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DISCOVERY OF A THIRD GRAVITATIONAL LENS

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ABSTRACT

The two components of a quasar pair of separation 7''.3, discovered in a low-dispersion spectroscopic survey with the Canada-France-Hawaii telescope, were observed with the Multiple Mirror telescope and found to have redshifts of 2.152 and 2.147, with uncertainties of ±0.005. This pair, with approximate magnitudes of 19.5 and 21, is interpreted as the third known example of gravitational lensing. It is emphasized that survey techniques such as that used to discover this pair have found over 1000 quasars, and we are puzzled as to why pairs with smaller separations have not been found in this way.

Subject headings: gravitation — quasars

I. INTRODUCTION

Unlike so many other discoveries in astrophysics during the last two decades, gravitational lenses were predicted and theoretically explored long before any examples were actually found. Not until 1979 was the first convincing gravitational lens candidate reported (Walsh, Carswell, and Weymann 1979), but a year later a second case was found (Weymann *et al.* 1980). Subsequent observational and theoretical work strongly support the gravitational lens interpretation of these objects (e.g., Young *et al.* 1981*a*, 1981*b*). Although suggestions have been made that gravitational splitting might be operating in other cases (Paczyński and Gorski 1981), we regard the two cases above as being the only convincing cases of gravitationally split images to date. This is curious in light of several systematic searches in the optical (K. Hege, private communication) and radio (R. Perley and E. Turner, private communication) which, as far as we are aware, have not yielded further convincing candidates for lenses.

We report here the discovery of a third example of a multiple image that we interpret as being formed by a gravitational lens.

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[2]The research reported here is partly based on data acquired at the Multiple Mirror Telescope Observatory, a joint facility of the Smithsonian Institution and the University of Arizona.

II. OBSERVATIONS

The objects in question are shown in Figure 1 (Plate L1) from the blue print of the Palomar Observatory Sky Survey (POSS). The objects are very blue, if blue and red prints are compared. Coordinates were measured on POSS plates, and the positions are given in Table 1. The separation of the quasar image pair is 7''.3. This pair was discovered by one of us (D. W. W.) on a plate obtained 1981 August 2 with the 3.6 m Canada-France-Hawaii telescope on Mauna Kea. At the prime focus of this telescope, spectra of all objects in a field 45' in diameter can be obtained using a transmission grating replicated on the flat surface of the last lens of the wide-field corrector. This "grens" system requires that the lens be prismatic to correct the coma of the grating. The grens used was designed by E. H. Richardson to produce a nominal dispersion of 2000 Å mm^{-1}. As the plate scale is 13''.9 mm^{-1}, a 1'' seeing disk corresponds to a spectral resolution of about 150 Å. About 20 quasars were found by noting emission lines in the spectra on each plate obtained with good seeing conditions (1'' to 1''.5) with a limiting continuum magnitude of about 21. The close pair was found as two spectra of substantially different intensities but both having a single emission line at the same wavelength to within measurement uncertainties. The discovery images are shown in Figure 2 (Plate L1). The objects were estimated to be of magnitudes 20 and 21. On this plate, the full width of the spectra perpendicular to the direction of dispersion is 1''.2, indicating the seeing quality. The wavelength of the emission feature in each spectrum was determined from the displacement of the feature from the zero-order image, applying a dis-

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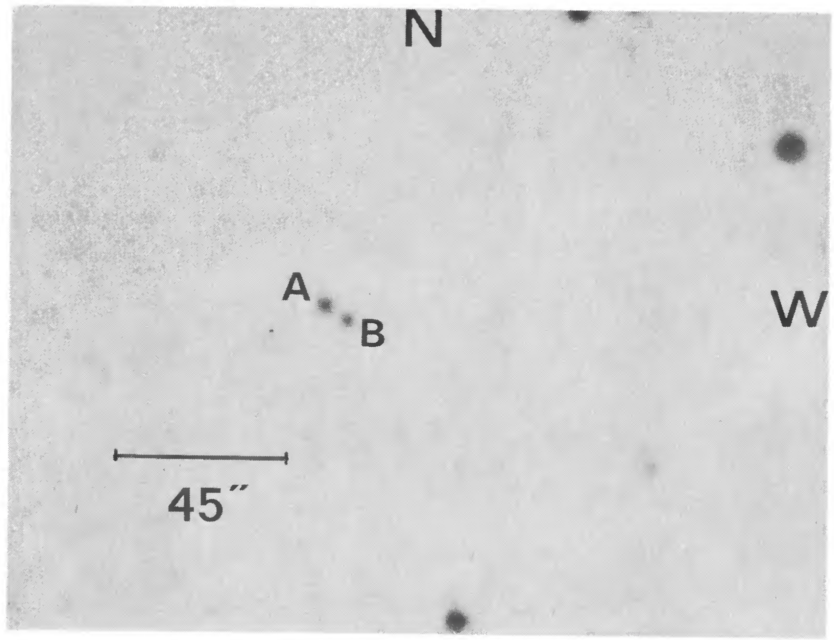

FIG. 1

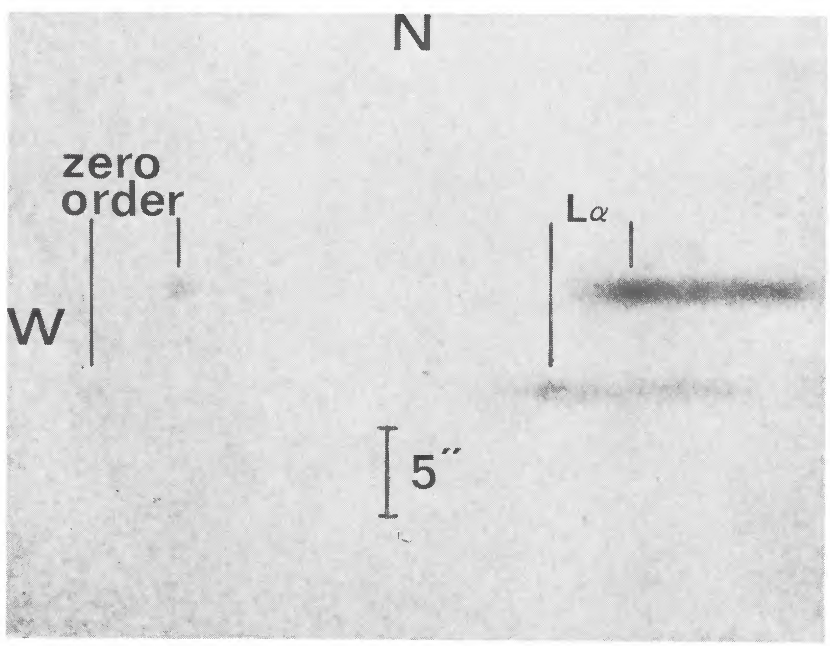

FIG. 2

FIG. 1.—Finding chart for the quasar pair 2345+007 AB from the blue print of the Palomar Observatory Sky Survey

FIG. 2.—Discovery spectra of 2345+007AB from a 60 minute exposure on IIIa-J emulsion, baked in forming gas, with the Canada-France-Hawaii 3.6 m telescope.

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persion determined by measuring known features in a quasar of known redshift on another plate obtained during the run. The dispersion measured in this way is 2120 ± 30 Å mm^{-1}, and the wavelength of the emission feature is 3940 ± 105 Å. The feature is resolved, appearing about 400 Å wide at zero line intensity, so its centroid was difficult to measure precisely.

A confirmation plate of this pair was obtained 1981 September 3 with the 4 m telescope at Kitt Peak National Observatory, using the "grism"—a transmission grating on a prism placed in front of the prime-focus plate (Hoag 1976). Seeing was good, and these spectra also had full widths perpendicular to the dispersion of 1″.2. Neither image was as conspicuous as on the CFHT plate, although both were confirmed. The wavelength of the emission feature was measured to be 3940 ± 80 Å, consistent with that from the CFHT plate.

The pair of objects was then observed at the Arizona-Smithsonian Astrophysical Observatory Multiple Mirror Telescope (MMT) on 1981 October 30 and 31 with the photon-counting Reticon system. A $2'' \times 3''$ aperture was used with a grating giving a resolution (FWHM) of 10 Å and covering the region from approximately 4200 Å to approximately 7200 Å. The seeing was approximately 2″, and because of the wide separation there is no significant contamination of the faint object by the brighter one. The two spectra are shown in Figure 3. The spectrum of the brighter object represents 80 minutes of integration, and that of the fainter companion represents 2 hr shortward of 6100 Å, and 1 hr longward. Due to the relatively small apertures used, together with the fact that blind offsetting was used to observe the fainter object, we obtained neither a reliable instrumental response function nor reliable absolute fluxes and, hence, plot only raw counts. We estimate the monochromatic magnitude at 5200 Å for the brighter object to be 19.5 ± 0.5. The observed ratio of the two fluxes at this wavelength is 1.7 ± 0.2 mag, subject again to an unknown error associated with the blind offset to the fainter object.

One strong and two weak emission lines are present in both objects, and both the wavelengths and character of the line profiles are the same to within the observational error. The measured wavelengths and the proposed identifications are presented in Table 2 and lead to an emission-line redshift of 2.15. The predicted position of Lyα is then 3830 Å, which is to be identified with the emission feature seen on the grism plate. It is also apparent from inspection of Figure 3 that the equivalent widths are systematically much stronger in the fainter object. This is borne out by the measured equivalent widths also presented in Table 2. Although the night-sky subtraction is imperfect, the residual in the night-sky lines is only a very small fraction of the original strength, so we believe that the measured equivalent width differences are real. When the spectrum of the brighter object is divided by the fainter one, the division shows no systematic color difference. Thus, if an underlying galaxy were diluting the brighter object (which appears stellar on the POSS glass copies), it would have to be as blue as the QSO continuum. We think this is unlikely and therefore are inclined to attribute the equivalent width difference to intrinsic variation in the continuum and time delay between the two images. If this interpretation is correct, the ratio of equivalent widths in the two objects should be the same, assuming the flux ratios and continuum colors do not vary. This appears to be the case for the Si IV + O IV/C IV ratio, but the C III] is too faint in component B to check in this way. (We thank J. Liebert for suggesting this test.)

In addition to the emission features, an apparent absorption feature appears in both channels of the brighter object at a wavelength of 4720 Å $\pm$ 10 Å. It is probably to be identified with C IV, yielding a redshift of 2.047, but higher resolution spectra are required. Suggestions of the same feature appear in some scans of the fainter object, but better signal to noise is required to establish its presence.

TABLE 1

POSS COORDINATES FOR 2345+007

Object	Right Ascension (1950)	Declination (1950)
2345+007A (bright) ...	23ʰ45ᵐ45ˢ.90	+00°40′40″.4
2345+007B (faint)	23 45 45.49	+00 40 36.5

III. DISCUSSION

Neither the intrinsic properties of the QSO nor the brightness ratio of the two images is especially remarkable, although the images are fainter and the redshift higher than in the two previously known lensed quasars. Before the discovery of this object, models of the distribution of angular separations in multiple images predicted that many small (0″.5–2″.0) separations should be found, given that two cases with splitting $\gtrsim$ 2″.0 are known (Turner 1980; Turner, Gott, and Ostriker 1982). The separation of 7″.3 for this third object contrasted with the lack of pairs found with significantly smaller separations is, therefore, of considerable interest. Consequently, we conclude with comments on the statistics and selection effects involved in the survey technique which led to the discovery of this object. Low-dispersion spectroscopic survey techniques are well suited to searching optically for quasar pairs with the same spectra, because quasar candidates are chosen from their spectroscopic appearance rather than simply color. To date, such surveys have been carried out either with objective prisms on Schmidt telescopes or with transmission gratings on large telescopes (see Smith

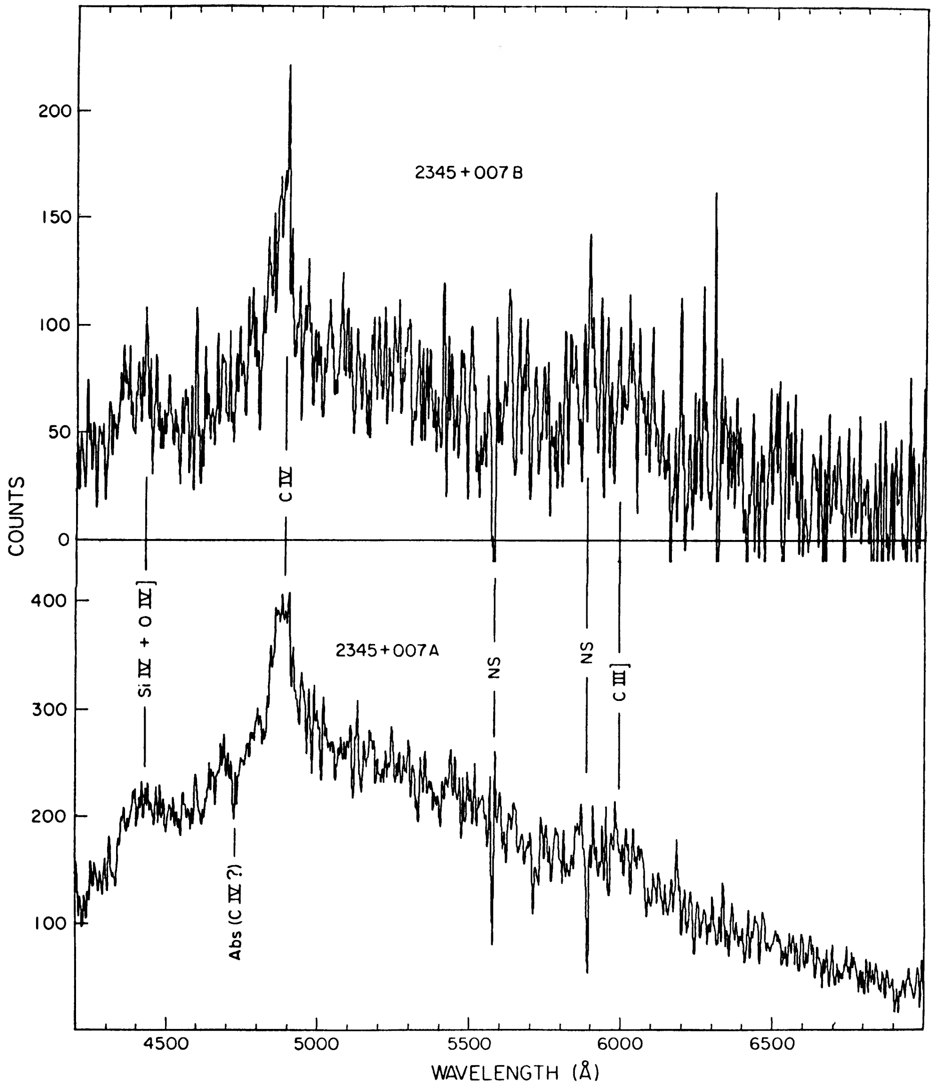

FIG. 3.—Spectra of 2345+007A (*bottom*) and 2345+007B (*top*) obtained with the MMT. Three identified emission lines are marked as well as a real absorption feature and two incompletely subtracted night-sky features.

1978 and Vaucher and Weedman 1980 for summaries). About 500 quasars have been published from Schmidt surveys (Osmer and Smith 1980; Lewis, MacAlpine, and Weedman 1979; Savage and Bolton 1979), and we know that a few hundred more are known but not published (private communications from C. Hazard, G. MacAlpine, N. Sanduleak, and data of D. W. W.). Another 307 quasars have been reported from surveys with the 4 m telescopes (Hoag and Smith 1977; Sramek and Weedman 1978; Hoag *et al.* 1977; Bohuski and Weedman 1979), and there are between 100 and 200 unpublished (private communications from A. Hoag, D. Wills, and data of D. W. W.). With the addition of the CFHT to this survey capability, about 200 more quasars have been found recently (private communications from P. Véron, J. Hutchings, and data of D. W. W.). All in all, substantially more than 1000 quasars discovered by spectroscopic survey techniques are certainly known. But except for the pair described in the present paper, only one other pair has been reported from these surveys with the properties expected for a lensed quasar. This is a faint pair of separation 5″ and with apparently similar redshifts (KP 1634.9+26.7AB) as seen on a 4 m grism plate (Sramek and Weedman 1978), but this pair has not yet been confirmed to have identical spectra.

As these surveys provide one of the best ways available for determining the fraction of quasars that are detectable as lensed, we point out here some observational constraints for the survey techniques now in use. The Schmidt surveys register recognizable quasar spec-

TABLE 2

LINE IDENTIFICATIONS, REDSHIFTS, AND STRENGTHS IN 2345+007

	2345+007A (bright)			2345+007B (faint)			
LINE	λ_{obs}	Redshift	EW_{obs} (Å)	λ_{obs}	Redshift	EW_{obs} (Å)	NOTES[a]
Lyα 1216	3940 ± 90	2.24 ± 0.08	...	3940 ± 90	2.24 ± 0.08	...	1
Si IV + O IV 1400	4406 ± 8	2.143 ± 0.006	36 ± 16	4399 ± 19	2.142 ± 0.014	90 ± 17	2
C IV 1549	4883 ± 1.5	2.152 ± 0.001	39 ± 19	4874 ± 11	2.147 ± 0.007	93 ± 30	...
C IV 1549	4720 ± 10	2.047 ± 0.006	...	...	...	...	3
C III 1909	5989 ± 26	2.137 ± 0.014	47 ± 10	5974 ± 26	2.129 ± 0.014	200:	...
Weighted mean emission redshift		2.152 ± 0.005			2.147 ± 0.005		

[a](1) Estimated wavelength, from grens and grism spectra.
(2) Mean wavelength for Si IV + O IV blend from Young, Sargent, and Boksenberg 1981.
(3) Absorption feature. Identification is not certain.

tra to continuum magnitudes of 18.5–19.5, depending on the telescope used and the features searched for in the spectra (Osmer and Smith 1980; Lewis, MacAlpine, and Weedman 1979; Savage and Bolton 1979). Surveys with larger telescopes can detect quasars to continuum magnitudes of 21, although the limit depends strongly on seeing. Because of the plate scale of the Schmidt surveys, the plates obtained with objective prisms have spectral images with full widths perpendicular to the dispersion direction of $2.''5$–$3.''0$ even in the best seeing conditions, and plates worse than this are generally not used for quasar surveys. Objects that are diffuse or extended, even only slightly, stand out in contrast to the starlike objects that produce the great majority of spectra on the plates. Double images would be confidently recognizable as having identical spectra only if the spectra were not blended. This constraint means that the Schmidt surveys would not find candidates for lensed pairs if the separations are $\lesssim 3'' \sin\theta$, where θ is the acute angle between the direction of dispersion and the line connecting the image pair, such that $0° \leq \theta \leq 90°$. For pairs with equal distributions over all position angles, therefore, the Schmidt surveys miss, because of blending, a fraction f_m given by $f_m \approx [\sin^{-1}(3''s^{-1})]\,90^{-1}$, where s is the pair separation in seconds of arc. For separations $3'' \lesssim s \lesssim 4.''2$, this says that more than half the pairs would be missed, and 20% would be missed even for separations of 10″. For grism and grens surveys with large telescopes, the width of a spectrum depends primarily on seeing. As most quasars are found on plates with the best seeing, the minimum separation in practice for recognizing unblended spectra is $\lesssim 1.''5$. The fraction of quasars missed because of blending would then be $f_m \approx [\sin^{-1}(1.''5\ s^{-1})]\,90^{-1}$, which exceeds 50% only for $s < 2.''1$. For separations $2'' \leq s \leq 7''$, this selection effect does not strongly favor wider pairs, $f_m(2'')$ to $f_m(7'')$ ranging only from 54% to 14%, so we are less than twice as likely to find a pair of separation 7″ as one with a separation of 2″. We emphasize, therefore, that the pair reported here does not have a separation of $7.''3$ because such a value is highly favored by the discovery technique. We should have been able to recognize, without great loss of efficiency, image pairs with separations down to about 2″.

We encourage users of these low-dispersion spectroscopic survey techniques to examine quasar candidates carefully in search of double images. For the pair reported in this *Letter*, the obvious next step is to obtain deep direct exposures in search of the deflector.

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