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DISCOVERY OF A NEW GRAVITATIONAL LENS[1]

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ABSTRACT

The faint QSO pair 1635+267 A+B, discovered in a slitless spectroscopy survey by Weedman, are found to be at practically the same redshift, $z = 1.961 \pm 0.003$. Their redshift difference, determined with a cross-correlation technique, is found to be $(3.2 \pm 8.5) \times 10^{-4}$, corresponding to a rest-frame velocity difference of only (33 ± 86) km s^{-1}. This low value and the similarity of the spectra strongly argue that this is another case of a gravitational lens. Our deep CCD images do not reveal the presence of a lensing object down to a red magnitude of 23.5, if it is more than an arc second away from either QSO image. An absorption feature in the spectrum of the brighter QSO image may be a signature of the lens galaxy. We interpret this line as the Mg II λ2799 doublet, seen at the redshift $z_{\rm lens} = 1.118$.

Subject headings: gravitation — quasars — spectrophotometry

I. INTRODUCTION

The phenomenon of gravitational lensing provides one of a few nonlocal tests for the distribution of matter in the universe and is of some importance for the evolution of QSOs. So far, there have been only three lens systems reported (Walsh, Carswell, and Weymann 1979; Weymann *et al.* 1979; Weedman *et al.* 1982). The first one was a subject of very intensive study (e.g., Young *et al.* 1980, 1981). The third one may not be a lens at all, but rather a pair of QSOs with similar redshifts. Numerous authors have considered gravitational lensing in the context of cosmological evolution of QSOs and have made quantitative predictions for the surface density of lensed QSOs (Turner 1980; Tyson 1981, 1983; Avni 1981; Peacock 1982). Extensive modeling of the phenomenon has been performed by Bourassa and Kantowski (1976), Dyer and Roeder (1980), and others. A very good review of this topic is given by Peacock (1983). Turner (1983) reviews the "cosmological uses" of the gravitational lenses. According to the number-count predictions of some of the authors cited above, it is not improbable that another lens may be found at about 20th magnitude. (While this *Letter* was in the refereeing stage, we learned about the discovery of another gravitational lens by Lawrence *et al.* 1983).

II. INITIAL OBSERVATIONS

The QSO pair 1635+267 A+B was discovered in a slitless spectroscopy survey by Weedman and found to be radio-quiet (Sramek and Weedman 1978). Exact coordinates and the finding chart are given by Sramek and Weedman. As quoted by these authors, the slitless spectra suggested somewhat different redshifts. We observed this pair hoping to find the QSOs indeed to be at slightly different redshifts, thus signifying an extremely distant possible cluster.

We obtained the CCD spectroscopic and imaging data with the Miller-Robinson-Stover CCD system (Miller 1983) at the Lick 3 m telescope, on the night of 1983 June 14 UT. Because of instrumental problems, the data were not very good, and the fainter QSO (B) was poorly detected. The stacked calibrated spectrum for the brighter QSO (A) is shown in Figure 1. The total exposure time was 5600 s. The two prominent emission lines have a wavelength ratio of 1.234 ± 0.005. We interpret them as C IV λ1549 and C III] λ1909 at $z = 1.96$, in agreement with the interpretation of the slitless spectrum by Weedman. Other line combinations corresponding to that ratio seem less likely (on account of strength) and would require the presence of other lines which we did not observe.

Imaging data were obtained on the nights of 1983 June 10, 13, and 14, and July 6 UT. A total of eight exposures of 300 s each were obtained. A subset of those data is shown in Figure 2. The bandpass is defined by the TI CCD response, a sky-suppressing red filter, and the telescope optics; it has $\lambda_{\rm eff} = 6500$ Å and a width of about 1400 Å. We have interpolated the flattened CCD frames to half the original pixel size (from 0''.71 to 0''.355) and registered and stacked them together. Aperture photometry was performed on the QSO images by using the frame of the flux standard Feige 92 as a calibrator (Stone 1977). In this bandpass, we obtain the magnitudes 19.15 (A) and 20.75 (B) for the QSO images. Their separation is found to be

$$\Delta\delta_{\rm A-B} = -3''.72, \qquad \Delta\alpha_{\rm A-B} = 0''.63.$$

III. FURTHER OBSERVATIONS AND REDSHIFTS

Much higher quality CCD spectra were obtained on the nights of 1983 October 7 and 8 UT with the CRYOCAM spectrograph (De Veny 1983) on the Kitt Peak 4 m telescope.

[1]Based in part on observations done at Lick Observatory, University of California.

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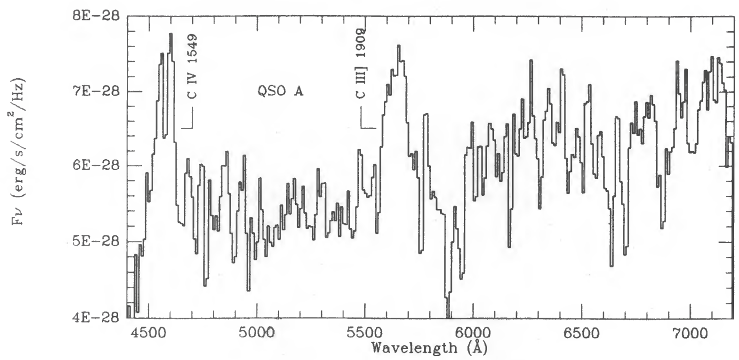

FIG. 1.—The spectrum of the 1635+267 A, obtained at Lick. The proposed line identifications are shown. The spectrum has been rebinned to 10 Å bins.

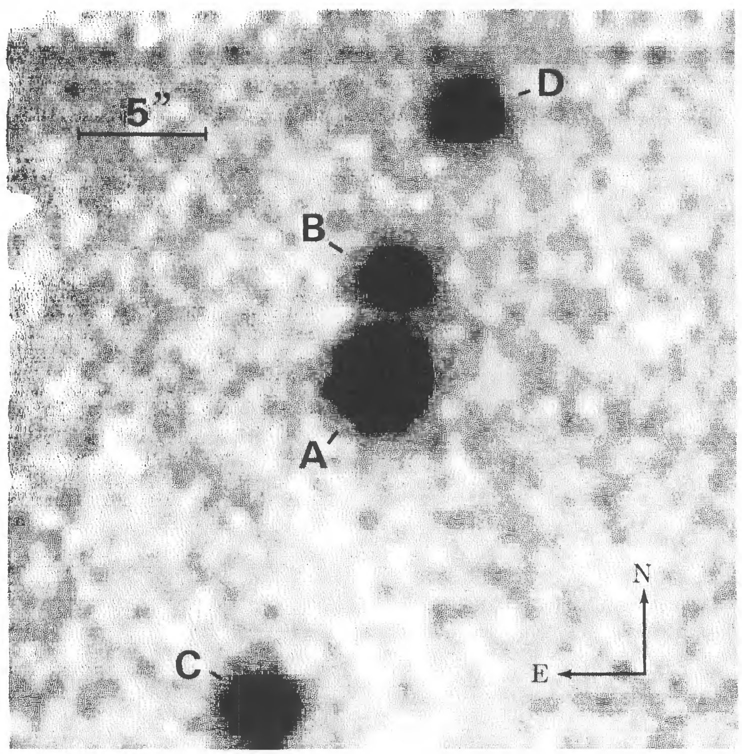

FIG. 2.—A stack of six distinct CCD images of the 1635+267 A+B, with a total exposure 1800 s. Objects C and D are galactic stars.

Two exposures of 2000 s each were obtained, at high hour angles ($\sim 4^{\rm h}20^{\rm m}$). The first exposure had the spectrograph slit oriented at PA = 0°, and the second one at PA = 160°, in order to catch the objects which we have denoted as C and D in Figure 2. They have turned out to be foreground galactic stars. The spectra were reduced with the procedure described by Djorgovski and Spinrad (1983), using Kopff 27 as a flux standard (Stone 1977). The calibrated spectra are shown in Figure 3. Note the possible presence of a third emission line, C II] λ2326.

In order to obtain the redshift, we have performed a Gaussian derivative kernel centering on the line assumed to be λ1909. This method was chosen as more suitable than line peak fitting for the broad lines. It consists of convolving the part of the spectrum containing a line with an optimal sigma Gaussian derivative function and searching for the zero value in the new array. We obtain

$$z_{\rm QSO\ A,1909} = 1.961 \pm 0.003 .$$

The error bar was determined from the difference of measurements for the two independent exposures and is dominated by the wavelength-scale zero-point error. This is caused by mechanical shifts within the spectrograph at large observing hour angles.

A more precise technique was employed in order to obtain the redshift difference, viz., the cross-correlation method, described in detail by Tonry and Davis (1979). Here we have used the spectrum of the brighter QSO image (A) as a template for the fainter one (B). We find that the results are not

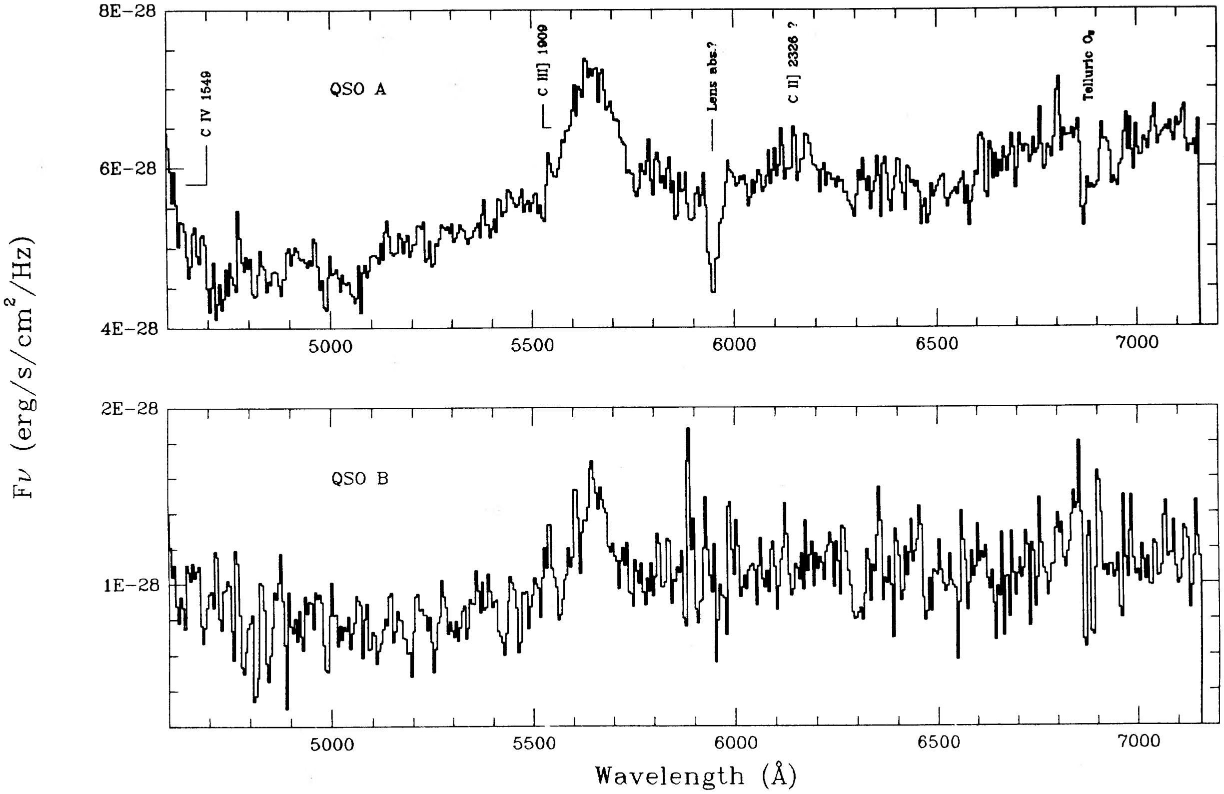

FIG. 3.—Spectra of the QSO images A (*upper*) and B (*lower*), obtained at Kitt Peak. Notice their similarity in shape. The spectra have been rebinned to 5 Å bins before the stacking.

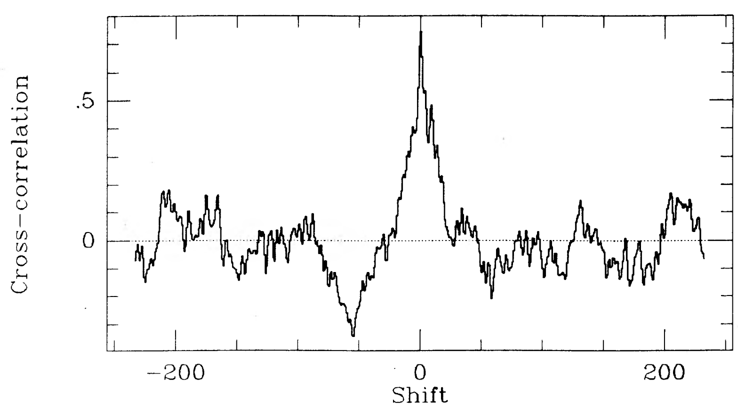

FIG. 4.—The cross-correlation function for the QSO B spectrum, with the QSO A spectrum as a template. One bin shift in the abscissa corresponds to the wavelength shift of 5 Å.

very sensitive to the particular bandpass filter used. The cross-correlation, shown in Figure 4, has a very prominent and unambiguous peak at the zero-shift bin. From a parabolic least squares centering to the central seven bins, we obtain

$$\Delta z_{\mathrm{B-A}} = (3.2 \pm 8.5) \times 10^{-4},$$

which corresponds to a rest-frame velocity shift of

$$\Delta v_{\mathrm{rf,\,B-A}} = (33 \pm 86) \text{ km s}^{-1},$$

or about 1.9 Å in the wavelength. This is well within our resolution limits (~ 15 Å); we have 5 Å pixels and an approximately 1 Å rms wavelength error in each spectrum. In order to test whether the cross-correlation is influenced by the telluric features in the red (*B*-band, etc.), we performed the cross-correlation on the sections of spectra containing λ1909 and λ2326 lines and avoided the telluric absorption features. We then obtained an even better redshift agreement, $\Delta z = (1.4 \pm 3) \times 10^{-4}$. Another question is whether the sky emission-line subtraction glitches will influence the cross-correlation? Their extent is less than about 4 pixels, and at the corresponding Fourier frequencies the cross-correlation power spectrum is some four orders of magnitude lower than at the low frequencies; thus, they are not likely to influence the cross-correlation much.

The velocity width of the λ1909 line appears smaller in the QSO B spectrum than in that of QSO A. This is likely caused by the imperfect sky subtraction in the λ5577 line, which is troublesome enough when the QSO images are this close on the sky. When the spectra are divided, or rescaled and subtracted, there is no obvious velocity residual above the noise level. We estimate the velocity width difference to be some 20%, with the estimated error at least as large.

Considering all of the above, we conclude that this is most likely a case of a gravitational lens and not a physically distinct pair of QSOs. There is, however, a small chance that this is a physical pair (or a cluster?) at high redshift, but we think that very unlikely.

IV. SEARCH FOR THE LENSING OBJECT

The stack-frame of all our direct CCD exposures was processed by a maximum entropy algorithm in order to enhance the tentative lensing galaxy (cluster?) image. Nothing was found between the QSO images, or in their immediate vicinity, down to the limit of our data (~ 23.5 mag in our bandpass). An attempt was made to subtract each QSO image from the other, appropriately scaled; again, no close neighbor was found down to our noise limit. There is also no trace of a tentative tertiary image (Dyer and Roeder 1980; Burke 1981). Let us point out, however, that the effective seeing FWHM for our stack image is 3″, i.e., the seeing was not very good. Thus, we conclude that the lensing object and a possible tertiary image are likely to be at subarcsec separation from one of the QSO images (probably the more amplified one, A), or very dim, or both. The lensing object may well be beyond $z = 1$ itself.

There is a very curious absorption feature in the spectrum of QSO image A at λ5930 (Fig. 3). It seems to be real (it is present in both exposures and not associated in position with any CCD defect). The wavelength does not correspond to any plausible spectroscopic feature at the QSO redshift. This feature may be due to a blueshifted cloud near the QSO, but the absence of strong absorption in the QSO B spectrum argues against this hypothesis. We believe that this line may be due to the lensing galaxy itself. The choice of plausible interpretations is not very large: it should be a strong permitted transition with λ_{rf} between 2000 Å and 5900 Å, and with a redshift such that no other strong absorption lines should be seen in our observed wavelength range. We think that the most likely candidate is the blended Mg II λ2799 doublet, seen at $z = 1.118$. This redshift is then consistent with the dimness of the lens galaxy and places it at a favorable geometrical position for strong lensing. The observed equivalent width of this feature is (45 ± 10) Å, which for our interpretation corresponds to a rest-frame equivalent width of about 20 Å. This is somewhat higher than the values for this blend typically observed in the QSO foreground absorption systems (~ 5 Å; see, e.g., Wolfe and Wills 1977), but still is plausible. If this interpretation is correct, there should be detectable absorption due to C IV λ1549 at 3280 Å and Ca II H and K lines at 8400 Å.

Imaging with finer pixels and in better seeing conditions will be necessary in order to improve the situation. Since there are strong upper limits to the radio flux from this object, it is unlikely that radio mapping will be of much help.

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