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2237+0305: A NEW AND UNUSUAL GRAVITATIONAL LENS[a)]

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ABSTRACT

We have discovered a new gravitational lens system which consists of a quasar at $z = 1.695$ nearly centered on a 15 mag spiral galaxy, 2237 + 0305, at $z = 0.0394$. At 2″ resolution, only a single optical image of the quasar is visible; its centroid is located within approximately 0″.3 of the center of the galaxy. "Snapshot" observations at the VLA yielded no detectable radio radiation, placing an upper limit of about 0.5 mJy on the combined flux density of the galaxy and quasar at $\lambda = 6$ cm. We discuss a simple gravitational lens model that accounts for these observations.

I. DISCOVERY

Zwicky suggested that galaxies acting as gravitational lenses are practically a "certainty" (Zwicky 1937a,b; see also Barnothy 1965). The lens systems that have been reported to date all consist of high-redshift quasars imaged by either high-redshift galaxies, clusters of galaxies, or as yet unseen lenses (Turner, Ostriker, and Gott 1984). Because of their great distances or invisibility, such lenses are exceedingly difficult to study. We report here the first discovery of a nearby ($z = 0.0394$) gravitational lens.

As part of the Center for Astrophysics Redshift Survey, one of us (EH) observed the $m_{pg} = 15.2$ mag galaxy 2237 + 0305 (Zwicky, Karpowicz, and Kowal 1965) with the 1.5-m Tillinghast reflector of the Whipple Observatory on 23 September 1984. Our initial spectrum, covering the range 4600–7300 Å, showed a relatively smooth continuum with a single broad emission line at 5180 Å. A second spectrum on the nucleus covering the region 3200–7400 Å was obtained on 27 September 1984 with the MMT (JH). This spectrum proved to be that of a quasar at a redshift of $z \simeq 1.7$. However, the object's image on the Palomar Sky Survey E and O prints was lenticular and approximately 1′.0×0′.5 in size. CCD images were obtained the next night with the 61-cm reflector at the Whipple Observatory (SK) in the J and F bands (4000–5400 Å and 5800–7300 Å, respectively). These images showed that the outer regions of the object exhibit spiral structure and that the quasar is centered on the disk. We then obtained spectra off the nucleus at the 1.5 m (JH and JP) and at the MMT (JH and GS), which revealed the "surrounding" object to be a galaxy at redshift of $z = 0.0394$. At this point, we concluded that we were observing a simple gravitational lens system in which a galaxy imaged (magnified) a quasar almost directly behind it.

II. OPTICAL AND RADIO OBSERVATIONS

Figure 1 is the MMT spectrum of the QSO plus contamination from the center of the galaxy. The contribution from the galaxy is estimated to be of order 10% (see below). The Lyman α, O I, Si IV, C IV, He II, and C III] lines are marked in the figure. The emission-line redshift of the QSO is $z = 1.695$. The Lyman α and C IV lines appear self-absorbed (Fig. 2). Although it is difficult to see any of the galaxy's absorption features, cross correlation against standard galaxy spectra yields a velocity of 11 640 ± 60 km s^{-1}. The QSO continuum slope is $\alpha \simeq -3.5$ (where $f_\nu \sim \nu^\alpha$), and is much steeper than the average (-0.6, e.g., Richstone and Schmidt 1980). This steepening is probably due to absorption by dust in the intervening galaxy. Figure 3 is the MMT spectrum of the galaxy taken approximately 5″ to the west of the QSO through a 2″×3″ aperture. The strong break due to Ca II H + K absorption is easily seen at about 4100 Å and the Mg b + MgH feature is seen near 5400 Å. Cross correlation against our standard template gives a velocity of 11 380 ± 45 km s^{-1}, confirming the velocity obtained from the observations of the galaxy center. The difference in the velocities on and off the nucleus, 260 ± 75 km s^{-1}, is a crude measurement of the rotational velocity of the galaxy typical for a galaxy of early type and large luminosity. The position and velocity of the galaxy place it in the outskirts of the Pegasus II cluster.

Figure 4 (Plate 58) is the contoured 20-min F image of the lens system. A small amount of structure is visible in the disk of the galaxy, suggesting that its classification is approximately Sa or Sb. No evidence for multiple bright images of the QSO is seen with our 2″ resolution; the structure in the outer part of the galaxy may also hide very faint images. The second brightest object visible in the disk (7″ E and 4″ N of the center) is about 3 mag fainter than the QSO on the F frame and is not visible on the J frame. It is much redder than the QSO and therefore is unlikely to be another image. Thus, outside of the inner few arcseconds, we see no evidence for other images within 3 mag of the central image.

Figure 5 gives the surface-brightness profiles of the major and minor axes with the latter scaled downwards by 5 mag. The galaxy-quasar profile has been modeled by the sum of a point source and an inclined exponential disk of the form $I = I_0 e^{(-x/x_0)}$, convolved with a Gaussian seeing profile of 2″ FWHM determined from the image of a nearby star. The "best fit" model has a disk scale length of 5″.9 ($= 3.4$ kpc with $H_0 = 100$ km s^{-1} Mpc^{-1}), a central, face-on B surface brightness, $\mu_B = 20.8$ mag arcsec^{-2}, and an ellipticity of

[a)] Research reported here is based in part on observations made with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and The University of Arizona.

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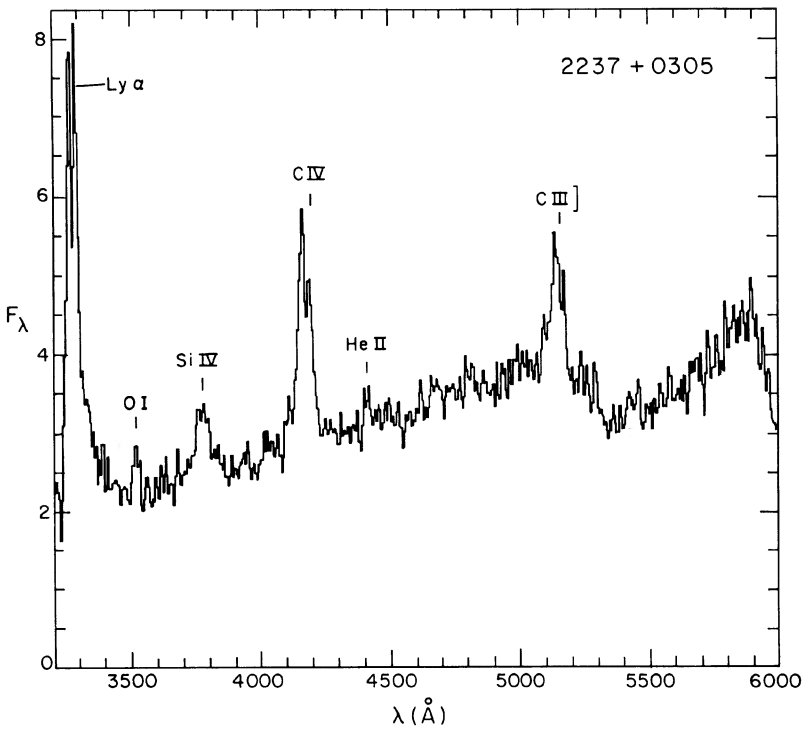


FIG. 1. Spectrum of the central object taken with the MMT. The flux scale is relative since the observations were made with a small slit (1″ × 3″).

0.47 which corresponds to an axial ratio of 2.3. Note that we have transformed our J and F photometry into the more standard B and V system via Kent (1985). The observed integrated magnitude of the galaxy plus quasar, minus the estimated contribution of the quasar, is $B_T = 15.6$. The absolute B magnitude of the galaxy is then -21.0 or about 1 mag more luminous than M31. The photometric parameters, as well as our above crude rotation velocity of 260 km s^{-1}, are typical of *luminous* early-type spiral galaxies (Rubin *et al.* 1982).

Most spiral galaxies exhibit two discernible components in their surface-brightness profiles—a disk and a bulge. Unfortunately, we can not separate the galaxy bulge component from the QSO contribution on our CCD image. However, our spectroscopic data indicate that most of the light in the central 1 or 2 arcsec is coming from the QSO. The lack of a visible H + K break at 4100 Å in the QSO + galaxy spectrum (compare Figs. 1 and 3) limits the galaxy contribution in the inner 1″ × 3″ to ~10% of the total. If we assume that all of the excess over the extrapolated exponential disk is attributable to the QSO, its magnitude and color are $B = 16.8$ and $B - V = 0.7$. Its absolute B magnitude is then $M_B = -28.5$ (Peebles 1971, with $q_0 = 0.1$).

We have tried to measure the position of the QSO relative to the lensing galaxy by calculating the variation in the centers of the isophotes of different intensity levels. Because our CCD frames were taken in fair seeing (2″), we can conclude only that the centroid of the QSO lies within ~0.″3 of the center of the galaxy. The results of the optical observations are summarized in Table I. Unless otherwise given, the errors in measured quantities are ± 1 in the last quoted significant figure (except for the parameters of the fit to the surface-brightness profile, where correlated systematic errors are possible).

On 11 October 1984, the object was observed at 2, 6, and 20 cm with the VLA (RP) in the D configuration. The object was not detected. Table II gives the integration times, flux limits, and effective beam sizes. The limit at 20 cm is poor due to confusion with a 3 mJy source located about 20″ north of the QSO. Further 20-cm observations are planned with higher spatial resolution (B configuration).

We note that the QSO does not appear in any lists of optical or radio selected AGN despite its relative brightness.

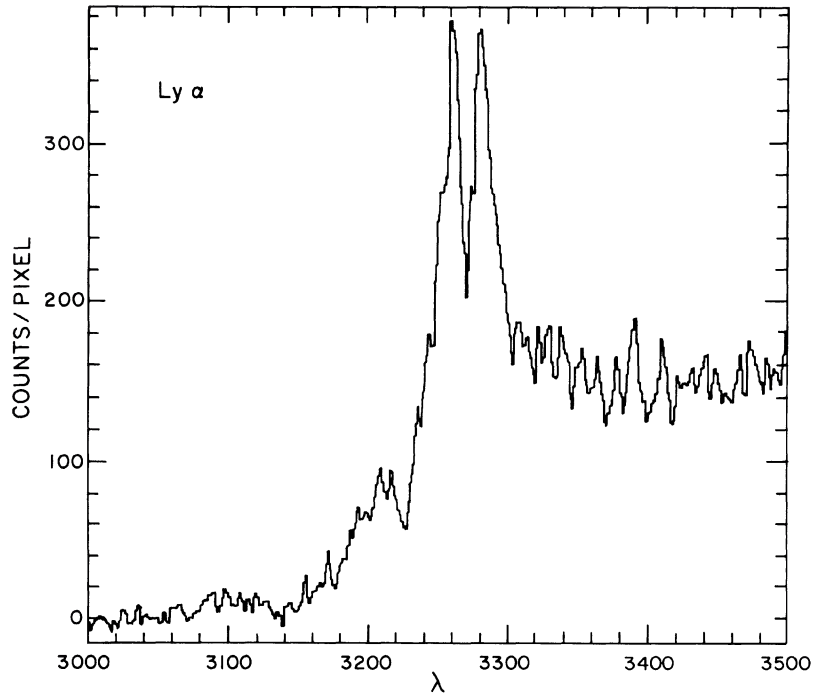
III. STATISTICS AND MAGNIFICATION

Although estimation of probability after the fact is often a dangerous exercise, it can be informative. What is the probability that we would have discovered this lens system? We consider the answer to this question in two parts. First, what is the probability that we would have found a 17 mag, unmagnified quasar behind a galaxy in the CfA Redshift Survey? Note that if the QSO were unmagnified, its intrinsic luminosity would then be in the top 2% of all known quasars (e.g., Schmidt and Green 1983; Kuhr *et al.* 1984). The surface density of QSO's brighter than 17 mag is only about 0.05 per deg^2 (Schmidt and Green 1983). For the CfA Redshift Survey (Davis, Huchra, and Latham 1983), we have now measured approximately 7000 nearby galaxies through either 3.″2 × 12.″8 or 3.″2 × 6.″4 slits, with an average slit area of about 35 arcsec^2, covering approximately 250 000 arcsec^2 or 0.02 deg^2 of the sky. Assuming that the positions of galaxies and QSO's are independent and that both are randomly distributed on the sky with negligible correlation, we find the probability for observing a 17 mag QSO inside the slit to be only 0.001. If we include the constraint that the QSO must lie within 0.″3 of the galaxy center, the number drops to $\sim 8 \times 10^{-6}$.

Second, we consider the modification to these numbers introduced by possible magnification of the quasar light. Clearly, any numerical answer depends on details of the mass distributions in the central regions of galaxies. What

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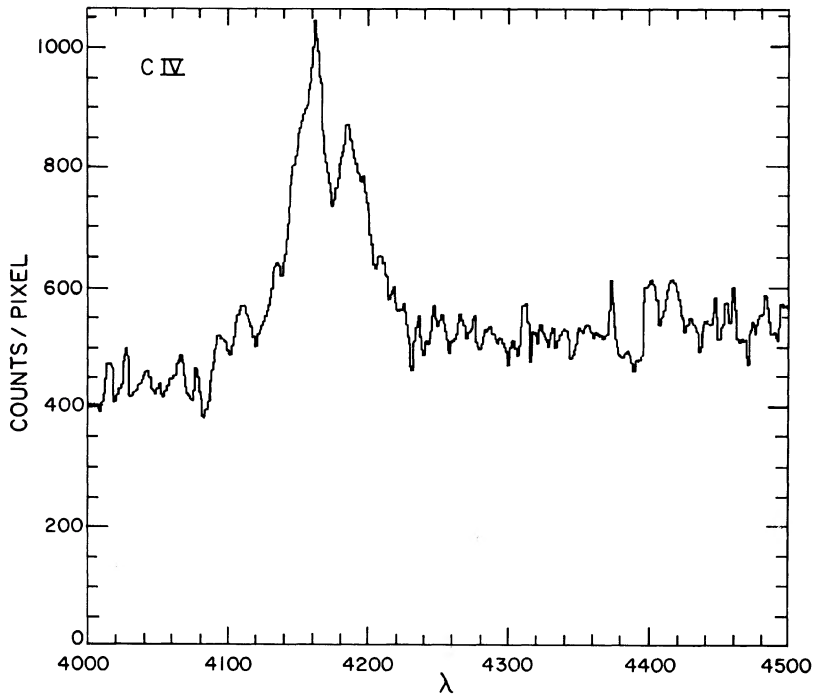


FIG. 2. The Lyman α (top) and C IV (bottom) line profiles showing the central absorption. This feature is *not* seen in C III], which indicates that it is absorption rather than two velocity components.

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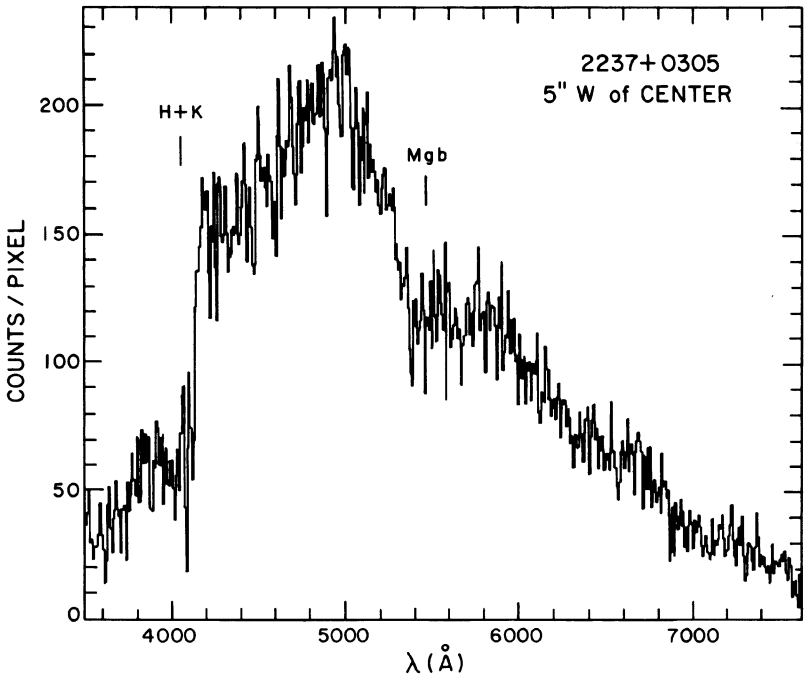


FIG. 3. Spectrum of the galaxy taken ~5″ to the west of the QSO. Absorption features are marked.

magnification is necessary to increase the probability to a "reasonable" value? For example, let us consider magnification by a factor of 40. Such magnification implies that the apparent magnitude of the unlensed QSO is 4 mag fainter. Since the QSO number density rises with magnitude much more steeply than Euclidean, the surface density of 21 mag QSO's is about 50 per deg^2 (Schmidt and Green 1983). Including the magnifying effect of the lens, which decreases the area of the sky observed by a factor of 40, we then infer (*a posteriori*) the probability of finding such a QSO within a few arcseconds of the center of a redshift-survey galaxy to be increased to ~0.03 and the corresponding number for observing one within 0″.3 to be $\sim 2\times 10^{-4}$. These statistical considerations imply the likelihood of strong magnification of the quasar light by the galaxy lens.

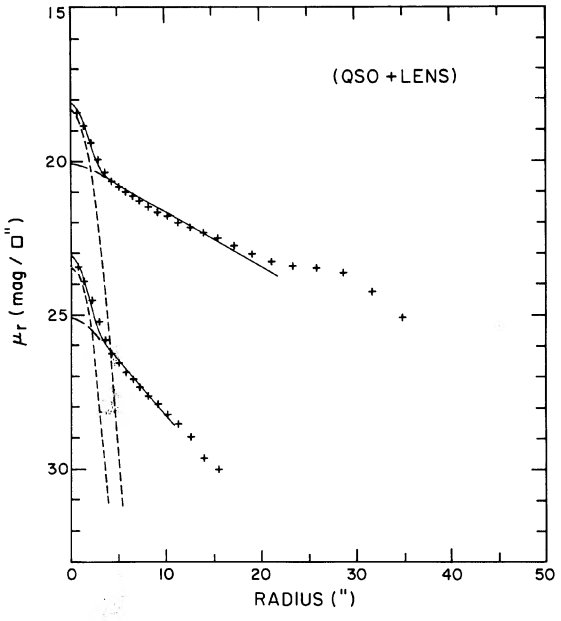


FIG. 5. Major- and minor-axis surface-brightness profiles of QSO + lens galaxy in the *F* band. The minor-axis profile has been scaled down by 5 mag. The crosses are the data. The long-dashed lines are the fit of the outer part of the profile to an exponential disk (see the text). The short-dashed lines are the fit to the seeing-broadened central object. The solid lines are the sum of the model components (indistinguishable from the disk alone at large radii).

There is an additional, albeit weak, reason to suspect that the QSO is amplified. There exists a negative correlation (albeit poor) between the luminosity of a QSO and the equivalent width of the C IV line in emission (Baldwin 1977; Richstone and Schmidt 1980; but see also Richstone, Ratnatunga, and Schaeffer 1980 for a negative view). For Baldwin's cosmological model, our QSO's "apparent" absolute monochromatic luminosity at 1450 Å is $L \simeq 10^{32}$ erg s^{-1} Hz^{-1}. The C IV line rest-frame equivalent width is approximately − 25 Å (Fig. 2); Baldwin's calibration would then predict a continuum luminosity of only $L \simeq 1.6\times 10^{31}$, or about a factor of 6 smaller than the observed luminosity. Correcting the equivalent width for the galaxy contribution through a 1″ × 3″ slit would only increase the difference between observed and predicted luminosities, as would correcting the QSO luminosity for absorption in the intervening galaxy.

IV. A SIMPLE LENS MODEL

We show here that the observations of 2237 + 0305 are consistent with a simple model in which the galaxy (hereafter referred to as the deflector) forms only a single, highly magnified image of the QSO, lying within 0″.3 of the center of the galaxy. We defer until later (Gorenstein *et al.* 1985, hereafter referred to as Paper II) discussion of deflector models that yield multiple images that are consistent with the data.

We assume that the deflector's surface mass distribution is uniform, circular, and transparent, and that the center of the deflector is collinear with the observer and the source. By

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TABLE I. Summary of QSO and galaxy properties.

Right Ascension (1950)	$22^h\,37^m\,57^s.3$
Declination (1950)	$+03°05'49''$
QSO redshift	1.695 (galactocentric)
Galaxy redshift	0.0394
Galaxy distance	118 Mpc
Galaxy rotation velocity	260 ± 75 km s^{-1}
Disk model	
Scale length x_0	5".9
	3.4 kpc
Ellipticity ϵ	0.47
Central surface brightness μ_B	20.74
Photometry	
Galaxy	$B = 15.6$
	$B - V = 1.0$
	$M_B = -21.0$
QSO	$B = 16.78$
	$B - V = 0.65$
	$M_B = -28.5$
Emission-line equivalent widths	
Lyα	− 25 Å
Si IV	− 8
C IV	− 22
C III]	− 10

Notes to TABLE I

Distance dependent parameters calculated assuming $H_0 = 100$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$; for $h = 0.5$, subtract 1.5 from absolute magnitudes and double the distances.
Equivalent widths are not corrected for the overlying galaxy flux but are corrected to the QSO rest frame. A crude estimate of the galaxy contribution would increase them by approximately 10%.

symmetry, an image will appear at the center (but not necessarily accompanied by a ring image; see below). To compute its magnification, we note that the radial deflection angle is $\alpha(\theta) = -4\pi\mu_0 D_d^{-1}\theta$, in units where $G = c = 1$, where μ_0 is the deflector's surface mass distribution (in units of mass steradian^{-1}), where D_d is the observer-deflector angular-size distance, and where θ represents radial distance on the plane of the sky measured from the center of the deflector. The deflector thus acts like a lens with focal length $f = D_d^2/4\pi\mu_0$. From geometric optics, we know that a lens with focal length f magnifies the brightness of an image by $\bar{M} = (1 - f_0/f)^{-2}$, where $f_0 = D_d D_{ds}/D_s$, and where D_s and D_{ds} are, respectively, the observer-source and the deflector-source angular-size distances. Note that the critical surface mass density that produces infinite magnification is $4.6 \times 10^9\, h^{-1}\, M_\odot$ arcsec^{-2}. If we then take the contributions to the central surface brightness of the galaxy from the disk and bulge to be approximately equal (see Sec. II and Fig. 5), and if we use $z_s = 1.695$, $z_d = 0.0394$ (galactocentric), and $H_0 = 100\, h$ km s^{-1} Mpc^{-1}, we find $f_0/f = 0.040\,(M/L)h^{-1}$, where M/L is the mass-to-light ratio in solar units. For $\bar{M} = 40$, say, we require $f_0/f \simeq 0.84$ or 1.16, corresponding to the two roots of the quadratic equation. Only for the first solution and for a surface mass distribution that monotonically decreases with θ will a single image be obtained independent of the position of the source and, in particular, no ring image will appear for collinear alignment of source, lens, and observer. For that case and for $h^{-1} = 1$, we note that a value for M/L of 21 yields $(f_0/f) = 0.84$. This value is within the range inferred for M/L from observations of nearby galaxies (Faber and Gallagher 1979).

Finally, we note that the deflector's ellipticity, which gives rise to an astigmatism, introduces only a small numerical modification of the magnification; moreover, the magnification is essentially unchanged for offsets of the image from the galaxy's center that are less than the minor-axis scale length.

Future work (Paper II) will consider (1) models that contain different radial mass distributions, (2) the possible conundrum presented by the fact that the quasar image lies so close to the center of the galaxy, and (3) the effects of microlensing.

V. CONCLUSIONS

We believe we have found evidence for a unique gravitational lens: a nearby, bright, and apparently well-isolated galaxy that images a distant quasar. Significant magnifica-

TABLE II. VLA observations.

wavelength (cm)	integration time (min)	upper limit (mJy)	beam size FWHM (arcsec)	Comments
2	20	1.3	5	No detection
6	30	0.5	14	No detection
20	20	2.3	45	Source confusion

Notes to TABLE II

Upper limits on the QSO + galaxy flux density are 5 times the rms noise.

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tion of the quasar by the galaxy is plausible, although our present lack of knowledge of the central mass and surface-brightness distributions of the galaxy prevents placing any strong constraints on models for the lens. Although the apparent alignment of this quasar and galaxy might be taken as evidence for noncosmological redshifts (e.g., Arp 1973), the conventional interpretation is reasonable: this discovery in a survey of galaxy redshifts is not too unlikely because the unmagnified quasar can be rather faint and the surface density of faint quasars is very large. This object also offers a unique opportunity to study the nature of the cool gas at a galaxy's center via absorption features seen against the QSO's continuum.

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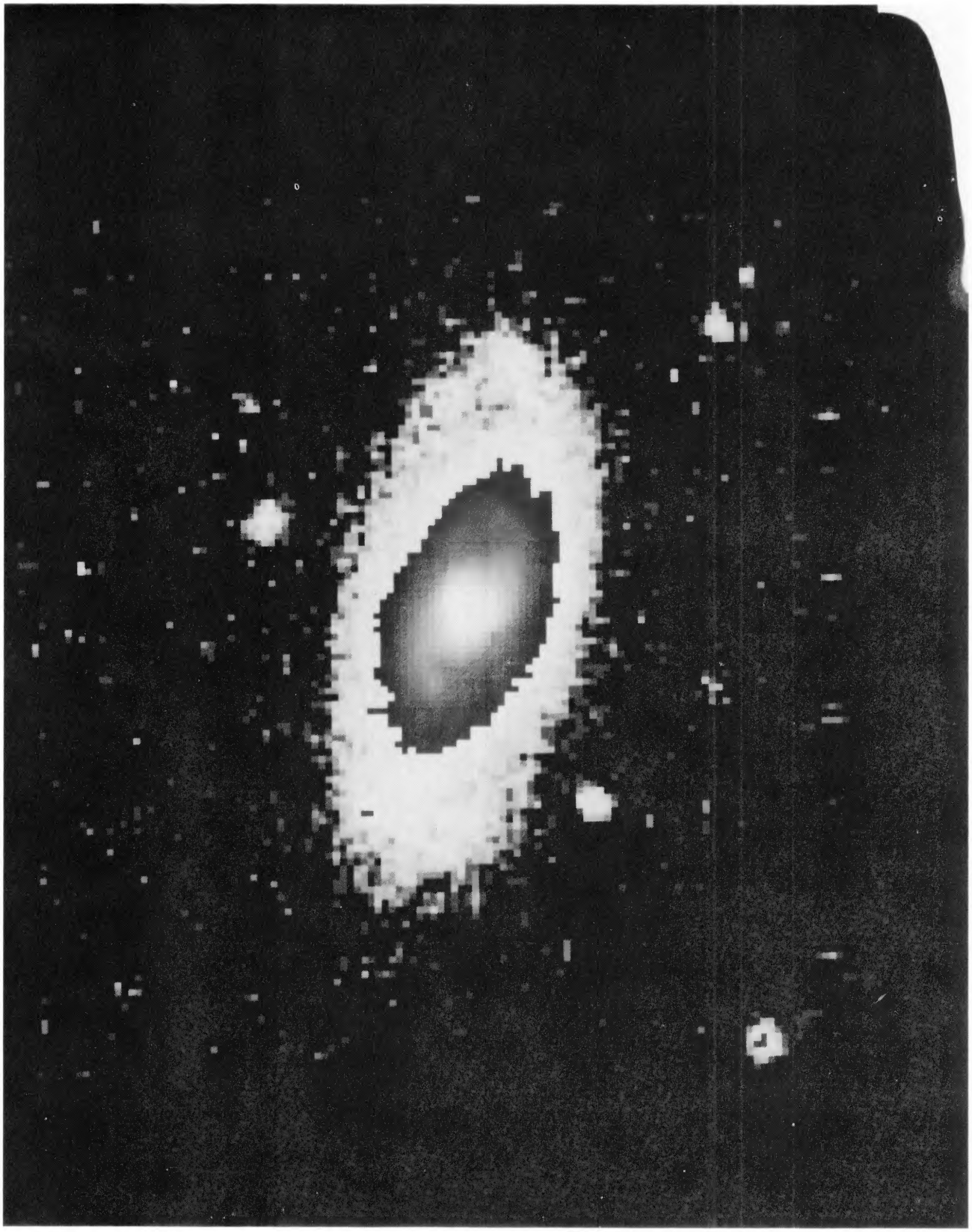


FIG. 4. Contoured image of the gravitational lens 2237 + 0305. This image is a 20-min exposure through an *F* filter on a thinned RCA CCD. The galaxy image is 64″ × 28″ and the scale is 0.″75 per pixel. The intensity scale is logarithmic and has been allowed to "wraparound" once in the center to increase the dynamic range (top is at left).

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