolved at the $\sim 0.4''$ level, but the position angle of the substructure is not consistent with that found by Nieto *et al.* (1988). Steidel & Sargent (1990) obtained moderate dispersion spectra of Q2345 + 007A,B over the wavelength range 5100–9000 Å, and found that the emission redshifts agree to within 44 ± 40 km s^{-1}, and that the continuum shapes are indistinguishable, but that the emission line intensity ratio C III]/Mg II is significantly different for the two spectra. While Foltz *et al.* (1984) and Nieto *et al.* (1988) concluded that their observations strongly supported the gravitational lens hypothesis, both Steidel & Sargent (1990) and Weir & Djorgovski (1991) tentatively concluded that Q2345 + 007A,B was probably an example of a "binary" QSO. Duncan (1991) has used the statistics of the Lyman α forest lines observed along the two lines of sight to conclude that the odds are 4:1 of the objects being lensed; however, as we shall see in Sec. 4, this argument may no longer be so compelling. Here we reexamine the emission lines and continua of Q2345 + 007A,B (this time over a different range in wavelength) in yet another attempt to resolve the controversy.

In Fig. 4 we have plotted Q2345 + 007A,B after scaling the spectrum of B by a constant factor of 2.51, which was determined by calculating the ratio of the two spectra in spectral regions deemed relatively free of emission lines. This factor is in itself interesting, as the possibility that the brightnesses of the objects are variable has been a subject of controversy; Sol *et al.* (1984) found evidence for variability in the ratio of Q2345 + 007A to Q2345 + 007B, although a rather consistent magnitude difference of ~ 1.4 mag. seemed to have been reproduced several times over the past 10 yr or so (see Steidel & Sargent 1990). On the other hand, Weir & Djorgovski (1991) have summarized all of the known pho-

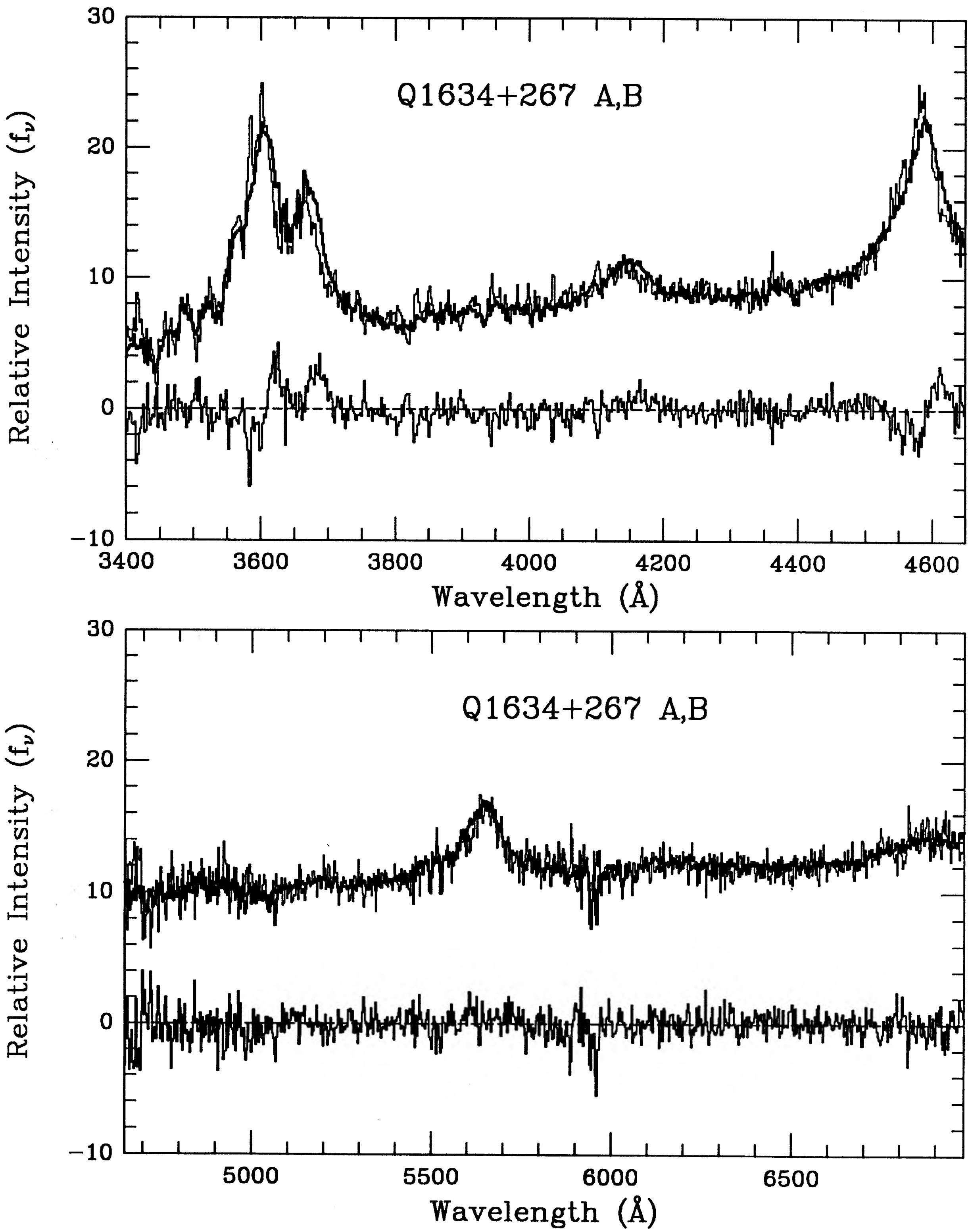


FIG. 2. Plots of Q1634 + 267A,B after the spectrum of B has been multiplied by the factor 3.28. The spectrum of A is drawn with the dark histogram, and that of B with the light histogram. The residual spectrum (A-3.28B) is also shown.

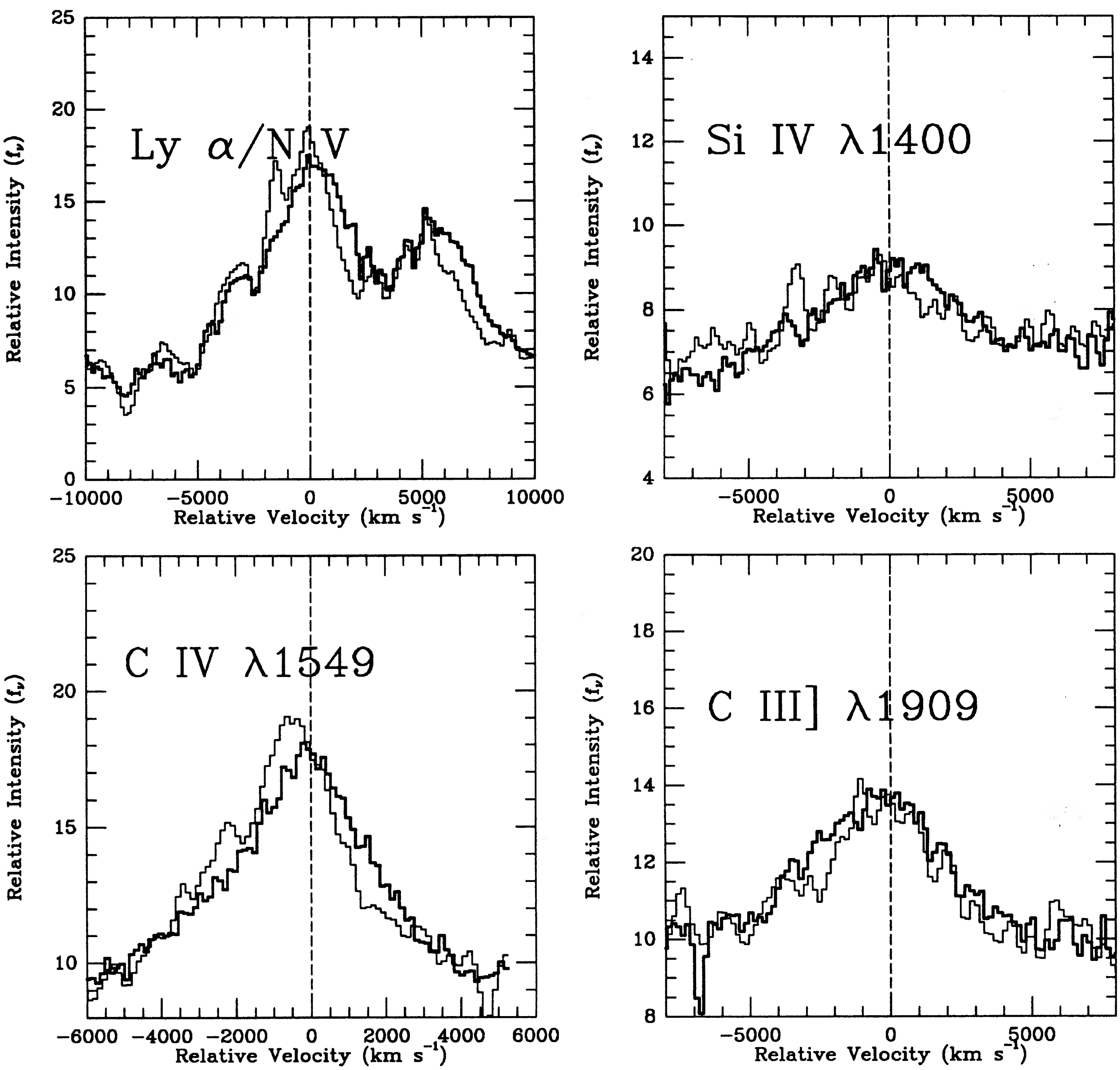


FIG. 3. Plots showing the line profiles of four of the prominent emission lines observed in the spectra of Q1634 + 267A,B. The velocity zero point has been arbitrarily set to the redshift given by the peak of the C IV λ 1549 emission in the spectrum of Q1634 + 267A. The continuum scaling factor of 3.28 has been applied to Q1634 + 267B. In each panel, object A is represented with the dark histogram, and B with the light histogram. Note the substantial redshift of the Lyman α/N V, C IV, and possibly Si IV lines of Q1634 + 267A relative to the same lines in Q1634 + 267B, and the agreement of the C III] profiles (the difference in the C III] profile near -3000 km s^{-1} can be attributed to imperfect subtraction of the λ 5577 night sky feature).

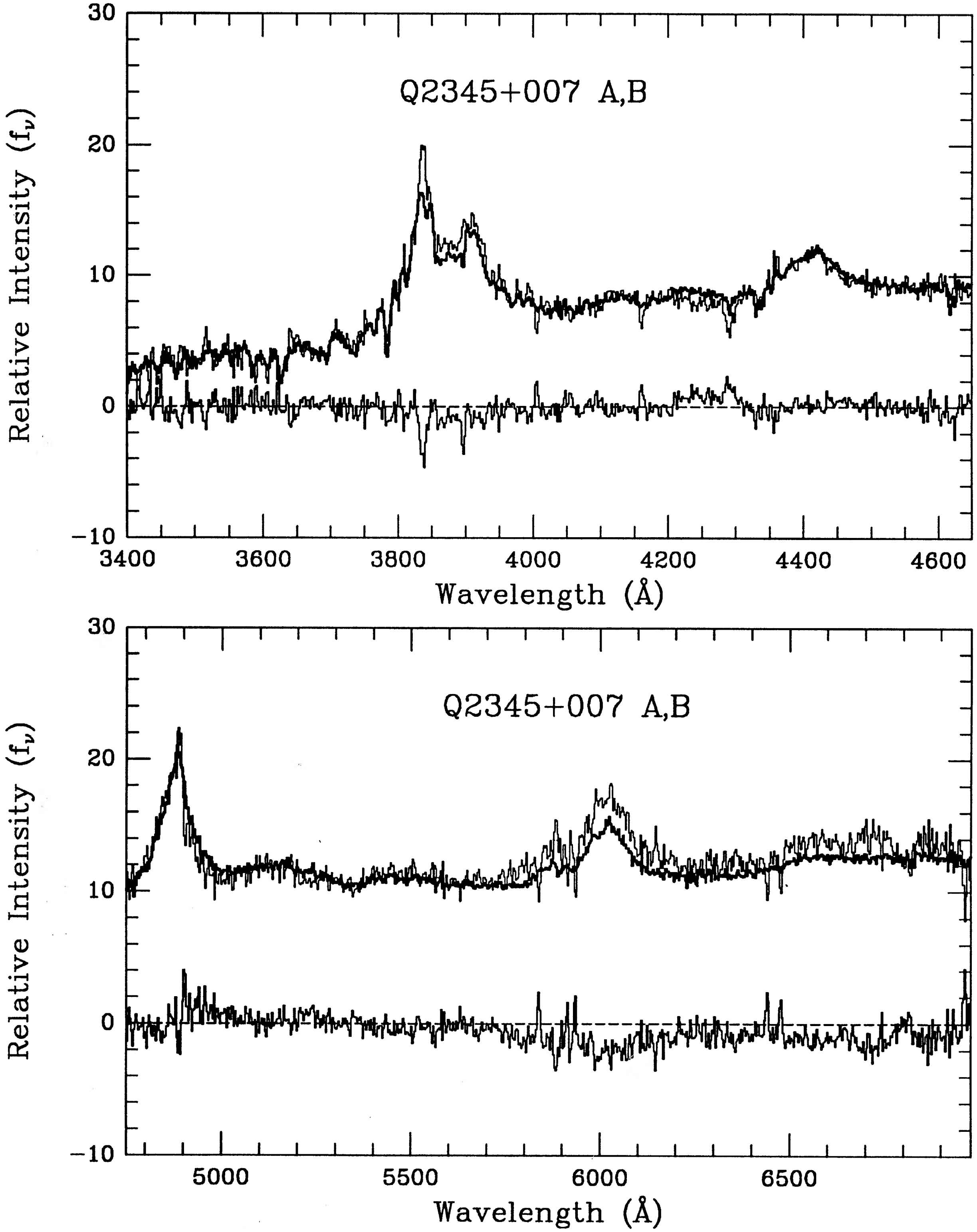


FIG. 4. Same as Fig. 2, for Q2345 + 007A,B. Here the spectrum of B has been scaled by a factor of 2.51.

tometric and spectroscopic measurements of the objects, and have concluded that the ratio is probably variable; they also confirm the results of Tyson *et al.* (1986) that object B is somewhat redder than object A on the basis of broadband relative photometry. They correctly point out the difficulty in interpreting flux ratios determined from spectroscopic measurements using a narrow slit (as was used in Steidel & Sargent 1990 and in the present work); however, one must also use caution in comparing the spectroscopic measurements with broadband measurements because of the placement of emission lines (which were excluded in evaluating the spectroscopic ratio) within each bandpass, since Steidel & Sargent (1990) have shown that the emission line intensities do not necessarily scale with continuum ratio for these objects. For example, the C IV emission line happens to fall near the wavelength corresponding to the peak transmission of the *g* filter, and *r* and *i* include many multiplets of Fe II. Thus, for example, a "redder" image of B may result from larger Fe II equivalent width, and not from an actual difference in continuum shape. In any case, using exactly the same position angle and general instrumental configuration as in 1989 August, we find a continuum ratio (A/B) which is *smaller* by a factor of ~ 1.5 based on the new observations obtained in 1990 July. It is very unlikely that this difference could be ascribed completely to differing observing conditions (despite the difficulties of differential atmospheric refraction discussed in Sec. 2) or small guiding errors (provided that the correct P.A. was used), thus we conclude that the continuum ratio of Q2345 + 007A to Q2345 + 007B is almost certainly variable.

Steidel & Sargent (1990) found that the intensity of the Mg II emission line scaled approximately with the continuum ratio (A/B), but that C III] λ 1909 had a significantly larger equivalent width in the spectrum of Q2345 + 007B than in A. Here we have several additional emission lines for comparison; referring to Fig. 4, we see that Lyman α, N V, C III], and the Fe II multiplets longward of 6300 Å all appear to show residuals which indicate that the line equivalent widths are larger in the spectrum of Q2345 + 007B; however, Si IV + O IV] λ 1400 appears to scale with the continuum ratio, and while the C IV line profiles are similar, there appears to be a hint that the red wing of C IV (and perhaps He II λ 1640) may be stronger in the spectrum of A than in B. In addition, there is a feature in the residuals at $\sim$4225 Å, which corresponds to the position of C II λ 1335 emission at the QSO redshift, and which appears to be stronger in the spectrum of A than in B. On the other hand, the *positions* of the lines, and their general profile shape, agree remarkably well between the two spectra—we have plotted the emission line profiles in velocity relative to the peak of C IV in the spectrum of Q2345 + 007A in Fig. 5. A cross correlation of the blue spectrum of B (excluding the bulk of the Lyman α forest region) using A as a template yields $\Delta v_{\rm B-A} = 15 \pm 20$ km s^{-1}, in agreement with the velocity difference limits set by Steidel & Sargent (1990), but somewhat more stringent. The very close velocity agreement of the two spectra (see Fig. 5 for an enlarged view of the Lyman α/N V region), together with the uncanny qualitative similarity of the profile of, e.g., the Lyman α/N V blend, makes it increasingly difficult to support the hypothesis that the QSO pair is two separate objects (as was suggested by Steidel & Sargent 1990), *despite the irregularities in the emission line intensity ratios.* Therefore, as for Q1634 + 267A and B, we tentatively conclude that the pair is in fact a lens, and thus the details of the rather odd behavior of the emission lines noted by Steidel & Sargent (1990) and in the present work must arise due to phenomena related to the nature of the lensing in combination with the physics of the QSO broad emission line regions.

4. ABSORPTION SYSTEMS

We have measured absorption lines in all of the spectra longward of the Lyman α emission line; because of the relatively low (4 Å) resolution of our spectra, line blending and confusion prohibit accurate quantitative measurement of individual absorption features within the "Lyman α forest." Only those lines exceeding the 4σ significance level[4] as determined from the local signal-to-noise ratio at each position in the spectrum have been retained; these are given in Tables 1 and 2. All wavelengths have been converted to their values in vacuum. Absorption lines were identified, where possible, in the usual fashion. The resolution of the spectra is barely adequate to resolve C IV $\lambda\lambda$ 1548, 1550 doublets; consequently, the separation of a putative C IV feature into two lines was somewhat subjective and thus the wavelengths and relative strengths of the doublet components are correspondingly uncertain. Mg II $\lambda\lambda$ 2796, 2803 doublets would be easily resolved in both the red and the blue spectra. We now turn to a discussion of the detected absorption redshifts.

4.1 Q1634+267A,B

The most prominent absorption system is the rather strong, low-ionization system (containing six identified lines of Mg II and Fe II) at $z = 1.1262$ in the spectrum of Q1634 + 267A. The Mg II doublet was recognized in the lower resolution spectra of Djorgovski & Spinrad (1984) and Turner *et al.* (1988). However, the wavelength and strength of the lines quoted by Djorgovski & Spinrad ($z = 1.118$, observed equivalent width $= 45 \pm 10$ Å) appear to have been seriously in error. The $z = 1.1262$ absorption system is not seen in the spectrum of Q1634 + 267B; if it is indeed present, the Mg II absorption lines must have equivalent widths at least five times smaller than in the spectrum of Q1634 + 267A.

An additional absorption system, which is considerably less secure, is found at $z_{\rm abs} = 1.8389$ in the spectrum of Q1634 + 267A on the basis of a probable C IV doublet. There is some evidence, at about the 2σ significance level, for a corresponding C IV doublet in the spectrum of Q1634 + 267B; if the feature is real, it would have roughly half the strength of the C IV doublet in the spectrum of Q1634 + 267A. It is interesting that, were this feature instead identified as Mg II, it would have roughly the same redshift ($z = 0.57$) as the postulated $R = 20$ galaxy which Turner *et al.* (1988) inferred to be present on the basis of residual red light associated with the spectrum of Q1634 + 267A. However, we consider it very unlikely that the absorption feature can be Mg II, and, as we argued in Sec. 3, there is some question about the reality of the tentative detection of the lensing galaxy by Turner *et al.* (1988) on the basis of residual flux in the spectrum of Q1634 + 267A.

Rather strong interstellar Ca II features at a heliocentric velocity of ~ 120 km s^{-1} are identified in the spectra of both

[4] The only exception to this procedure occurred if, for example, the stronger component or a doublet was detected at the 4σ level; in this case, the second component was included in the line list if it appeared to be present.

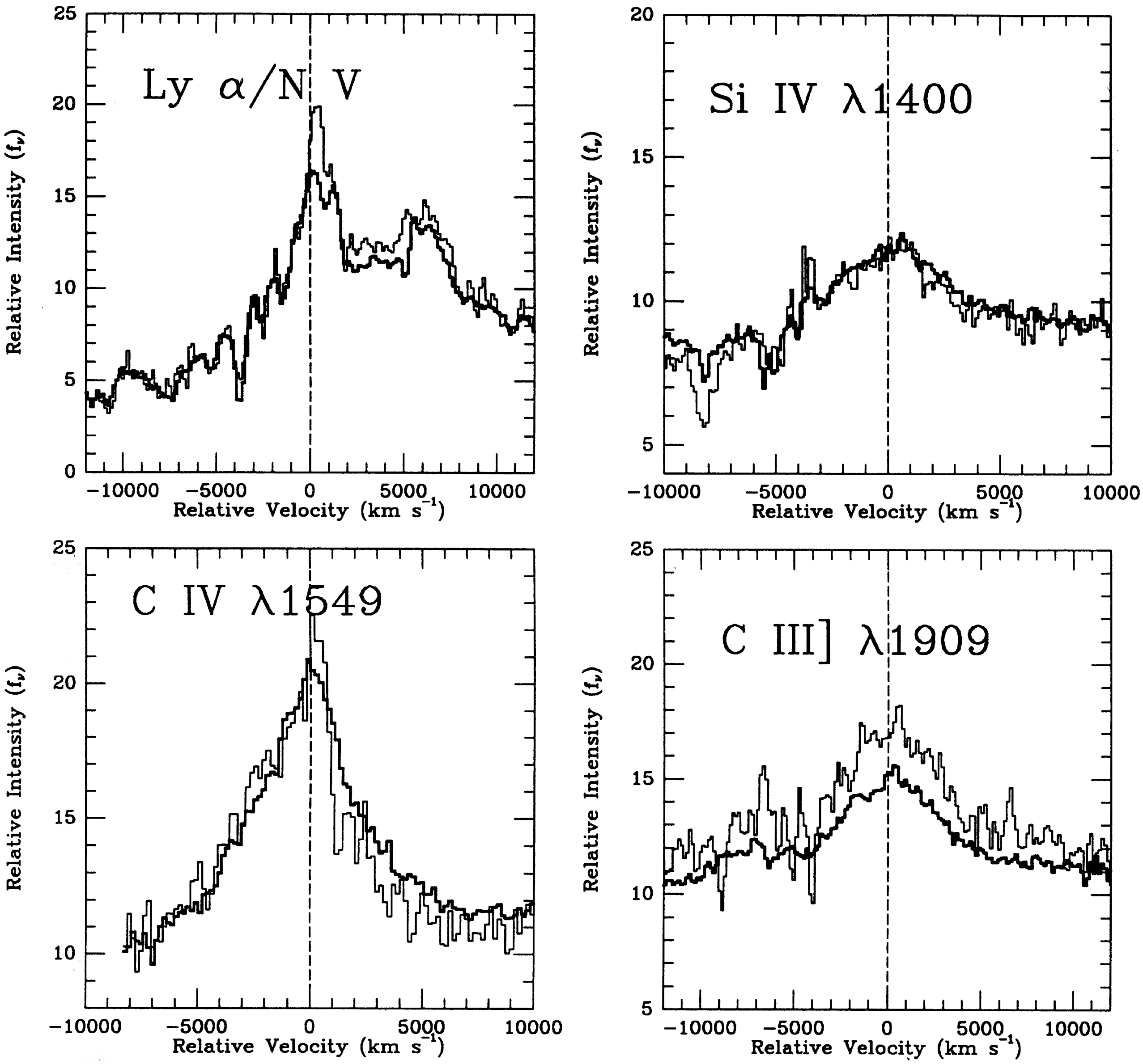


FIG. 5. Same as Fig. 3, for Q2345 + 007A,B. Note the extremely good agreement in the velocities of the Lyman α and N V emission lines.

objects A and B. If these features are real, it suggests the presence of high-velocity Galactic H I gas in the direction of Q1634 + 267A,B. Higher-resolution spectra would be required to confirm this possibility.

4.2 Q2345+007A,B

For the reasons mentioned above, we have not attempted to measure the equivalent widths of individual absorption lines shortward of Lyman α emission in the spectra of Q2345 + 007A,B; however, line lists from much higher-resolution spectra are available for precisely that region from the work of Foltz *et al.* (1984). Thus, in Table 2, we have included the lines listed by these authors (noted as "F84" in column 9) for the regions below Lyman α emission together with the lines measured from our new spectra, and those

TABLE 1. Absorption lines in the spectra of Q1634 + 267A,B.

No.	λ_{obs}	$\sigma(\lambda)$	W_{obs}	$\sigma(W)$	S/N	ID	z_{abs}
				Q1634+267 A			
1	3933.09	0.64	1.31	0.20	26.3	CaII(3934)	-0.0004
2	3967.72	0.64	0.54	0.15	27.2	CaII(3969)	-0.0005
3	4395.71	0.29	0.68	0.11	32.5	CIV(1548)	1.8392
4	4401.85	0.44	0.67	0.12	32.7	CIV(1550)	1.8385
5	5048.65	0.87	1.13	0.28	22.2	FeII(2374)	1.1269
6	5066.52	0.58	1.74	0.28	21.8	FeII(2382)	1.1263
7	5499.29	0.55	1.76	0.22	31.6	FeII(2586)	1.1260
8	5528.35	0.49	1.43	0.19	31.5	FeII(2600)	1.1261
9	5945.67	0.40	3.26	0.28	24.2	MgII(2796)	1.1262
10	5960.89	0.44	2.80	0.27	25.3	MgII(2803)	1.1262
				Q1634+267 B			
1	3819.08	0.72	2.84	0.58	8.5		
2	3932.80	1.01	1.62	0.47	10.6	CaII(3934)	-0.0005

TABLE 2. Absorption lines in the spectra of Q2345 + 007A,B[a].

No.	λ_{obs}	$\sigma(\lambda)$	W_{obs}	$\sigma(W)$	S/N	ID	z_{abs}	
				Q2345+007 A				
1	3482.17	0.25	1.51	0.31	...			F84
2	3513.15	0.11	0.72	0.17	...			F84
3	3587.82	0.11	1.65	0.21	...			F84
4	3609.20	0.30	1.63	0.24	...	OI(1302)	1.7717	F84
5	3627.37	0.15	1.49	0.21	...	HI(1215)	1.9838	F84
6	3629.96	0.15	1.70	0.24	...			F84
7	3684.08	0.30	0.67	0.15	...			F84
8	3724.30	0.30	0.49	0.15	...			F84
9	3732.55	0.26	0.58	0.15	...	CII(1334)	1.7969	F84
10	3735.42	0.29	0.59	0.15	...	CII(1334)	1.7990	F84
11	3740.59	0.32	1.11	0.31	...			F84
12	3784.87	0.10	2.77	0.19	...			F84
13	3789.54	0.16	0.97	0.12	...			F84
14	3798.73	0.13	0.50	0.09	...			F84
15	3814.75	0.20	0.82	0.13	...			F84
16	3818.62	0.22	0.38	0.09	...			F84
17	3843.63	0.29	0.32	0.09	...			F84
18	3856.71	0.20	0.56	0.11	...	CIV(1548)	1.4911	F84
19	3863.25	0.36	0.32	0.10	...	CIV(1550)	1.4912	F84
20	3970.78	0.40	0.66	0.09	51.4			
21	4293.13	0.31	1.14	0.08	64.1	CIV(1549)	1.7715	
22	4330.92	0.21	1.19	0.07	60.1	CIV(1548)	1.7974	
23	4338.89	0.20	1.28	0.08	59.6	CIV(1550)	1.7979	
24	4619.12	0.30	1.16	0.11	40.5	CIV(1548)	1.9835	
25	4625.77	0.32	0.78	0.10	39.3	CIV(1550)	1.9829	
26	6967.03	0.56	1.24	0.16	38.9	MgII(2796)	1.4915	SS90
27	8529.39	1.15	2.08	0.40	21.2			SS90
				Q2345+007 B				
1	3494.03	0.20	1.49	0.35	...	SiII(1260)	1.7721	F84
2	3514.04	0.33	1.10	0.35	...			F84
3	3587.68	0.10	1.56	0.30	...			F84
4	3609.37	0.21	2.14	0.42	...	OI(1302)	1.7718	F84
5	3627.02	0.21	2.18	0.42	...	HI(1215)	1.9836	F84
6	3629.77	0.17	2.69	0.51	...			F84
7	3672.98	0.18	1.09	0.30	...			F84
8	3683.94	0.30	1.09	0.36	...			F84
9	3723.62	0.25	0.89	0.24	...			F84
10	3739.86	0.10	1.32	0.21	...			F84
11	3785.20	0.13	2.30	0.21	...			F84
12	3789.61	0.24	0.37	0.12	...	SiII(1526)	1.4822	F84
13	3799.42	0.70	0.28	...	...			F84
14	3803.14	0.16	1.23	0.17	...	SiII(1526)	1.4911	F84
15	3814.26	0.27	0.31	...	...			F84
16	3818.90	0.30	0.41	...	...			F84
17	3843.80	0.13	1.32	0.14	...	CIV(1548)	1.4828	F84
18	3850.25	0.10	0.74	0.13	...	CIV(1550)	1.4828	F84
19	3857.01	0.37	0.68	0.19	...	CIV(1548)	1.4913	F84
20	3864.19	0.47	0.59	0.17	...	CIV(1550)	1.4918	F84
21	4006.76	0.48	1.65	0.26	17.0	FeII(1608)	1.4911	
22	4162.71	0.43	1.99	0.24	20.8	AlII(1670)	1.4914	
23	4292.36	0.49	4.13	0.31	21.6	CIV(1549)	1.7712	
24	4334.54	0.57	0.70	0.17	24.0	CIV(1548)	1.7997	
25	4342.21	0.48	0.85	0.17	23.6	CIV(1550)	1.8000	
26	4905.90	0.97	1.78	0.39	17.5	MgII(2796)	0.7544	
27	4919.16	0.97	0.84	0.31	17.3	MgII(2803)	0.7546	
28	5838.67	0.90	2.52	0.42	17.6	FeII(2344)	1.4907	
29	5915.02	0.61	1.99	0.34	18.1	FeII(2374)	1.4918	
30	5935.89	0.80	3.35	0.43	18.8	FeII(2382)	1.4912	
31	6442.09	0.84	2.17	0.34	21.9	FeII(2586)	1.4905	
32	6478.48	0.64	2.18	0.31	21.9	FeII(2600)	1.4916	
33	6743.33	0.52	1.18	0.23	23.4			
34	6967.36	0.46	5.66	0.58	10.9	MgII(2796)	1.4916	SS90
35	6983.76	0.62	3.78	0.55	11.5	MgII(2803)	1.4911	SS90

presented previously by Steidel & Sargent (1990) (noted as "SS90" in column 9). In addition to the previously known absorption systems at $z_{abs} = 1.4828$ and 1.4912 (the latter now having at least 12 corroborating line identifications in the spectrum of Q2345 + 007B), we find the following.

$z_{abs} = 0.7545$. We tentatively identify this redshift on the basis of the Mg II doublet apparently present in the spectrum of Q2345 + 007B; the lines only just satisfy our criterion for inclusion in the line list, but the redshift agreement between the two putative components of the doublet is quite good. The corresponding features appear to be absent in the spectrum of Q2345 + 007A.

$z_{abs} = 1.7717$. We identify this system on the basis of complex features which are ascribed to C IV at λ 4292; the feature is about four times stronger in the spectrum of Q2345 + 007B than in the spectrum of Q2345 + 007A. If the identifications are correct, then line #1 in the spectrum of Q2345 + 007B may be Si II λ 1260 at the same redshift, and line #4 in both A and B may be O I λ 1302. There is no evidence for an associated Mg II doublet in the spectrum of either object presented by Steidel & Sargent (1990), although the spectra are rather noisy in the appropriate wavelength range.

$z_{abs} = 1.7977;1.7998$. The C IV doublet is marginally resolved in the spectrum of both A and B although, interestingly, there is an apparent redshift difference amounting to ~ 225 km s^{-1} as measured from the C IV along the two lines of sight. The C IV absorption is also somewhat stronger in the spectrum of A than in B, and lines 9 and 10 in the spectrum of A may be plausibly attributed to C II λ 1334 in this redshift system. Corresponding lines appear to be absent in the spectrum of Q2345 + 007B.

$z_{abs} = 1.9832$. There is a clear C IV doublet in the spectrum of Q2345 + 007A which is not detected in the spectrum of Q2345 + 007B (the upper limit on the strength of a corresponding feature in the spectrum of B is roughly a factor of 2 weaker than in A). However, the Lyman α line is identified from the line list of Foltz *et al.* (1984) in *both* A and B. Clearly, these lines at λ 3627 in both spectra can no longer be considered "Lyman alpha forest" lines, since they appear to be associated with a system containing heavy elements.

Rather importantly, we note that these new heavy element system identifications may "eliminate" several of the lines which were previously identified as "Lyman alpha forest" lines by Foltz *et al.* (1984), and later used by Duncan (1991). In particular, of the four "forest" lines which occurred in one spectrum but (confidently) not in the other on the basis of the Foltz *et al.* data, at least three are probably associated with heavy element systems. The one remaining "forest" line without a counterpart along the other line of sight is line 1 in the spectrum of Q2345 + 007A. We will discuss the implications of this fact in Sec. 5.

5. DISCUSSION AND IMPLICATIONS

5.1 Emission Lines and Lensing

We now consider some possible implications of the gravitational lens interpretations for both of the QSO pairs. If the gravitational lensing hypothesis is correct, there are several possible explanations for differing emission line properties among the separate images: first, there are expected to be substantial time delays for the detection of any intrinsic variability in the QSO. These time delays, due to both geometrical and gravitational effects, depend to a large extent on the redshift of the lens and the detailed mass distribution within the lens; however, for the purposes of the discussion below, we have calculated approximate values of the expected time delays by assuming that in each case the lens can be represented by a point mass appropriate to produce the observed image splitting at the adopted lens redshift. We also assume that the two observed images in each case are discrete images rather than unresolved image pairs. Following Cooke & Kantowski (1975) and Young *et al.* (1980), in the case of Q1634 + 267A,B, taking the observed brightness ratio of $A/B \sim 3$, the expected time delay $\tau_{lens} \approx 1$–2 months if $z_{lens} = 1.12$ and several months if $z_{lens} = 0.57$. For Q2345 + 007A,B, taking $A/B = 3.7$, one expects $\tau_{lens} \approx 9$ months to a year if $z_{lens} = 1.49$ as suggested by Foltz *et al.* (1984) and Tyson *et al.* (1986). We shall discuss in Sec. 5.2.2 the possibility that $z_{lens} = 0.75$ for Q2345 + 007A,B; in this case, τ_{lens} will be *larger* by roughly a factor 2. Thus, modulo the large uncertainties in the lens redshifts and geometries for both systems, the expected lensing time delays are $\sim$ a few months and $\sim$ a year or two for Q1634 + 267A,B and Q2345 + 007A,B, respectively.

As has been seen in the recent results of the spectrophotometric monitoring of relatively nearby AGNs (e.g., Clavel *et al.* 1991), there is a finite time delay between variations in the continuum luminosity and the "response" of the broad emission lines. The actual time delay $\tau_{\rm BLR}$ and the amplitude of the line intensity variations appear to depend upon the ionization level of the ionic species, with the general trend that higher ionization lines respond most rapidly and with the largest amplitude of variation. If one applies the scaling relation with luminosity originally suggested by Davidson & Netzer (1979), $\tau_{\rm BLR} \propto L^{1/2}$, then using the time delays found by Clavel *et al.* (1991) for NGC 5548, one expects the characteristic $\tau_{\rm BLR}$ to be of the order of a year for QSOs of luminosity comparable to Q1634 + 267 and Q2345 + 007. Thus, the expected time lag of the broad emission lines $\tau_{\rm BLR}$ is of the same order as the time delay $\tau_{\rm lens}$ expected for the observation of continuum variations of the source. One can therefore envision a scenario in which these two comparable variability timescales "beat" against one another and conspire to produce a variety of line-to-continuum ratios, with the "phase" being dependent on the lens geometry, cosmology, and the characteristic time lag for the response of an emission line of a particular ionization level.

A second possible explanation for any observed differences in the broad emission line spectra of lensed QSOs may be gravitational microlensing. While microlensing is usually invoked to explain rapid *continuum* variability (see, e.g., Paczynski 1986, Kayser *et al.* 1986), Nemiroff (1988) has argued that microlensing amplification of specific regions of the more spatially extended QSO BLR may result in observable emission line profile differences. While the details of the effect are quite model dependent, Nemiroff has pointed out that microlensing can also slightly change (by up to $\sim$ 500 km s^{-1}) the redshift of an AGN whose BLR is dominated by Keplerian rotation. Clearly, in the case of microlensing, if the BLR is "stratified," then it is likely that the magnitude and character of the effect will depend upon the ionization level of the line. It is thus reasonable to suppose that the strongest (and therefore most easily observable) gravitational microlensing events will affect lines of higher excitation level, which appear to be concentrated closer to the continuum source on the basis of the time lag observations of Clavel *et al.* (1991).

Finally, one knows that lensed images separated by an angle α on the plane of the sky show the QSO as it would appear from directions differing by roughly the same angle at the source. In the case of an extended BLR whose characteristic scale is roughly a light year, each line of sight may be sampling slightly different parts of the extended QSO BLR, so that the observation of subtle differences in the line profiles among the various images may constitute a unique probe of the structure of the BLR (e.g., Kayser *et al.* 1986; de Robertis & Yee 1988). However, this effect is not likely to be important for "macrolensing" by a normal galaxy or cluster, where the angular scale subtended by the BLR will be effectively "unresolved" and small differences in aspect will probably not yield an observable difference in line profiles. Here again microlensing by stars or other compact objects in an intervening galaxy (possibly the lensing galaxy itself) might be invoked to explain observed emission line *profile* differences. Such subtle profile differences have been observed in the case of Q2237 + 0350 lens system (Filippenko 1988), for which direct evidence in favor of microlensing has been observed (Yee 1988; Kent & Falco 1988; Schneider *et al.* 1988). On the other hand, it is unlikely that globally constant multiplicative factors in the emission line intensities (as we observe in the case of Q2345 + 007A,B) can be produced by microlensing events.

Given the possibilities briefly outlined above, we favor the variability explanation in the case of Q2345 + 007A,B, where the emission line profiles and velocities are in excellent agreement in the two images, but where the line intensity ratios depend on the ion. Since there is now considerable evidence for significant continuum variability of the two images, the observed emission line idiosyncracies are reasonably attributed to the convolution of time delays produced by the lens geometry and by the timescale for response to continuum variations of the various emission lines. Unfortunately, at present, the objects are not sampled well enough temporally with *spectrophotometric* observations to untangle the underlying physical situation, and of course despite our conclusion that the objects are probably lensed, no truly satisfactory model of the lensing geometry has been devised, so that many free parameters remain.

The situation for Q1634 + 267A,B is perhaps even less satisfactory. The observed velocity shift of up to $\sim$1000 km s^{-1} for the high ionization lines might have been used to reject the lensing hypothesis out of hand; however, the very close agreement in the continuum and emission line intensities, together with the excellent agreement in the redshifts of lower ionization species such as C III] (Turner *et al.* 1988; this work) and Mg II (Turner *et al.* 1988) have led us to conclude that the objects are very likely to be lensed. The interpretation of velocity shifts remain problematic; the magnitude of the shift is somewhat larger than the range which could plausibly be produced by microlensing of a BLR undergoing Keplerian rotation (Nemiroff 1988). It is now well known that the velocities of the broad emission lines in QSOs can exhibit velocity shifts relative to the narrow lines and low-ionization broad lines (taken to define the "true" redshift of the QSO) which can reach values exceeding 2000 km s^{-1}, with a mean blue shift for C IV of $\sim$ 500 km s^{-1} (Gaskell 1982; Wilkes 1986; Corbin 1990; Espey *et al.* 1989; Steidel & Sargent 1991). The scatter in the observed velocity differences for a sample of QSOs is very large, however, and the mean blueshifts are produced by a "high velocity tail" in the distribution (Steidel & Sargent 1991). Thus, it would not be particularly surprising to find two QSOs whose Mg II and C III] redshifts were the same to within the measurement errors, but whose Lyman α, N V, and C IV redshifts differed by varying amounts up to 1000 km s^{-1}. Under the lensing hypothesis, though, an explanation is required. One possibility is that the effective velocity shifts of the high ionization lines may be *variable*. In general, the uncertainties in the measurements of velocity shifts of the broad lines in QSOs have been large, so that for a given QSO having multiple observations (in all likelihood by different observers using different instruments), actual variations in the shifts might have gone unnoticed. Indeed, Steidel & Sargent (1991) have noted that some of their measurements are highly discrepant (well in excess of the quoted measurement uncertainties) when compared to observations of the same QSOs from other studies. Since the cause of the velocity shifts of the high ionization broad lines is not known, it is difficult to assess the plausibility of variable velocity shifts. One possibility which comes to mind is *anisotropic* continuum radiation, such that different parts of the BLR producing the high ionization lines might be illuminated at a given time, and the lens time delay would result in different line profiles for the two images at a given *observed* time. However, if that were the case it would be difficult to understand why the line intensities should scale with one another, as they appear to for Q1634 + 267A,B.

5.2 *Intervening Absorption Systems*

5.2.1 *Q1634+267A,B*

As discussed in Sec. *4.1*, we have detected only two heavy element absorption systems in these spectra, both along the line of sight to Q1634 + 267A. We do not find any corroborating evidence for the presence of a galaxy with $z = 0.57$ contaminating the spectrum of object A, as was suggested by Turner *et al.* (1988), although we cannot rule it out on the basis of our spectroscopic data. Thus, one still cannot be confident about the redshift of the lensing galaxy in this case. Indeed, the splitting of this lens candidate, 3.77″, is somewhat larger than can easily be produced by a lens consisting of a single galaxy (e.g., Kochanek 1991). Djorgovski & Spinrad (1984) have suggested that the lensing galaxy may be associated with the strong low-ionization absorption system at $z = 1.1262$ in the spectrum of Q1634 + 267A, but we should point out that the lens may not be detected in absorption in either of the QSO spectra; to our knowledge, for cases in which the lensing object has been identified, there has never been any detection of interstellar absorption features at the redshift of the galaxy or cluster in the spectrum of the lensed QSO (cf. Steidel & Sargent 1991). This might be attributed to the fact that galaxies producing image separations which are easily "discoverable" in lens searches tend to be more massive, gas-poor objects.

Q1634 + 267A,B is at sufficiently high redshift that it is useful as a probe of the Lyman α forest clouds. Spectra of much higher resolution than those presented here will be necessary to study the details of the correlations along the two lines of sight; because of the faintness of these objects ($R \sim 19.2$ and 20.4 for A and B, respectively), such a study will probably have to await the availability of 8 m class telescopes. However, we do note that, as expected, the Lyman α forest regions of the two spectra are very similar to the extent that one can see from our present data. If the lensing object is at $z = 1.1252$, then the proper separation of lines of sight to A and B under the lensing hypothesis ranges from 0 to $(6.0,8.4)h^{-1}$ kpc over the wavelength range accessible from the ground (corresponding to redshifts between 1.96 and 1.63). (Here $h = H_0/100$ km s^{-1} Mpc^{-1} and the range in parentheses indicates the effect of variations in the value q_0 between 0 and 1/2.)

5.2.2 *Q2345+007A,B*

As discussed in Sec. *4.2*, the discovery of three, and possibly four, new heavy element redshifts in the spectra of Q2345 + 007A,B may have a significant effect on the interpretation of both the lens system and the implications of the correlations in the Lyman α forest region. For example, both Tyson *et al.* (1986) and Duncan (1991) have proceeded under the hypothesis that the two heavy element redshifts near $z = 1.49$ are associated with the lensing material. One might also seriously consider the possibility that there may be a compact galaxy with $z = 0.7545$ directly under image B, and that perhaps this galaxy is responsible for both the marginally redder color of object B (Tyson *et al.* 1986; Weir & Djorgovski 1991) and the fact that object B has been marginally resolved by two separate groups (Nieto *et al.* 1988; Weir & Djorgovski 1991). We note that the required mass to produce the observed image separation for Q2345 + 007A,B is substantially reduced if the lens is placed at $z = 0.75$; using the isothermal galaxy model of Turner *et al.* (1984), one finds that the requisite velocity dispersion of the lensing mass distribution is reduced from ~ 900 to ~ 500 km s^{-1} when the lens is moved from $z = 1.49$ to 0.75 (although the velocity dispersion is still much larger than that associated with a single galaxy). However, the hypothesis that there is a relatively "poor" cluster [$\sim 30L^*$, assuming that the Faber–Jackson relation (Faber & Jackson 1976) can be applied] along the line of sight to Q2345 + 007A,B at $z = 0.75$ may be more plausible than an extremely massive, "dark" cluster at $z = 1.49$ as suggested by Tyson *et al.* (1986) and Duncan (1991). Moreover, the differential lensing cross section for a QSO with $z_{em} = 2.156$ peaks at $z_{lens} \approx 0.64$ (Turner *et al.* 1984). It is interesting that Tyson *et al.* (1986) noted the possibility of a concentration of "brighter" galaxies in the vicinity of Q2345 + 007A,B on the plane of the sky. It would be important to confirm the reality of the putative Mg II absorption at $z_{abs} = 0.7545$ in the spectrum of Q2345 + 007B, and perhaps to obtain spectra of some of the brighter galaxies ($R \sim 22.5$) in the field.

Despite the very exciting results obtained by Smette *et al.* (1991) on the lower limit on the size of the Lyman α forest clouds using spectra of the confirmed gravitational lens system UM 673 A, B ($z = 2.727$; separation = 2.2″; $z_{lens} = 0.493$; Surdej *et al.* 1988), the pair Q2345 + 007A,B still has the most promising potential to actually *determine* the characteristic size of the forest clouds because of the wide angular separation and the fact that the lens may be at a rather large redshift (so that the separation of the diverging rays is comparatively large and is a strong function of redshift over the redshift range accessible from the ground). Specifically, over the redshift range $z = 1.6$–2.1 which is accessible using both UM 673 A,B and Q2345 + 007A,B, the path separation of the latter pair exceeds that of the former by a factor of ~ 3 if $z_{lens} = 0.75$ and a factor of ~ 10 if $z_{lens} = 1.49$. Steidel & Sargent (1990) considered the possibility that Q2345 + 007A,B were not lensed, in which case the characteristic size of the Lyman α forest clouds would be $\gtrsim 100h^{-1}$ kpc rather than $\gtrsim 10h^{-1}$ kpc as originally suggested by Foltz *et al.* (1984). While we are now convinced that Q2345 + 007A,B is indeed a lens, detailed statistical analyses of the data for both Q2345 + 007A,B (McGill 1990; Duncan 1991) and for UM 673 A, B (Smette *et al.* 1991) suggest that the clouds may in fact be considerably larger than what had become the commonly quoted value of ~ 10 kpc. Because the confidence limits on the sizes depend critically on the relatively few lines which are *not* observed in the spectra of both objects, it is of the utmost importance to remove lines associated with heavy element absorption systems, which may have smaller coherence lengths than the Lyman α forest clouds (or, any heavy element transitions misidentified as Lyman α may be probing very different scales than one is led to believe because the path separation is a strong function of z). As emphasized by Duncan (1991), higher signal-to-noise ratio spectra of Q2345 + 007A,B would be invaluable; however, the one *caveat* which is stressed by the present work is that one must obtain spectra of comparable or even greater sensitivity to the long wavelength side of Lyman α emission so that any heavy element absorption systems may be detected and excluded from the analysis. There may be additional, as yet undiscovered, heavy element absorption systems which "contaminate" the Lyman α forest sample.[5]

Although the present data do not represent an improvement over the data of Foltz *et al.* (1984) in the Lyman α forest region, we are in a position to comment on the implications for the sizes of the heavy element system absorbing regions. In Table 3 we have listed the proper separation in units of h^{-1} kpc (where $h \equiv H_0/100$ km s^{-1} Mpc^{-1}) for the light paths corresponding to Q2345 + 007A and B assuming two different lens redshifts, $z_{\rm lens} = 0.75$ and 1.49. Note that the separation of the light paths at the redshift of the four known heavy element absorption systems with $z > 1.4$ varies by about a factor of 4 depending on the adopted lens redshift. (An expanded plot of the spectral region including the newly discovered C IV absorption from the systems at $z = 1.77$, 1.80, and 1.98 is shown in Fig. 6.) The path separation at $z = 0.75$ does not depend on whether or not the lensing hypothesis is correct, as long as the lens does not have a redshift lower than 0.75; it is not surprising that, with a path separation of $\sim 30h^{-1}$ kpc, the $z = 0.7545$ absorption system is not seen along both lines of sight, as this scale is roughly the same as the typical cross-sectional radius of Mg II absorbing galaxies' gaseous halos at comparable redshift (Bergeron & Boisse 1991), so that the probability of observing no Mg II absorption along sightline A given the observed absorption along sightline B is ~ 0.5.

The statistical implications of the correlations between the C IV absorption systems are made somewhat more difficult to assess by the fact that the spectra of objects A and B do not have the same sensitivity; e.g., the absorption system at $z = 1.77$ is detected along both lines of sight, with the line strength ~ 4 times larger in the spectrum of object B, while we could not have detected the system at $z = 1.98$ in the spectrum of B if it had a strength less than half of the strength observed in the spectrum A (there is some evidence that C IV absorption may be present at this redshift in the spectrum of B, but it is certainly weaker than that in A). On the other hand, the differences in line strength (and, in the cases of the $z_{\rm abs} = 1.77$ and 1.80 systems, differences in kinematics) do indicate that, even if the two sightlines are intersecting the same object (e.g., the halo of the same galaxy), the scale of the finer structure must be significantly smaller than the path separation. If one considers the $z_{\rm abs} = 1.98$ redshift in the spectrum of B and the $z_{\rm abs} = 1.4828$ system in the spectrum of A to be nondetections, then one can make generalizations about the "typical" transverse sizes of the absorbing objects by assuming some geometrical form. McGill (1990) has shown that, for spherical "clouds," the

TABLE 3. Path separation for Q2345 + 007A,B heavy element systems[a].

	$z_{\rm lens} = 0.75$		$z_{\rm lens} = 1.49$		No Lens	
$z_{\rm abs}$	$q_0 = 0.5$	$q_0 = 0$	$q_0 = 0.5$	$q_0 = 0$	$q_0 = 0.5$	$q_0 = 0$
0.75	28.8	34.8	28.8	34.8	28.8	34.8
1.49	7.3	9.2	30.1	42.9	30.1	42.9
1.77	3.5	4.5	14.4	21.0	29.5	44.5
1.80	3.2	4.1	13.0	19.0	29.4	44.6
1.98	1.4	1.8	5.7	8.5	28.9	45.4

a) in units of h^{-1} kpc, where $h = H_0/100$ km s^{-1} Mpc^{-1}

probability of intersecting a cloud along one sightline given that it is intersected along the other is

$$P_h = (2/\pi)[\cos^{-1}\beta - \beta(1-\beta^2)^{1/2}],$$

where β is the ratio of the ray path separation $S_{\rm AB}$ to the cloud diameter D_c. Following McGill (1990), the likelihood function for a given value of the cloud size, D_c, is given by

$$L(D_c) = \Pi_i P_h[\beta(z_i)]\Pi_j\{1 - P_h[\beta(z_j)]\},$$

where the index i corresponds to "hits" and j to "misses." $L(D_c)$ for the various lensing configurations is plotted in Fig. 7. We see that, under the lensing hypothesis, $L(D_c)$ is very strongly dependent on whether or not the $z = 1.98$ system is present in the spectrum of Q2345 + 007B, since $S_{\rm AB}$ is smallest at this redshift. In the case where Q2345 + 007A,B are *not* lensed, then the observed three "hit" and two "miss" configuration suggests that the characteristic sizes of the aggregate C IV absorbing regions is $\sim 100h^{-1}$ kpc. Spectra of higher sensitivity would be crucial to inferring "characteristic" scales of the absorbing regions, and a better spectrum of Q2345 + 007B in the vicinity of the expected position of C IV at $z_{\rm abs} = 1.98$ would alone greatly constrain the likelihood functions in both lensed and nonlensed scenarios.

It is clear that a detailed comparison of the kinematics of the heavy element absorption systems along the lines of sight to Q2345 + 007A,B would be extremely interesting. The fortuitously rich heavy element absorption line spectra of these objects may provide some of the most valuable information on the size and structure of the high-ionization component of the heavy element absorption systems if spectra of high S/N and high dispersion can be obtained.

6. SUMMARY

We have obtained high S/N spectra of two candidate gravitational lens pairs, Q1634 + 267A,B and Q2345 + 007A,B, over the wavelength range 3100–7000 Å at 4–6 Å resolution in order to compare the emission line, continuum, and absorption line properties. We find the following principal results.

(1) The continuum shapes of Q1634 + 267A,B over the observed wavelength range agree remarkably well, and a constant multiplicative factor of 3.28 is found for the ratio A/B over the whole observed wavelength range. We do not confirm the "excess" flux associated with object A which has been attributed to an $R \sim 20$ galaxy at $z \sim 0.57$ by Turner *et al.* (1988). However, because of the difference in effective spectroscopic aperture used by us and by Turner *et al.* (1988), such a galaxy would have to have a centroid more than 1″ from that of Q1634 + 267A, and this appears to have been ruled out by Djorgovski & Spinrad (1984).

(2) In agreement with previous investigations by Turner

[5] We have performed a preliminary statistical analysis of the Lyman α forest in the spectra of Q2345 + 007A,B after removing the lines which are probably associated with the newly discovered heavy element systems. This sample has 11 lines in common, and one which is not in common, to the two lines of sight. Using methods outlined by McGill (1990), and described later in this section, we find maximum likelihood values of the cloud diameters to be $\sim 43h^{-1}$ kpc if $z_{\rm lens} = 1.49$ and $\sim 11h^{-1}$ kpc if $z_{\rm lens} = 0.75$ ($q_0 = 0.5$); clouds which are considerably larger or slightly smaller cannot be ruled out, and the numbers represent conservative lower limits if the one line which is not in common turns out to be associated with a presently undetected heavy element system. The inferred values are consistent with those found by Smette *et al.* (1991).

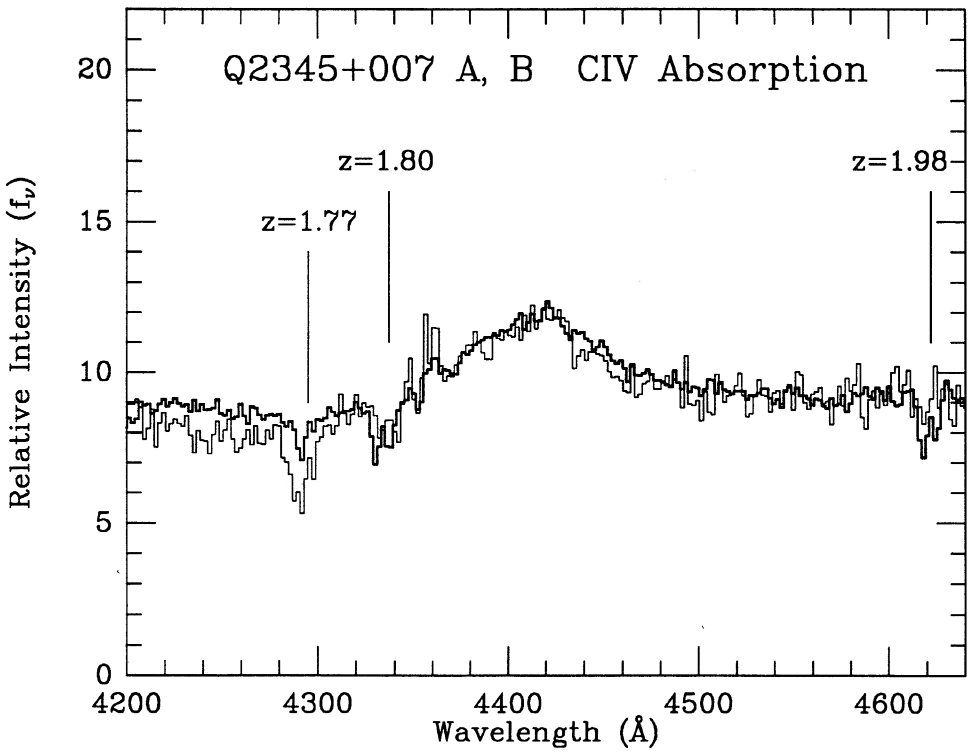


FIG. 6. An expanded view of the spectral region containing the C IV features associated with the newly identified heavy element systems at $z_{abs} = 1.77$, 1.80, and 1.98. The spectrum of Q2345 + 007A is represented with the dark histogram, and Q2345 + 007B with the light histogram. The spectrum of B has been multiplied by a factor of 2.51. Note the difference in velocity width and line strength in the $z_{abs} = 1.77$ system, and the velocity shift of ~ 250 km s^{-1} between the two sightlines in the $z_{abs} = 1.80$ system. The noise spikes near 4360 Å are due to imperfect subtraction of the λ 4358 line of Hg in the night sky.

et al. (1988) and Djorgovski & Spinrad (1984), we find that the redshifts of the C III] λ 1909 emission line are consistent with zero relative velocity shift and that the line profiles in the two images are identical. However, suitably scaled difference spectra reveal differences in the redshifts or line profiles of the Ly α + N V blend, the Si IV + O IV] blend, and the C IV emission line between Q1634 + 267A and B. The shift between A and B amounts to ~ 1000 km s^{-1} in the case of N V and is about 600 km s^{-1} for C IV and Ly α, always in the sense that $z(\mathrm{A}) > z(\mathrm{B})$. The low contrast S IV + O IV] blend has the same qualitative behavior.

(3) Apart from these velocity differences, the strengths and shapes of the emission lines are remarkably similar in the two images.

(4) The continua of Q2345 + 007A and B match tolerably well over the whole observed wavelength range if a constant scaling factor A/B = 2.51 is used. This ratio is significantly smaller by a factor of about 1.5 than that measured a year earlier by Steidel & Sargent (1990), adding to the growing evidence in the literature that the intensity ratio A/B varies with time.

(5) Scaled difference spectra show that the Ly α, N V, C III] and Fe II emission lines are stronger relative to the continuum in Q2345 + 007B than in A, adding to the differences in line strength which led Steidel & Sargent (1990) to conclude that the two images are not a result of gravitational lensing. However, the redshifts and general profile shapes of the emission lines are remarkably similar in the two images; the velocity difference $\Delta v_{B-A} = 15 \pm 20$ km s^{-1} is very small.

(6) In view of the above facts, we are driven to the conclusion that the pairs of images constituting Q1623 + 267A and B and Q2345 + 007A and B both result from gravitational lensing. Accordingly, the equivalent width differences observed in the spectra of Q2345 + 007A and B and the remarkable redshift differences observed in several of the emission lines in Q1634 + 267A and B must be due to the slight difference in aspect presented by the QSO in the two light paths, to microlensing, or to temporal variations in the QSO spectrum (coupled with the convolution of the gravitational lens time delay and the time delay for the "response" of the various emission lines to continuum variations). We discussed all three possibilities and favor the hypothesis that the redshifts and/or equivalent widths of the individual emission lines in QSO spectra vary with time. *We predict that a program to monitor a suitable sample of single QSOs over a period of a few years would result in the discovery of large temporal variations in the relative redshifts of the emission lines produced by different ions.* To the best of our knowledge, this has not been done for a sample of *luminous* QSOs.

(7) Confirming the earlier work of Djorgovski & Spinrad (1984), the spectrum of Q1634 + 267A contains a strong Mg II and Fe II absorption system at $z_{abs} = 1.1262$ which must be at least five times weaker in the spectrum of

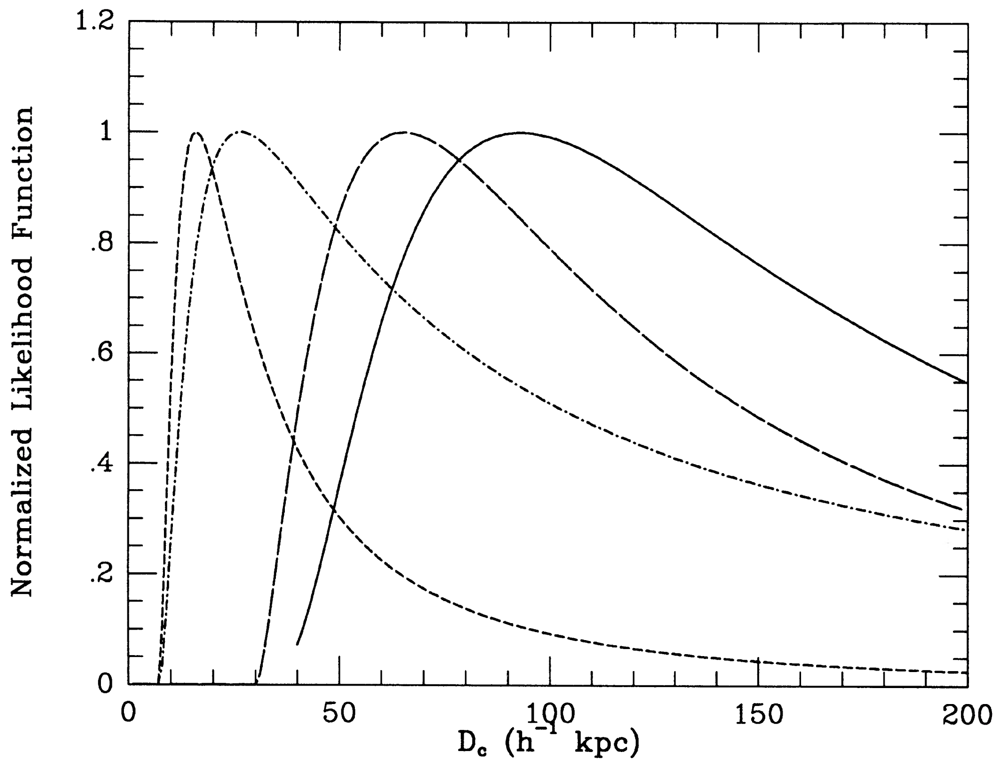


FIG. 7. Plot showing the normalized likelihood function $L(D_c)$ obtained from observations of five C IV selected heavy element absorption systems in the redshift range $1.48 \leqslant z_{abs} \leqslant 1.98$ under various assumed lensing configurations for Q2345 + 007A,B. The likelihood function reflects the relative probability for various sizes of the aggregate absorbing regions, assuming that the population of C IV absorbers can be represented by a characteristic size D_c. The solid curve is for the no-lensing case; the long-dashed curve obtains for $z_{lens} = 1.49$, the short-dashed curve for $z_{lens} = 0.75$, and the dot-dash curve shows how the likelihood function would be altered for the $z_{lens} = 0.75$ case if the $z_{abs} = 1.98$ system were detected in the spectrum of Q2345 + 007B. All curves assume $q_0 = 0.5$ (taking $q_0 = 0$ increases the cloud size by $\sim 40\%$, on average). See Sec. *5.2.2* of the text for discussion.

Q1634 + 267B. An additional, less secure, system is observed at $z_{abs} = 1.8389$ in the A component, but again not in B. Despite the high galactic latitude of Q1634 + 267, high velocity interstellar Ca II features are observed in the spectra of both A and B.

(8) Earlier work had led to the identification of two absorption redshifts, with $z_{abs} = 1.4828$ and 1.4912, in the spectra of Q2345 + 007A and B. We have identified four new redshifts in the present paper—$z_{abs} = 0.7545$ (in B only), 1.7717 (four times stronger in B than A), $z_{abs} = 1.7977$ (A) and 1.7998 (B) (slightly stronger in A, but there is a velocity shift of ~ 225 km s^{-1} between A and B), and 1.9832 (observed in A and not in B). The Lyman α or heavy element lines associated with the three newly discovered high redshift systems can account for three out of the four "Lyman α forest" lines which were found *not* to be common to the two images by Foltz *et al.* (1984).

(9) The redshift at $z_{abs} = 0.7545$ may arise in the lensing galaxy (or galaxy associated with a lens), which has so far eluded direct identification. The elongation and slightly redder color of the B image of Q2345 + 007 may be due to such a galaxy.

(10) Our conclusion that Q2345 + 007A,B are in fact gravitationally lensed images nullifies the argument given by Steidel & Sargent (1990) in favor of bloated Lyman α clouds ~ 100 kpc in diameter rather than the ~ 10 kpc clouds which have been assumed since the original observations of Q2345 + 007A,B by Foltz *et al.* (1984). However, our new results have increased the *proportion* of Lyman α forest lines common to the two images, leading to an increase in the estimated cloud size. A preliminary statistical analysis of the remaining forest lines yields maximum likelihood cloud diameters of $\sim 43h^{-1}$ kpc for $z_{lens} = 1.49$ and $\sim 11h^{-1}$ kpc for $z_{lens} = 0.75$ ($q_0 = 0.5$), although considerably larger or slightly smaller clouds cannot be ruled out. Both values are consistent with the recent work by Smette *et al.* (1991) for the Lyman α forest in the gravitational lens system UM 673 A,B.

(11) Our new spectra add considerably to a growing body of evidence that the heavy element redshifts exhibit less similarity in closely separated lines of sight than the Lyman α forest lines (although the size of the *aggregate* heavy element absorbing regions may be comparable to or larger than those of the Lyman α forest absorbers). Accordingly, the observations of absorption lines in the spectra of gravitationally lensed pairs of QSOs reinforce the hypothesis that the heavy element redshifts and the Lyman α forest have different physical properties and arise in different kinds of objects.

(12) The unusually rich heavy element absorption line spectra of Q2345 + 007A,B provide an excellent opportuni-

ty for a study of the detailed kinematics and structure of the heavy element absorbing entities if spectra of higher resolution and sensitivity can be obtained.

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