THE ASTROPHYSICAL JOURNAL, 386:L43–L45, 1992 February 20

THE CENTRAL VELOCITY DISPERSION OF THE LENSING GALAXY IN THE QUADRUPLE LENS SYSTEM Q2237+0305

CRAIG B. FOLTZ
Multiple Mirror Telescope Observatory, University of Arizona, Tucson, AZ 85721
PAUL C. HEWETT
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
RACHEL L. WEBSTER
Canadian Institute of Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, Ontario, Canada M5S 1A1
AND
GERAINT F. LEWIS
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
Received 1991 October 16; accepted 1991 December 2

ABSTRACT

We report a measurement of the projected central velocity dispersion for the lensing galaxy in the quadruple gravitational lens system Q2237+0305. Observations of the galaxy nucleus taken in superb seeing conditions with the 4.2 m William Herschel Telescope produce a value for the central velocity dispersion of $\sigma_p = 215 \pm 30$ km s^{-1}. The value is consistent with the predictions of theoretical models of the lensing galaxy's mass distribution, but the measurement suggests there is evidence for some degree of anisotropy in the velocity dispersion of the galaxy bulge.

Subject headings: galaxies: kinematics and dynamics — gravitational lensing

1. INTRODUCTION

The quadruple gravitational lens system Q2237+0305 (Huchra et al. 1985) is one of the most interesting yet discovered. The system is unusual in that the lens, a bright, nearly face-on, barred spiral galaxy, is located at a redshift of only $z \sim 0.04$, providing an opportunity to study the galaxy's mass distribution in detail, using the observed configuration of the lensed quasar as an additional constraint. The Q2237+0305 system has already provided unique information on the size and structure of the continuum-emitting region in quasars (Rauch & Blandford 1991) following the detection of a number of microlensing events, at least one of which occurred on a time scale of only weeks (Irwin et al. 1989; Corrigan et al. 1991).

With the aim of increasing our understanding of the dynamics of the lensing galaxy we undertook a series of spectroscopic observations at the Roque de los Muchachos Observatory with the William Herschel Telescope, and we report here a determination of the central velocity dispersion of the galaxy bulge. This observation provides a direct test of whether the mass of the galaxy inferred from the lensing configuration can be accounted for by current models of the distribution of mass in galaxies.

2. OBSERVATIONS

Spectra of the nucleus of the galaxy in the Q2237+0305 system were obtained at La Palma on 1991 August 12/13 using the William Herschel Telescope equipped with the ISIS spectrograph. A 1200 lines mm^{-1} grating with an EEV 1180 × 800 CCD as a detector gave a spectral coverage of $\lambda\lambda$5105–5550, at 0.36 Å per pixel resulting in a resolution of 0.8 Å, or 46 km s^{-1}. Observations were performed in long-slit mode with 200 pixels along the slit, at a scale of 0".3 per pixel, giving a coverage of 1' on the sky. Sequences of bias frames were taken at the beginning and end of the night, and DC level changes were monitored using the CCD overscan region. CCD pixel-to-pixel sensitivity variations were calibrated using exposures of a tungsten lamp obtained at the end of the night.

The transparency was good throughout the period of observations, and the seeing was excellent. The four quasar components were clearly visible on the acquisition and guiding TV, and direct imaging observations obtained immediately following the spectroscopic observations produced images with full width half-maximum of 0".55. The slit width was 0".7, and the slit was oriented at a position angle of 39°, which corresponds to the position angle of the bar in the galaxy and also minimizes the contamination from the four quasar images. The geometry of the quasar components and the principal features of the galaxy are shown in Figure 3 of Yee (1988). A total of seven 1800 s exposures were obtained over a period of 4.6 hr. Copper-neon-argon calibration lamp spectra were obtained before and after each exposure. Short exposures, using the identical instrumental configuration, of three bright standard stars of spectral type K (HD 155500: K0, HD 172401: K0, and HD 182293: K3) were obtained immediately prior to the observations of the Q2237+0305 system.

Bias subtraction, flat-fielding, and trimming were performed using standard procedures in IRAF. The calibration arcs indicated significant curvature was present across the frames, and a full two-dimensional wavelength calibration was performed, following which the frames were transformed into an orthogonal coordinate system. The residuals from the wavelength fits, performed using fourth-order Chebyshev polynomials, were 0.04 Å or 0.1 pixel rms. The spectra were extracted from each frame using an optimal extraction procedure employing a profile which was truncated where the signal from the galaxy/quasar dropped below 10% of its maximum value. Using this criterion the full width of the extraction profile was ~12 pixels or 4". The width of the extraction window varied slightly from frame to frame, depending on the atmospheric conditions, but was always within the range 3″.5–4″.3. The IRAF optimal extraction procedure was extremely resilient to the presence of cosmic rays, and it was not necessary to apply any cosmic-ray identification routines. The seven individual spectra were then combined by averaging the spectra together employing an iterative 3 σ clipping routine. The resulting spectrum has a signal-to-noise ratio of $\sim$40 per pixel and is shown, along with the 1 σ noise level, in Figure 1.

The slit position angle of 39° minimized the contamination from the quasar images, but the spectrum contains a substantial fraction of light from the quasar. The equivalent width of the C III] λ1909 emission line in our spectrum is 18 ± 4 Å, corresponding to $\sim$7 Å in the quasar rest frame. Huchra et al. (1985) give 10 Å for the C III] equivalent width in the quasar rest frame but note that a correction of order 10% is appropriate to allow for the presence of the underlying galaxy. Our estimate of the equivalent width is dominated by the uncertainty in defining the continuum to the blue of the C III] line which lies close to the short-wavelength limit of our spectrum. The Huchra et al. estimate must also be subject to considerable uncertainty given the quality of their spectrum and the uncertain contamination from the underlying galaxy. However, from the relative equivalent widths, approximately half of the flux in our spectrum can be ascribed to the quasar, which means the signal-to-noise ratio in the galaxy spectrum is $\sim$20 per pixel. An alternative measure based on the ratios of the peak heights of the C III] lines in our and the Huchra et al. spectra suggests the contamination from the quasar may be as large as 70%.

The wavelength region observed was chosen to include the Mg *b* λ5177 triplet, Fe I λ5268 blend, and a number of weaker features present at intermediate wavelengths in both the template stars and the galaxy. Matthew Colless kindly agreed to undertake the analysis of the galaxy spectrum. Standard Fourier quotient techniques (Sargent et al. 1977) were applied to the rest wavelength range $\lambda\lambda$5120–5300 of the galaxy and the templates. Cross-correlation (Tonry & Davis 1979) of each template spectra with the galaxy gave a heliocentric velocity $cz = 11{,}696 \pm 40$ km s^{-1} and peak height–to–noise ratios, R, of 4–5. The observed velocity dispersions and R parameters for the individual templates were 223 km s^{-1} $R = 4.15$ (HD 155500), 209 km s^{-1} $R = 4.09$ (HD 174201), and 213 km s^{-1} $R = 4.87$ (HD 182293). The internal error in the procedure is small judging by the consistency of the results using the different templates, and we adopt a value of 215 km s^{-1} as our estimate of the velocity dispersion. However, the errors in the velocity dispersion estimates from spectra with R values $\sim$5 are typically 15% (Tonry & Davis 1979), and a 1 σ error of 30 km s^{-1}, incorporating both internal and external errors, is more realistic. Hans-Walter Rix applied the template broadening technique (Rix & White 1991) to the galaxy spectrum using the HD 182293 spectrum, deriving a value of 231 km s^{-1} for the velocity dispersion, with a 1 σ internal error of $\pm$16 km s^{-1}. This template broadening value is ≤ 1 σ from the Colless value using either the error estimate of $\pm$30 km s^{-1} for the Fourier quotient determination or the $\pm$16 km s^{-1} template broadening error estimate, confirming that the velocity dispersion estimate is not sensitive to the details of the analysis procedure.

Unrelated to the galaxy, but of potential relevance for detailed modeling of the system, are the presence of Mg II $\lambda\lambda$2796.35, 2803.53 absorption systems in the spectrum. Two strong, narrow absorption features are present at λ5511.4 and λ5525.6 along with a weaker feature at λ5501.5 and weak blended features at λ5312.5 and λ5526.2. We identify these as a probable Mg II doublet at $z = 0.9709$ and additional, possible systems at $z = 0.9674$ and $z = 0.9713$.

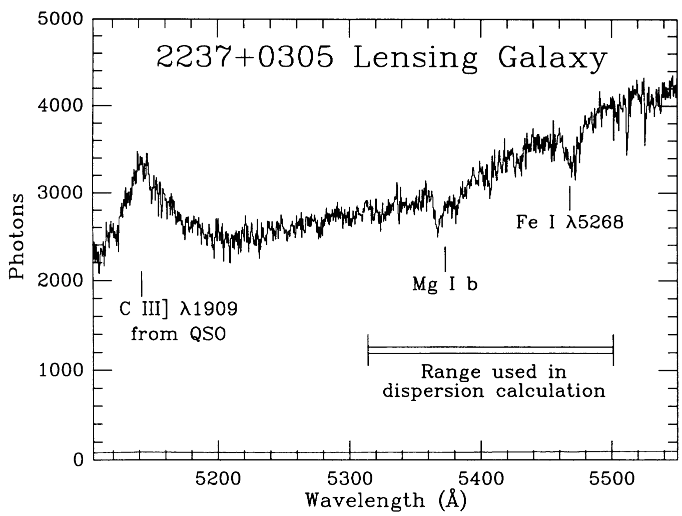

FIG. 1.—Spectrum of the nucleus of the 2237+0305 lensing galaxy. The lower curve is the 1 σ error level as calculated from photon statistics and CCD readout noise. Positions of stellar features in the galaxy spectrum as well as contaminating C III] λ1909 emission from the QSO are marked. The range of wavelengths used in the dispersion calculation is indicated.

3. DISCUSSION

Gorenstein, Falco, & Shapiro (1988), who consider the general problem of constraining the characteristics of lenses from observed parameters, have shown that there are a number of transformations which leave the observables unchanged, but effect the distribution of surface mass density in the lens. Q2237+0305 is no exception, and the observable parameters of the quasar images and the galaxy surface brightness distribution in the Q2237+0305 system do not provide a unique description of the galaxy's mass distribution.

The locations of the four brightest quasar images relative to the center of the galaxy surface brightness distribution provide constraints on the models. In addition the approximate relative brightnesses of the four quasar images are known, though these ratios are affected by microlensing of the individual components. A limit on the brightness of the fifth image has been set by Crane et al. (1991), and Racine (1991) has claimed a detection. From the surface brightness distribution of the galaxy, the center, ellipticity, inclination, and position angle of the major axis of the galaxy have been determined (Racine 1991; Irwin et al. 1989). Analysis of the light distribution in the central part of the galaxy shows the surface brightness distribution is well fitted by a de Vaucouleurs profile (Racine 1991), but a bar and ring structure are also observed.

Models of the galaxy mass distribution have been published by Schneider et al. (1988) and Kent & Falco (1988). The former fitted a de Vaucouleurs profile to the central portion of the light distribution of the galaxy and used both the quasar image positions and amplifications to constrain the mass-to-light ratio. Kent & Falco assumed analytic King and de Vaucouleurs profiles with isotropic velocity distributions for the mass distributions and used image positions and amplifications to determine the galaxy parameters, including the projected velocity dispersion, ellipticity, position angle, and scale lengths. Both calculations produce similar values for the total mass enclosed by the quasar images (as must occur, by Birkoff's theorem), and the mass and the mass-to-light ratio are determined to within ~20% for the region of the galaxy interior to a radius of ~0".9. Using m_r (<1") = 16.75 and $M(<0''.9) \sim 10^{10}\ M_\odot$ (Kent & Falco), with suitable adjustments for the enclosed mass (Young 1978), one obtains $M/L_r \sim 5$. In addition, Kent & Falco showed that the best-fit position angle was not along the major axis, but weighted toward the position of the bar, suggesting that the mass in the bar is a significant fraction of the total in the inner regions. The values of the ellipticity and scale lengths obtained by Kent & Falco are consistent with measured values (e.g., Racine 1991).

Our measured value of $\sigma_p = 215 \pm 30$ km s^{-1} is within 2 σ of the predicted value for the de Vaucouleurs model calculated by Kent & Falco. This is marginally consistent with their predicted value but raises the possibility that the velocity dispersion may be significantly higher. The mass interior to ~0".9 is well determined, and the constraint on the brightness of the fifth image, which implies a small effective radius for the galaxy bulge, also suggests that the central velocity dispersion is higher than that predicted by Kent & Falco.

Can the otherwise successful Kent & Falco model account for such a high velocity dispersion? A number of assumptions enter into the Kent & Falco model, one of which is the isotropy of the galaxy velocity dispersion. There is considerable evidence from studies of ellipticals and spiral galaxy bulges that a significant degree of anisotropy may not be uncommon in such systems. If the effective radius, $r_e = 7''$, and $M(<0''.9) \sim 10^{10}\ M_\odot$, then the numerical tables of Young (1978) can be used to determine the total mass of the bulge (assuming it to be spherical), and therefore the scaling factor $(GM_{\rm tot}/r_e)^{0.5} \sim 366$ km s^{-1}. Richstone & Tremain (1984) have calculated σ_p for sperical galaxies with a de Vaucouleurs profile. If the orbits are assumed to be isotropic, they calculate $(GM_{\rm tot}/r_e)^{0.5} \sim 165$ km s^{-1}, in agreement with Kent & Falco. If, however, the orbits are allowed to be anisotropic, then the observed value of σ_p can have a substantial range, depending on the size and shape of the aperture used for the measurements. Although Richstone & Tremain (1984) have not calculated the range for a slit aperture similar to the one used for these observations, interpolating from their figures suggests a range for the observed velocity dispersion of σ_p is ~90–270 km s^{-1}, comfortably bracketing our measurement. Since our observation was made with a narrow slit, the fact that our observed σ_p is larger than the value expected for an isotropic model suggests that the radial component of the velocity dispersion is greater than the tangential.

Statistically the observed projected velocity dispersion is consistent with the theoretical models of Kent & Falco. However, confirmation of a value equal to or greater than our best estimate would suggest the velocity dispersion in the central part of the galaxy is anisotropic, with the radial component larger than the tangential. A detailed model for the Q2237+0305 system will have to take account of the presence of the group of Mg II absorbers at $z \sim 0.9$.

This *Letter* is based on observations made with the William Herschel Telescope operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. It is a pleasure to thank Matthew Colless and Hans-Walter Rix for their time and the use of their software in producing the velocity dispersion estimates, and Emilio Falco for constructive comments. This project was made possible in part by the award of a NATO Collaborative Research Grant (0801/88) to P. C. H. and R. L. W., who gratefully acknowledge the continuing support of their research by NATO. C. B. F. acknowledges the support of the National Science Foundation under grant AST 90-01181. R. L. W. thanks Scott Tremaine and acknowledges support from NSERC of Canada.

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