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EVIDENCE FOR Mg II λ2798 PROFILE DIFFERENCES IN THE GRAVITATIONALLY LENSED QSO 2237+0305A, B[1]

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ABSTRACT

Long-slit near-infrared CCD spectra of the gravitational lens system 2237+0305 confirm that at least three of the four starlike images in the central region of the $z = 0.0394$ galaxy are QSOs with redshift 1.696 ± 0.001. The high-quality Mg II λ2798 data for components A and B yield a relative velocity definitely smaller than 150 km s^{-1}, and possibly $\lesssim 50$ km s^{-1}. There are, however, slight differences in the Mg II *profiles* of A and B. The intrinsic variability time scale of typical QSOs is much longer than the maximum relative time delay between A and B. Hence, the most likely explanation is that the two images sample different portions of the QSO's broad-line region.

Subject headings: gravitational lenses — quasars

I. INTRODUCTION

Several years ago Huchra *et al.* (1985) discovered a most unusual candidate gravitational lens system: the spectrum of the nucleus of the relatively nearby spiral galaxy 2237+0305 ($z = 0.0394$) looked like that of a high-redshift QSO ($z = 1.695$). Since the probability of finding such a bright QSO ($m_B \approx 16.8$, $M_B \approx -28.5$; $H_0 = 100$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$) within 0\".3 of the center of a $m_{pg} = 15.2$ mag galaxy is very small, they concluded that gravitational lensing caused the QSO's brightness to be magnified significantly (e.g., by a factor of 40). However, only a single image of the QSO was visible at optical wavelengths at a resolution of 2\".

Burbidge (1985) and Arp (1987) questioned the gravitational lens interpretation. They argued that the probability of a chance superposition is so low that the QSO and the galaxy are more likely to be at the same distance, and physically associated with one another. CCD images obtained by Tyson (1986; see also Tyson and Gorenstein 1985), on the other hand, showed that at least two starlike objects are present near the nucleus of the galaxy; this strengthened the gravitational lens interpretation. More recently, Yee (1988) and Schneider *et al.* (1988) obtained CCD images of even higher quality. It is now quite clear, particularly from Yee's (1988) data, that *four* starlike images are arranged in a crosslike pattern around the galactic nucleus of 2237+0305. In addition, Yee (1988) demonstrated that a single underlying spectrum modified by unequal amounts of interstellar extinction can account for the different colors of the four components. Finally, theoretical lens models constructed by Schneider *et al.* (1988), as well as by Kent and Falco (1988), easily account for their relative separations and the approximate brightness differences.

Despite the strong evidence against it in this case, the possibility of noncosmological redshifts cannot be fully rejected until the starlike images are shown to have identical redshifts. De Robertis and Yee (1988) accomplished this by obtaining spectra of C III] λ1909; at least three of the four components do indeed exhibit a broad emission line at the same wavelength and with essentially the same profile. To remove any remaining doubts about the gravitational lens interpretation, and to search for possible differences among the line profiles in the separate components, I recently obtained long-slit near-infrared CCD spectra of the system. The results are discussed in this *Letter*.

II. OBSERVATIONS

Data were obtained in photometric conditions on 1988 October 3 UT, with the "UV Schmidt" spectrograph (Miller and Stone 1987) at the Cassegrain focus of the 3 m Shane reflector at Lick Observatory. A TI three-phase 800 × 800 pixel^2 CCD was used as a detector. The atmospheric seeing (full width at half-maximum; FWHM) was 0\".7–0\".8, judging from the ease with which at least three, and sometimes all four, of the QSO images were visible on the TV acquisition screen.

A grating having 300 grooves mm^{-1} and blazed near 7500 Å was used in conjunction with an OG570 filter to cover the wavelength range 6830–10050 Å. The resolution (FWHM) was 10–14 Å, being close to 12 Å near Mg II λ2798. The slit of length 2\'.2 and width 0\".7 was oriented at a position angle of 160°, through components A and B in the notation of Yee (1988) and Schneider *et al.* (1988). A 45 minute exposure was begun at 6:08 UT, just 10 minutes before 2237+0305 crossed the meridian (air mass 1.2). The parallactic angle corresponding to the midpoint of the exposure was 185°, 25° from the actual angle, so that differential light losses caused by atmospheric dispersion should be minimal over the observed wavelength range (Filippenko 1982). A 1 hr exposure at a position angle of 245° (components C and D) was begun at 7:48 UT, but by this time the seeing had degraded to $\gtrsim 1$\", making the spectrum less useful than the first one.

Figure 1 shows a spatial cut (i.e., along the slit) through the first two-dimensional spectrum at the expected wavelength of Mg II λ2798 in the QSO. Each pixel corresponds to 0\".66 on the sky. Components A and B are clearly separated in this cut, especially when the underlying galaxy continuum is subtracted. Owing to the brightness of the underlying galaxy, the two QSO images were not clearly resolved in spatial cuts at continuum wavelengths. Comparison with the CCD images published by Yee (1988), however, shows that the intensity profile was definitely broader than that of the galaxy alone.

It appears in Figure 1 that component B is slightly brighter

[1] Based on observations obtained at Lick Observatory, which is owned and operated by the University of California.

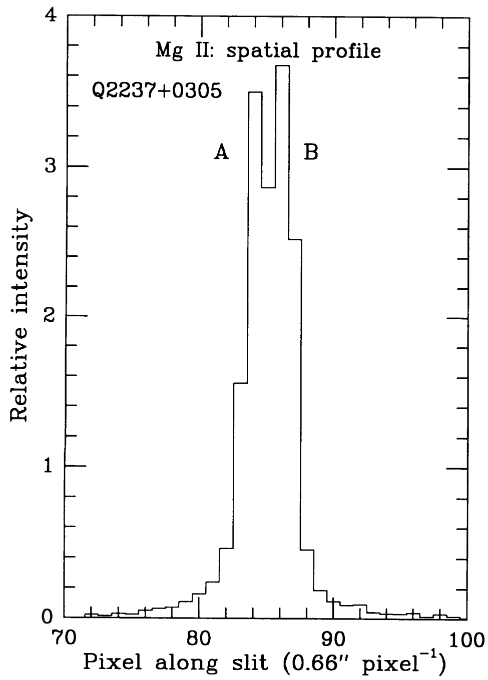

FIG. 1.—Spatial profile of Q2237+0305A, B in a spectral region centered on the Mg II λ2798 emission line. The galaxy continuum has not been subtracted.

than A, in agreement with the image decomposition of Schneider *et al.* (1988; red image obtained on 1986 September 28). Note, on the other hand, that Yee (1988; red image obtained on 1987 September 25) finds A to be slightly brighter than B. This provides very marginal evidence for variability of the components, perhaps due to microlensing by stars in the bulge of the spiral galaxy. I emphasize, though, that the brightness difference in Figure 1 cannot be taken too seriously; the images were quite undersampled with the large pixel scale, and the QSOs may not have been perfectly centered in the narrow slit.

III. THE SPECTRA

Bias levels were subtracted from both two-dimensional frames, and the results were flattened with spectra of the dome ceiling illuminated by a quartz lamp. When extracting the one-dimensional spectra, background sky was determined by summing regions along the slit 12–30 pixels away from the center of the galaxy. Cosmic rays were excised from the relevant portions of all data. A slight tilt of the dispersed light with respect to the CCD columns was taken into account by fitting a polynomial through the centroid of the flux in all 800 CCD rows. The wavelength scale was established with an exposure of a Ne-He-Ar lamp. The standard star HD 19445 (Oke and Gunn 1983) was used to calibrate the instrumental response, as well as to remove (by division) all atmospheric absorption lines in the near-infrared region (see, for example, Wade and Horne 1988). This division was not of perfect quality, since a relatively wide slit (2") was used during observations of the standard star.

An overall one-dimensional spectrum was obtained from each of the two two-dimensional spectra by summing light from the central 8 pixels. The average of these is illustrated in Figure 2. The flux scale is only approximate, since the slit was very narrow, and both the seeing and slit width were different during observations of the standard star. As expected from the spectral appearance at shorter wavelengths (Huchra *et al.* 1985), broad (FWHM ≈ 2600 km s^{-1}) Mg II λ2798 with a measured redshift of 1.696 is prominent. No other strong, broad lines should appear in this wavelength range. Low-frequency undulations in the continuum are likely to be caused partly by Fe II emission lines in the QSO, and partly by absorption bands from late-type stars in the superposed galaxy. A weak line at ~9226 Å may be [Ne V] λ3426 at the redshift of the QSO, but the very narrow emission line near 7316 Å is unidentified. The presence of [O II] λ3727 cannot be ascertained because its expected position, 10048 Å, corresponds to the last pixel in the spectrum.

Spectra of the individual QSO candidates were obtained by careful extraction from portions of the two-dimensional data that minimize image overlap. Specifically, the spectrum of image A was formed by summing pixels 82, 83, half of 81, and half of 84 in Figure 1; that of image B includes pixels 87, 88, half of 86, and half of 89. Thus, the central pixel (85) was excluded from the analysis, and the immediately adjacent pixels (84, 86) were given half weight. As above, the tilt of the two-dimensional spectrum was eliminated by use of the appropriate polynomial. It is possible that components C and D

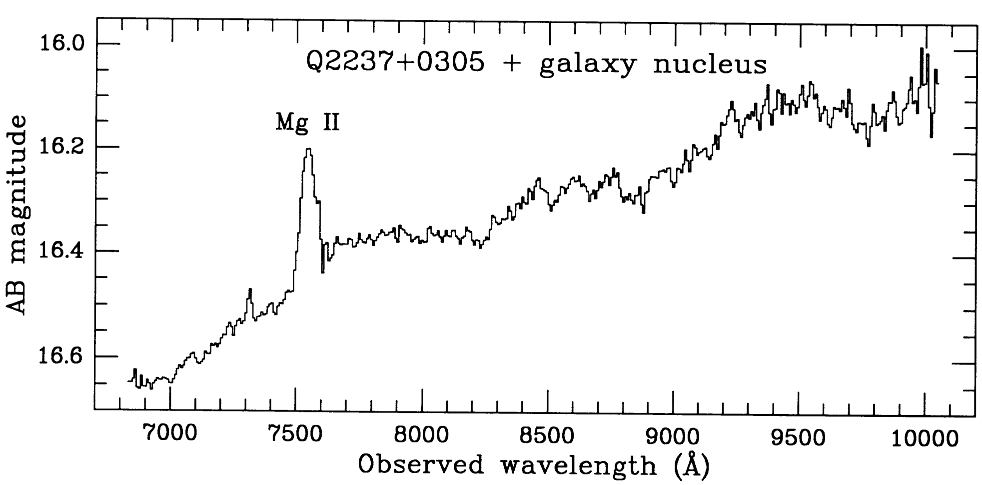

FIG. 2.—Near-infrared spectrum of Q2237+0305, representing a composite of the galaxy nucleus and of QSO components A, B, C, and D. The magnitude scale is only approximate. AB mag = $-2.5 \log f_\nu - 48.6$ (Oke and Gunn 1983), with f_ν measured in ergs s^{-1} cm^{-2} Hz^{-1}. Each bin is 8 Å wide.

contribute to the derived spectra of A and B, but the contamination does not seriously affect the results. The two-dimensional spectrum of C and D, on the other hand, must have included a greater contribution from A and B, due to the geometry of the configuration and to the noticeably inferior seeing. Since component C was observed to be at its expected location in the two-dimensional data, rather than at the expected locations of components A and B, scattered light from A and B did not dominate. The spectrum of C could therefore be isolated reasonably well, but that of D could not.

Figure 3 illustrates a portion of the extracted spectra of components A and B, both before and after removal of atmospheric absorption bands (in this case mainly the A band, caused by O_2). A Gaussian smoothing function with FWHM = 8 Å, smaller than the spectral resolution ($\sim$12 Å), has been applied. Spectra (*a*) and (*b*) are of A and B, respectively, prior to division by the standard star. The two spectra are superposed in (*c*). Similarly, spectra (*d*) and (*e*) are of A and B, respectively, after division by the standard star, and the two are superposed in (*f*). It is clear that a broad Mg II λ2798 emission line at the same redshift, $z = 1.696 \pm 0.001$, is present in both components. The line is also visible in the spectrum of component C, which is not shown. This confirms the conclusion of De Robertis and Yee (1988), made with spectra of lower signal-to-noise ratio, that at least three of the four starlike images are QSOs of the same redshift.

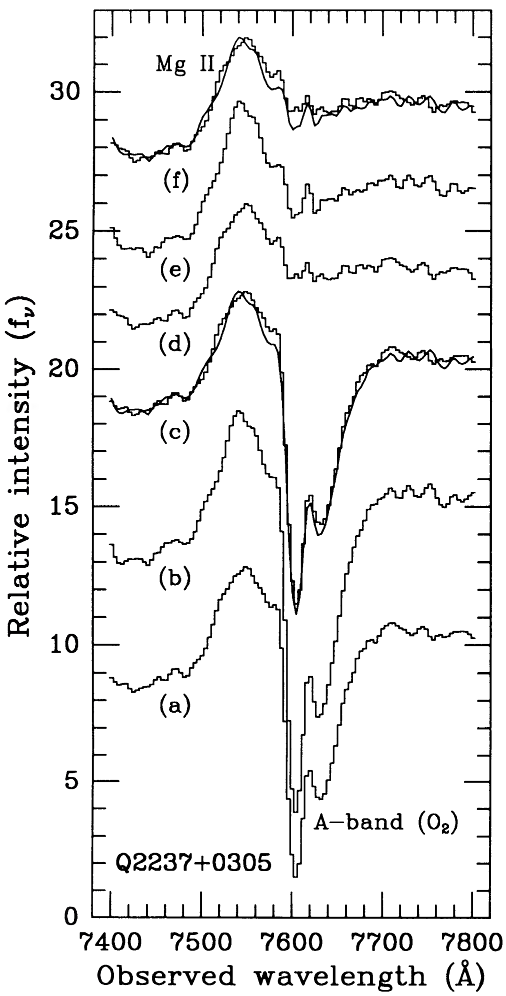

FIG. 3.—Spectra of Q2237+0305 components A and B, both before and after removal of atmospheric absorption bands. Spectrum (*a*) represents component A offset by −2 units, whereas (*b*) is component B with no offset. In (*c*) the two are superposed, after rescaling B (*solid line*) by 0.805 and adding +8 units to each spectrum. Spectrum (*d*) shows component A devoid of atmospheric absorption and offset by +11 units; (*e*) is the same, but for component B. In (*f*) the two are superposed, after rescaling B (*solid line*) by 0.805 and adding +17 units to each spectrum. Note the differences in the Mg II λ2798 emission line in components A and B; specifically, A is broader than B over much of the profile. A slight offset of the continua of A and B is visible in (*c*) and (*f*) redward of Mg II, but a similar offset cannot produce the observed emission-line differences. Each bin is 4 Å wide.

A surprising aspect of Figure 3, however, is that the profile of Mg II is different in the two QSO images. Component A is markedly broader than B over much of the profile, becoming slightly narrower in the blue wing, and its peak is at a longer wavelength by $\sim$300 km s^{-1}. These differences are not an artifact of the division by the standard star; they are visible even in the undivided spectra. Furthermore, the atmospheric A band has a sharp blue cutoff which lies in the red wing of the Mg II profile, whereas most of the profile differences occur at wavelengths shorter than this cutoff. The spectrum of component C is more similar to that of A than to that of B, but contamination from A itself could be part of the reason for this. The Mg II profile in both A and B exhibits a peculiar bump of unknown origin at $\sim$7585 Å.

It is interesting to note that the spectra taken by De Robertis and Yee (1988), although not of sufficiently high quality to unambiguously reveal the profile differences, nevertheless reinforce my conclusion. Close scrutiny of their Figure 3 shows that component A seems to have a larger FWHM than component B. In the superior spectra illustrated here, the profiles are clearly different; A is $\sim$26% wider than B at two-thirds of peak intensity, and at least 23% wider than B at half of peak intensity (depending on how much of the "bump" near 7585 Å is included). The observed differences, if produced by noise, would require a systematic correlation over $\sim$20 contiguous pixels, whereas the continua of A and B typically show oscillations over segments of only $\sim$5 pixels. Moreover, the signal-to-noise ratio is higher in the Mg II line than in the continuum of each spectrum. A rough estimate suggests that the observed overall profile difference is statistically significant at a level of nearly 3 σ.

The asymmetries in the line profiles, together with the unequal positions of the peaks, make it difficult to ascertain that the wavelengths of components A, B, and C are identical to an accuracy smaller than $\sim$150 km s^{-1}; the measurements depend on the width over which the profile is examined. At two-thirds of peak intensity, however, the profiles appear fairly symmetric, and the centroids agree to within 50 km s^{-1}. Thus, the hypothesis of noncosmological redshifts must certainly be abandoned for this system. At least three, and probably all four, of the starlike images have the spectrum of a QSO at the same redshift, and the profile differences are minor compared with the overall spectral similarities. For comparison, several spectral discrepancies are easily visible in the two components of the probable binary quasar discovered by Djorgovski *et al.* (1987).

IV. DISCUSSION

The most important result of this study is the evidence for slight differences in the profiles of Mg II λ2798 in components A and B of the lensed QSO. One obvious possibility is that the intrinsic Mg II emission-line profile varies with time, and that components A and B represent the QSO at two sufficiently different times. This, however, is easily ruled out: the very reasonable models of Schneider *et al.* (1988) and of Kent and Falco (1988) show that the relative time delay between A and B is at most a few days, and possibly as small as 0.03 days. No significant variations of broad emission lines have previously been seen on such short time scales in luminous QSOs.

Another, more plausible, hypothesis is that components A and B are images of slightly different parts of the spatially extended broad-line region in the QSO. The possibility of studying the physical conditions of substructures within the broad-line region was anticipated by De Robertis and Yee (1988), but their data did not unambiguously show profile differences. Theoretical models of this system should address the question of whether the smooth, relatively shallow potential in the nucleus of a normal barred spiral galaxy can give rise to profile discrepancies of the sort observed here. A more centrally concentrated mass (black hole?) might be necessary for consistency, or perhaps microlensing by stars is responsible (Kayser, Refsdal, and Stabell 1986). Also, it should be possible to estimate the size of the broad-line region from the magnitude of the differences.

The obvious next step is to obtain high-resolution spectra, with very large signal-to-noise ratios, of other emission lines in the Q2237+0305 system. Differences among the profiles in each QSO image, and among all four of the images, could be used as valuable probes of both the lensing potential and of the stratified QSO broad-line region (Kayser, Refsdal, and Stabell 1986). Attempts should also be made to obtain high-quality spectra of the individual components in other lensed QSOs. For example, I note that close scrutiny of the published spectra of the "clover leaf" QSO, H1413+117 (Magain *et al.* 1988), reveals some marginal differences in the emission-line profiles, but these must be verified with better data.

Finally, it is possible that gravitational microlensing will cause the emission-line intensity ratios in different parts (i.e., different velocities) of the line profiles to vary with time. The time scale for this can be as short as a year (Young 1981; Paczyński 1986). There is already some very weak evidence for microlensing: comparison of the red data presented here, by Yee (1988), and by Schneider *et al.* (1988), suggests that the relative brightnesses of components A and B have changed with time. Moreover, part of the reason Tyson's (1986; see also Tyson and Gorenstein 1985) images, taken on 1984 October 27, differ from those mentioned above might be attributable to microlensing, as already noted by Kent and Falco (1988). Microlensing of different parts of the broad-line region should lead to observable variations in the line profiles.

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REFERENCES

Arp, H. 1987, *Quasars, Redshifts, and Controversies* (Berkeley: Interstellar Media).
Burbidge, G. 1985, *A.J.*, **90**, 1399.
De Robertis, M. M., and Yee, H. K. C. 1988, *Ap. J.* (*Letters*), **332**, L49.
Djorgovski, S., Perley, R., Meylan, G., and McCarthy, P. 1987, *Ap. J.* (*Letters*), **321**, L17.
Filippenko, A. V. 1982, *Pub. A.S.P.*, **94**, 715.
Huchra, J., Gorenstein, M., Kent, S., Shapiro, I., Smith, G., Horine, E., and Perley, R. 1985, *A.J.*, **90**, 691.
Kayser, R., Refsdal, S., and Stabell, R. 1986, *Astr. Ap.*, **166**, 36.
Kent, S. M., and Falco, E. E. 1988, *A.J.*, **96**, 1570.
Magain, P., Surdej, J., Swings, J.-P., Borgeest, U., Kayser, R., Kühr, H., Refsdal, S., and Remy, M. 1988, *Nature*, **334**, 325.
Miller, J. S., and Stone, R. P. S. 1987, Lick Observatory Technical Report 48.
Oke, J. B., and Gunn, J. E. 1983, *Ap. J.*, **266**, 713.
Paczyński, B. 1986, *Ap. J.*, **301**, 503.
Schneider, D. P., Turner, E. L., Gunn, J. E., Hewitt, J. N., Schmidt, M., and Lawrence, C. R. 1988, *A.J.*, **95**, 1619; erratum: 1988, *A.J.*, **96**, 1755.
Tyson, J. A. 1986, in *IAU Symposium 119*, *Quasars*, ed. G. Swarup and V. K. Kapahi (Dordrecht: Reidel), p. 551.
Tyson, J. A., and Gorenstein, M. 1985, *Sky and Tel.*, **70**, 319.
Wade, R. A., and Horne, K. D. 1988, *Ap. J.*, **324**, 411.
Yee, H. K. C. 1988, *A.J.*, **95**, 1331.
Young, P. 1981, *Ap. J.*, **244**, 756.

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