

APM 08279 + 5255: KECK NEAR- AND MID-INFRARED HIGH-RESOLUTION IMAGING¹

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ABSTRACT

We present Keck high-resolution near-IR ($2.2 \mu\text{m}$; FWHM $\sim 0''.15$) and mid-IR ($12.5 \mu\text{m}$; FWHM $\sim 0''.4$) images of APM 08279 + 5255, a $z = 3.91$ IR-luminous broad absorption line quasi-stellar object with a prodigious apparent bolometric luminosity of $5 \times 10^{15} L_{\odot}$, the largest known in the universe. The *K*-band image shows that this system consists of three components, all of which are likely to be the gravitationally lensed images of the same background object, and the $12.5 \mu\text{m}$ image shows a morphology consistent with such an image configuration. Our lens model suggests that the magnification factor is ~ 100 from the rest-frame UV to mid-IR, where most of the luminosity is released. The intrinsic bolometric luminosity and IR luminosity of APM 08279 + 5255 are estimated to be $5 \times 10^{13} L_{\odot}$ and $1 \times 10^{13} L_{\odot}$, respectively. This indicates that APM 08279 + 5255 is intrinsically luminous, but it is not the most luminous object known. As for its dust contents, little can be determined with the currently available data because of the uncertainties associated with the dust emissivity and the possible effect of differential magnification. We also suggest that the lensing galaxy is likely to be a massive galaxy at $z \sim 3$.

Subject headings: gravitational lensing — infrared: galaxies — quasars: individual (APM 08279 + 5255)

1. INTRODUCTION

In the course of a survey for distant cool carbon stars in the Galactic halo, Irwin et al. (1998) serendipitously discovered an extremely luminous broad absorption line quasi-stellar object (QSO) at $z = 3.91$, APM 08279 + 5255.² Its phenomenally large apparent luminosity is immediately clear from its observed magnitude: the observed *R* magnitude of 15.2 mag corresponds to an absolute magnitude of $M_R = -33.2$ mag after a *K* correction. Furthermore, this object was also detected at 25, 60, and $100 \mu\text{m}$ in the *IRAS* Faint Source Catalog (Moshir et al. 1992) with flux densities of 0.23, 0.51, and 0.95 Jy. All together, the *apparent* bolometric luminosity of this object reaches an unprecedented level of $5 \times 10^{15} L_{\odot}$, which would make APM 08279 + 5255 the most luminous object known in the universe.³

The observations to date indicate that APM 08279 + 5255 is likely to be gravitationally lensed. Irwin et al. (1998) showed that the *R*-band image of this object, taken under a $0''.9$ seeing, is slightly elongated and that the image likely consists of two point sources separated by $0''.3$ – $0''.45$ with a flux ratio of 1.05–1.15, probably being two gravitationally lensed images of the same QSO. Subsequently, Ledoux et al. (1998) performed adaptive-optics observations in the *H* band, which achieved a spatial resolution of $0''.3$. Their image shows two point sources separated by $0''.35 \pm 0''.02$ with a flux ratio of 1.21 ± 0.25 , in good agreement with the values derived by Irwin et al. (1998). In addition, by using an optical integral-field spectrograph, Ledoux et al. (1998) showed that the optical spectra of these two sources are quite similar, strengthening the gravitational lensing hypothesis for this object.

At the same time, the far-IR and submillimeter observations have shown that APM 08279 + 5255 contains a large amount of gas and dust, making this object an extreme example of a hyperluminous/ultraluminous IR galaxy/QSO. In addition to the *IRAS* far-IR detections, its continuum was also detected in the submillimeter by Lewis et al. (1998). The blackbody dust temperature was estimated from the submillimeter spectral energy distribution (SED) to be 220 K, which in turn results in a dust mass with no magnification correction of $3.7 \times 10^9 M_{\odot}$ (Lewis et al.

¹ Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology, the University of California, and NASA.

² The redshift obtained by Irwin et al. (1998) was 3.87, but the CO line observation by Downes et al. (1999) later showed that the redshift of this system is 3.9110 and that the absorption lines measured by Irwin et al. (1998) are probably blueshifted as a result of the gas outflow in this object. To avoid confusion, we adopt a redshift of 3.91 throughout this paper.

³ Throughout this paper, we adopt the values of $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$.

TABLE 1

NEWLY MEASURED FLUX DENSITIES OF APM 08279 + 5255

λ (μm)	Band	Magnitude (mag)	Flux Density (mJy)
1.25.....	<i>J</i>	13.34 ± 0.03	7.19 ± 0.20
1.65.....	<i>H</i>	12.65 ± 0.03	8.97 ± 0.25
2.15.....	<i>Ks</i>	12.08 ± 0.03	9.40 ± 0.26
3.5.....	<i>L</i>	9.90 ± 0.04	27.3 ± 1.0
12.5.....		6.35 ± 0.15	74 ± 11
17.9.....		$5.2^{+0.8}_{-0.4}$	103 ± 50

1998). Later, Downes et al. (1999) detected two CO lines (4–3 and 9–8) by millimeter interferometry and derived a molecular gas temperature of ~ 200 K from the line ratio. The mass of molecular gas was calculated to be $(1-6) \times 10^9 M_{\odot}$ with a magnification factor of 7–20. From a simultaneous millimeter continuum observation, they also derived the dust mass of $(1-7) \times 10^7 M_{\odot}$ with a magnification factor of 7–30. The detection of the CO (9–8) line is especially important because this is direct evidence that this object contains hot and dense molecular gas.

APM 08279 + 5255 was also found to have a significant visual linear polarization ($p > 1\%$; Hines, Schmidt, & Smith 1999). Hines et al. also suggest that the broad absorption trough formerly identified as a $z = 3.07$ damped Ly α absorption system by Irwin et al. (1998) may be a O IV/Ly β broad absorption line intrinsic to the QSO because there is an increase of polarization in the trough.

From the currently available data, APM 08279 + 5255 looks very much like the hyperluminous IR QSO H1413 + 117 (Cloverleaf QSO) and the warm ultraluminous IR galaxy Mrk 231 in the sense that it contains a clearly visible QSO nucleus surrounded by a large amount of gas and dust. The major difference between these two objects and APM 08279 + 5255 seems to be the exceptionally large luminosity of the latter, which is likely the effect of gravitational lensing. In these systems, the existence of a powerful QSO nucleus seems to indicate that the QSO is the dominant luminosity source, generating the large IR luminosity by heating dust.

Here we present high-resolution images of APM 08279 + 5255 in the near- and mid-IR taken with the Keck telescope. Our high-resolution (FWHM $\sim 0''.15$) *K*-band image shows a third component between the two components previously detected. We argue that it is another lensed image of the same background QSO and examine the intrinsic properties of the lensed QSO based on the lens model. We especially try to constrain the effects of differential magnification since they could introduce a significant distortion in the observed SED as shown by Blain (1999).

After the initial submission of this paper, we were informed by R. A. Ibata and G. F. Lewis that a similar work was going to be submitted based on the analysis of *HST*/near-IR camera and multiobject spectrometer images of APM 08279 + 5255 (Ibata et al. 1999). The two sets of observational data are in excellent agreement. Both studies (1) detect a third image, (2) derive similar positions and relative brightnesses for all three images, and (3) conclude that the third image is likely to be another lensed image of the same background QSO and construct a similar lens model based on this assumption. Although our work was carried out

independently of their work, we have opted to incorporate their results whenever they provide critical pieces of information to understand this object.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Near-IR Imaging

The *K*-band images of APM 08279 + 5255 were taken on the night of UT 1998 October 3 with the near-IR camera (NIRC; Matthews & Soifer 1994) on the Keck I telescope on Mauna Kea in Hawaii. The NIRC uses a Hughes-SBRC 256×256 InSb array as the detector and is attached to the f/25 forward Cassegrain focus of the telescope, producing a pixel scale of $0''.15 \text{ pixel}^{-1}$ with a field of view of $38''$ on a side. For this observation, the NIRC image converter (Matthews et al. 1996) was used with the NIRC to achieve a high spatial resolution. The image converter changes the beam from f/25 to f/180, producing a pixel scale of $0''.0206 \text{ pixel}^{-1}$ with a field of view of $5''.3$ on a side. For *K*-band imaging, the integration time was 10 s per image. The highest resolution image was produced by combining the four images (40 s total) with the minimum image size (i.e., selective shift and add). The extremely good seeing that night resulted in an FWHM of $0''.15$ in this *K*-band image.

2.2. Mid-IR Imaging

The 12.5 and 17.9 μm images were initially taken on the night of UT 1998 October 3 using the MIRLIN mid-IR camera (Ressler et al. 1994) on the Keck II telescope. MIRLIN uses a Boeing 128×128 Si:As array and is attached to the f/40 bent Cassegrain visitor port of the telescope, producing a pixel scale of $0''.138 \text{ pixel}^{-1}$ with a field of view of $17''$ on a side. The total integration time was 15 minutes at each wavelength. These images were used to measure the mid-IR flux density of APM 08279 + 5255. Calibration was done by observing bright stars tied to the *IRAS* calibration at 12 and 25 μm (Beichman et al. 1988).

The higher spatial resolution 12.5 μm image of APM 08279 + 5255 was taken on the night of UT 1999 November 25 using the Long Wavelength Spectrometer (LWS; Jones & Puetter 1993) on the Keck I telescope in the imaging mode. The LWS uses a Boeing 128×128 Si:As array and is attached to the f/25 forward Cassegrain focus of the telescope, producing a pixel scale of $0''.08 \text{ pixel}^{-1}$ with a field of view of $10''.2$ on a side. The seeing was $0''.4$ FWHM, and the total integration time was 27 minutes.

2.3. Near-IR Photometry

Near-IR photometry was obtained on 1998 November 3 with the InSb camera on the 200 inch telescope at Palomar Observatory. Calibration was done by measuring stars listed by Elias et al. (1982).

The magnitudes and flux densities reported here are listed in Table 1. All the photometry was done with a $4''$ diameter beam.

3. RESULTS

3.1. The *K*-Band Image

The *K*-band gray-scale image with scale $0''.0206 \text{ pixel}^{-1}$ is shown in Figure 1a with the contour map of the same data in Figure 1b. It is immediately clear from this image that the *K*-band image consists of two bright components, which is

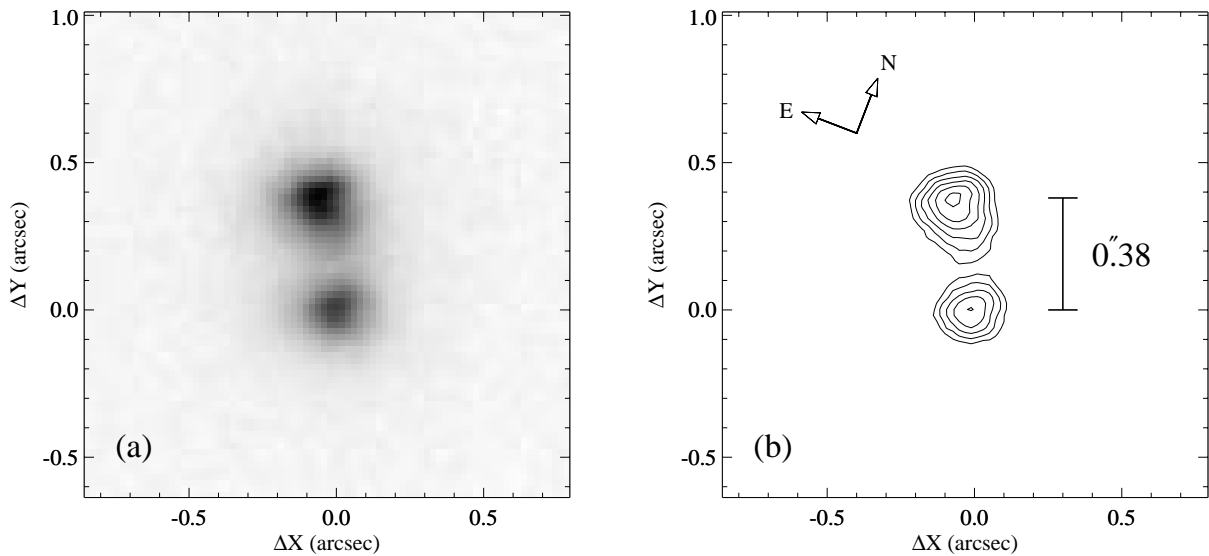


FIG. 1.—(a) *K*-band image of APM 08279 + 5255 taken with the NIRC with a pixel scale of $0''.0206 \text{ pixel}^{-1}$. The seeing was $0''.15$ FWHM. The coordinate origin was taken at the position of the lower component. The north is 21° clockwise from the vertically up direction (see the *arrows* in *b*). We chose not to rotate the image to avoid any smoothing. This orientation is adopted for all the subsequent images/contours in this paper except for Fig. 3, whose orientation differs by 3° . (b) Contour map of (a). The lowest contour is 18σ above the sky, and the subsequent contour levels increase by a factor of 1.25.

consistent with the previous observations by Irwin et al. (1998) and Ledoux et al. (1998). The northern brighter source is slightly extended to the southwest. Since the southern source is quite circularly symmetric, this suggests that the extension in the northern source is a third, fainter component.

We performed a point-spread function (PSF) fitting using DAOPHOT (Stetson 1987) on the *K*-band image. First, it was assumed that the two main bright components are basically point sources and that we could construct the PSF by using the upper half of the upper component and the lower half of the lower component. Two axisymmetric PSFs were first produced from two half-PSFs by self-reflection, and their average was taken to produce the final PSF. In other words, we assumed that the PSF is symmetric with respect to the horizontal axis in Figure 1.

To determine the position of the third component accurately enough as the starting point for the PSF fitting, we first performed the two-PSF subtraction. The position of the third component was determined in the residual image, and with this added information, we then performed the three-PSF subtraction.

The three components we have finally found are shown in Figures 2a and 2b together with their contour maps (Figs. 2c and 2d). We refer to these components as A, B, and C in descending order of brightness. The positions and relative

brightnesses determined from the PSF fitting for each component are listed in Table 2. Using the flux ratios, the *K* magnitudes of individual components were derived from a magnitude of $K = 12.08$ mag for the total system. The derived FWHMs indicate that the seeing was $0''.15$ when the image was taken. The FWHM of the component C indicates that this component is also pointlike. For our further discussions, we assume that the *K*-band image of APM 08279 + 5255 consists of three point sources.

Overall, our measured positions and relative brightnesses of the three components are in good agreement with the values derived by Ibata et al. (1999).

3.2. The 12.5 μm Image

The LWS 12.5 μm image of APM 08279 + 5255 is shown in Figure 3a. Figure 3b is an artificial image showing how the three components detected in the *K* band would look if observed with the LWS pixel scale ($0''.08 \text{ pixel}^{-1}$) under the same seeing condition (FWHM = $0''.4$). This image was simulated using the parameters listed in Table 2. Contour maps of the images are also shown in Figures 3c and 3d, respectively.

The morphological resemblance is clear. Although there might be a small difference in morphology between the two images, we cannot say with confidence that it is real. The 12.5 μm image shape changes from image to image con-

TABLE 2
POSITIONS AND BRIGHTNESSES OF THREE POINT SOURCES

Components	ΔX (arcsec)	ΔY (arcsec)	$\Delta\alpha$ (arcsec)	$\Delta\delta$ (arcsec)	Flux Ratio	<i>K</i>	χ^2/dof	FWHM (arcsec)
A.....	-0.060	0.377	-0.191	-0.330	1.28	12.82	0.93	0.15
B.....	0.000	0.000	0.000	0.000	1.00	13.09	0.93	0.15
C.....	-0.002	0.245	-0.090	0.228	0.26	14.55	0.92	0.15
Total.....						12.08		

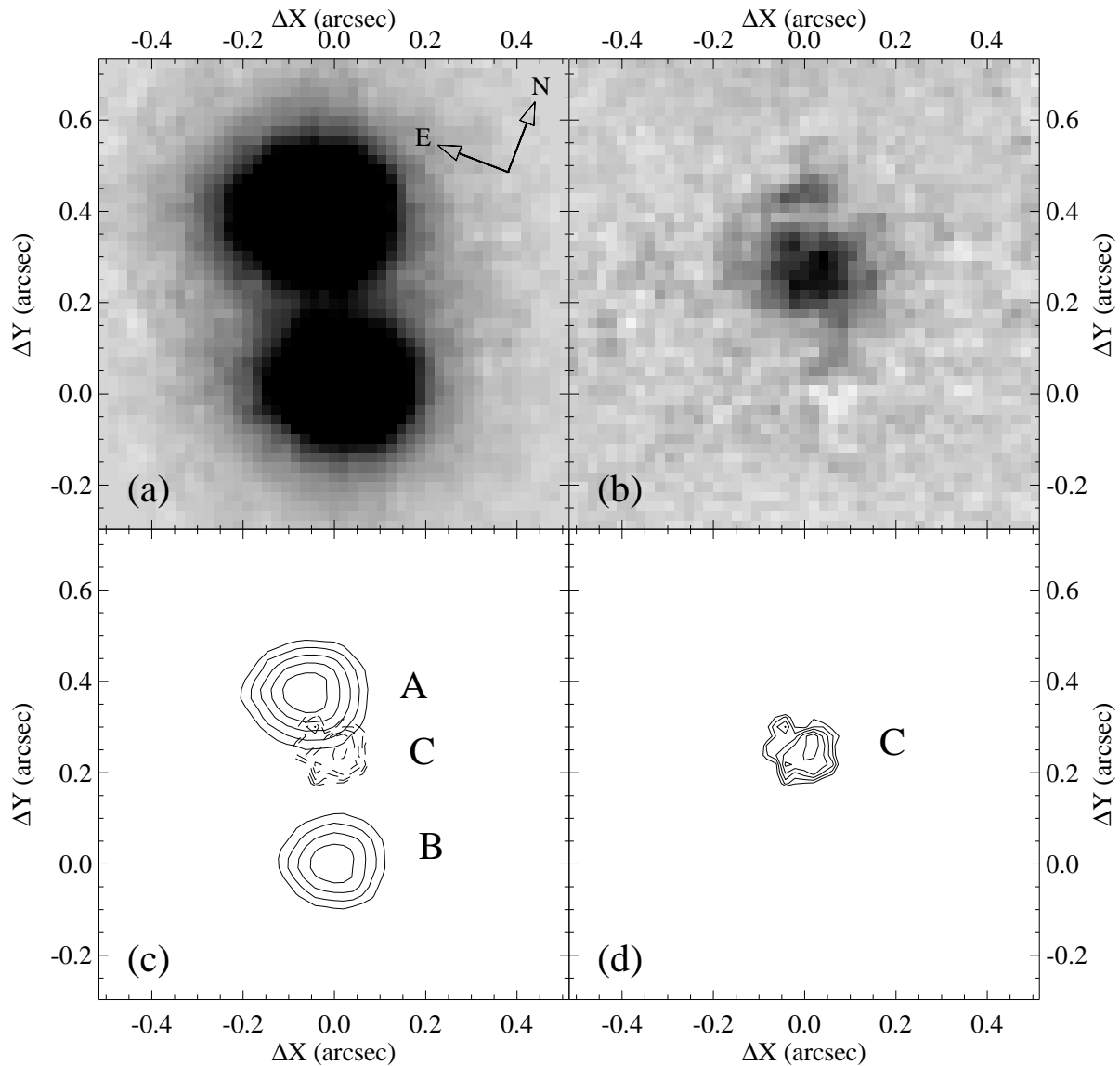


FIG. 2.—(a) K -band image of APM 08279 + 5255 showing components A and B. Component C was subtracted from Fig. 1a. The gray scale is the same as that of (b) so that the relative brightness can be compared directly. The coordinate origin was taken at the position of component B. (b) K -band image showing component C. Components A and B shown in (a) were subtracted from Fig. 1a. (c) Contour map of (a). The lowest contour level is 18σ above the sky, and the subsequent contour levels increase by a factor of 1.25. Component C, shown in (d), is overlaid. (d) Contour map of (b). The lowest contour level is 9σ above the sky, and the subsequent contour levels increase by a factor of 1.1.

siderably because of the lower signal-to-noise ratio, and the image shape might have been smeared when a large number of images were combined. Therefore, based on the overall ellipticity of the image contours, we conclude that the image configuration at $12.5\ \mu\text{m}$ is similar to that in the K band.

4. DISCUSSION

4.1. The Lens Model

To construct a gravitational lens model, we use the elliptical effective lensing potential ψ in the following form (Blandford & Kochanek 1987; Narayan & Bartelmann 1999):

$$\psi(\theta_1, \theta_2) = \theta_E [\theta_c^2 + (1 - \epsilon)\theta_1^2 + (1 + \epsilon)\theta_2^2]^{1/2}, \quad (1)$$

where θ_E is the Einstein radius, θ_c and ϵ are the core radius and ellipticity of the lensing potential, and θ_1 and θ_2 are rectangular coordinates in radians with respect to an arbi-

trarily defined optic axis. Although we treat the Einstein radius itself as a free parameter, it can also be expressed as

$$\theta_E = \frac{D_{1s}}{D_s} 4\pi \frac{\sigma_v^2}{c^2}, \quad (2)$$

where D_{1s} is the standard angular distance between the lens and the source (cf. Fukugita et al. 1992), D_s is the angular distance from the observer to the background source, σ_v is the internal velocity dispersion of the lensing galaxy (i.e., the mass), and c is the speed of light. For a given Einstein radius, this equation sets the constraints on the mass and redshift of the lens. In addition to these parameters specifying the shape of the potential, the center position (x_l, y_l) and the position angle (γ) of the lensing potential must be specified. All together, the model contains six unknown parameters (θ_E , θ_c , ϵ , γ , x_l , and y_l).

The major uncertainty with APM 08279 + 5255 is the nature of component C. There are two possibilities: it is

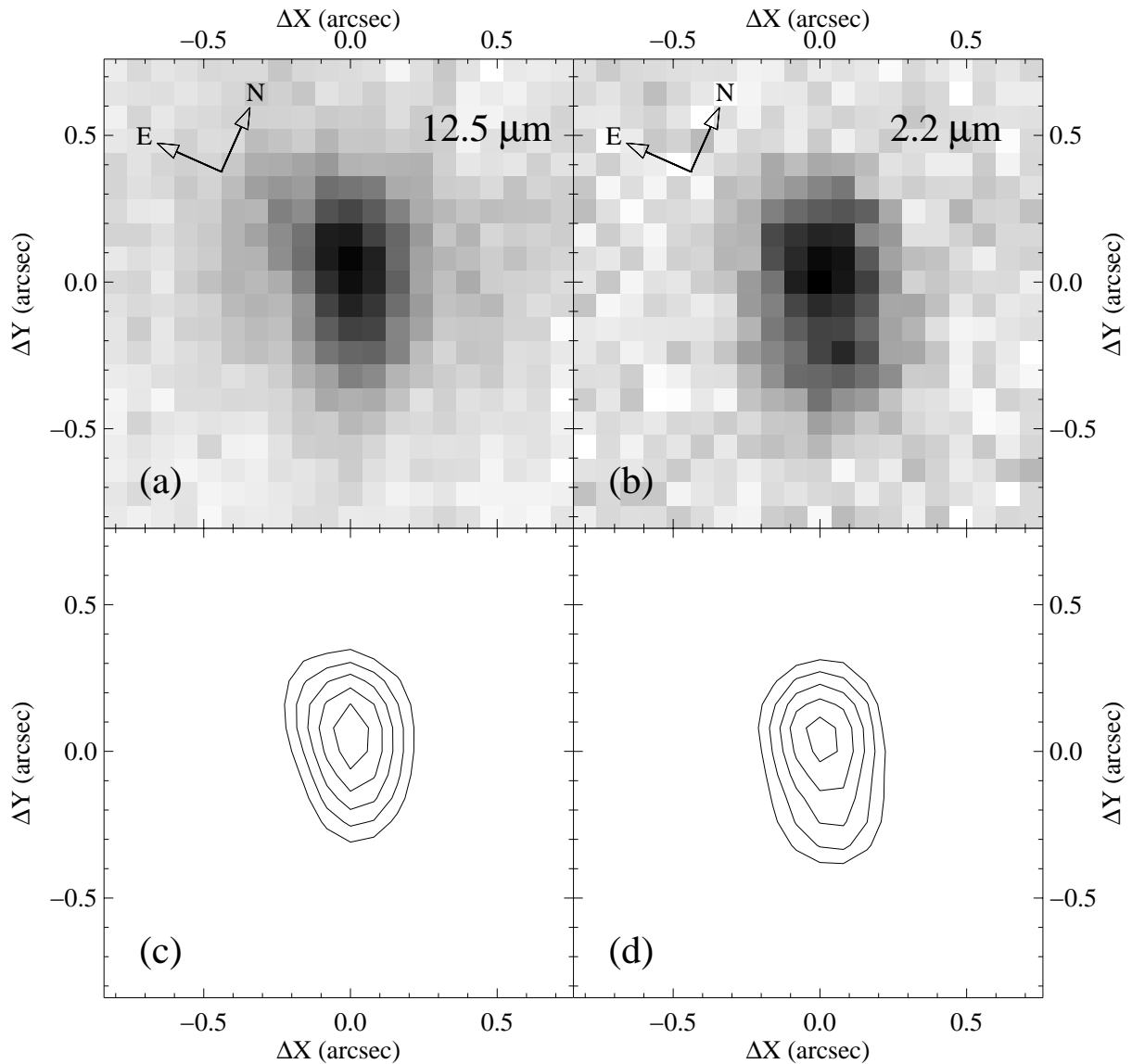


FIG. 3.—(a) 12.5 μm image of APM 08279 + 5255 taken with the LWS. The pixel scale is $0''.08 \text{ pixel}^{-1}$. The seeing is estimated to be $\text{FWHM} \sim 0''.4$. The coordinate origin was taken arbitrarily. North is 24° clockwise from the vertically up direction, 3° different from that in the K -band image. (b) Artificial image constructed from the three components detected in the K band. Three point sources with the relative positions and fluxes listed in Table 2 were convolved with a Gaussian with an $\text{FWHM} = 0''.4$ and were sampled with a pixel scale of $0''.08 \text{ pixel}^{-1}$. Then, a Gaussian noise with the level seen in the LWS image (a) was added. The orientation is same as that of (a), and the coordinate origin was taken arbitrarily. (c, d) Contour maps of (a) and (b), respectively. The contour levels correspond to 40%, 50%, 60%, 70%, 80%, and 90% of the peak level in each image (the sky level is subtracted).

either a third lensed image of the same background source or the lensing galaxy. We will construct models based on both these assumptions and evaluate their validity based on the available observational data.

4.1.1. *Three-Image Model*

Three lensed images provide six constraints: two relative brightnesses and four coordinates giving two relative image positions with respect to the other. Since the number of model parameters is also six, we can determine the values of the parameters but cannot assess the goodness of the fit. The best-fit model was searched by taking component B as the reference and varying the parameters such that the source positions of components A and C coincide with that of B while the derived relative magnifications approach the observed flux ratios. Our best-fit model parameters are shown in Table 3. Figure 4 shows the profile of the effective

TABLE 3
LENS MODELS

Parameter	Three-Image	Two-Image
Einstein radius (θ_E)	$0''.29$	$0''.19$
Ellipticity (ϵ)	0.012	0.083
Core radius (θ_c)	$0''.21$	$0''$
Position angle (E of N)	79	100
Lens position ^a	$(-0''.074, 0''.205)$	$(-0''.090, 0''.228)$
Source position ^a	$(-0''.069, 0''.196)$	$(-0''.067, 0''.184)$
Magnification for A ^b	34	3
Magnification for B ^b	43	4
Magnification for C ^b	9	
Total magnification ^b	86	7

^a The positions are $(\Delta\alpha, \Delta\delta)$ from component B.

^b The magnification factors are for a point source.

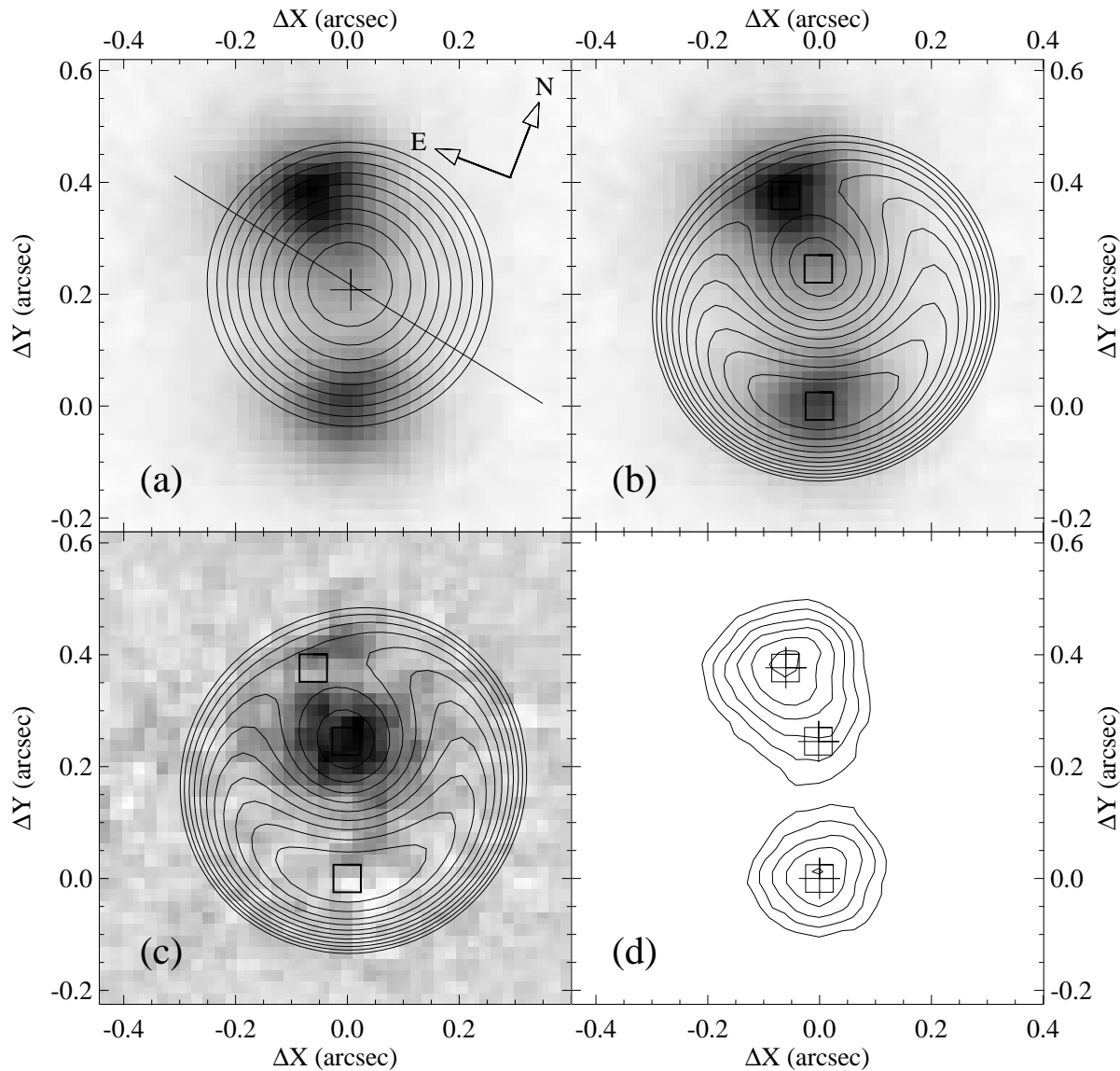


FIG. 4.—(a) Contour plot showing the effective lensing potential of the three-image model overlaid on the K -band image (Fig. 1a). The cross denotes the position of the background source while the solid line indicates the direction of the major axis of the potential. The coordinate origin was taken at the position of the component B. (b) Time delay surface overlaid on the K -band image. The three squares indicate the expected positions of the lensed images based on the model. (c) The same time delay surface overlaid on Fig. 2b, which contains the component C only. (d) Contour map from Fig. 1b with the three image positions measured in the K -band image (crosses) and those derived from the model (squares).

lensing potential, the time delay surface, and the expected image positions. Basically, this model reproduces the positions and relative brightnesses of three images well within the observational uncertainties. The lens is almost round ($\epsilon \sim 0.01$) and has a large core radius ($\theta_c \sim 0''.2$). This is because the three images are almost in a straight line (i.e., small ϵ) and the third image is very bright (i.e., large θ_c). The total magnification factor for a point source⁴ was calculated to be 86.

4.1.2. Two-Image Model

Ibata et al. (1999) presented the possibility that component C might be the lensing galaxy rather than a third lensed image. In this case, the number of the model param-

eters reduces to three (θ_E , ϵ , and γ). The core radius θ_c can be set to 0 because the lack of a third image implies a singular potential core while the position of component C directly determines the position of the lensing galaxy (x_l, y_l).⁵ On the other hand, two lensed images provide three constraints: one relative brightness and two coordinates giving one relative image position with respect to the other. Again, the number of the model parameters and that of the constraints are the same. The derived parameters are shown in Table 3. The major difference from the three-image model is the much lower value of total magnification (7). Also, the ellipticity of the potential is becoming significant (0.08). The overall structure of the time delay surface is very similar to that of the three-image model.

⁴ We originally derived a value of 71, which was quoted by Ibata et al. (1999), but our later calculation increased the value to 86, which agrees with Ibata et al.'s value of 90.

⁵ Our model is slightly different from that of Ibata et al. (1999) in that we fix the lens position at the position of component C. Their model treats the lens position as a free parameter.

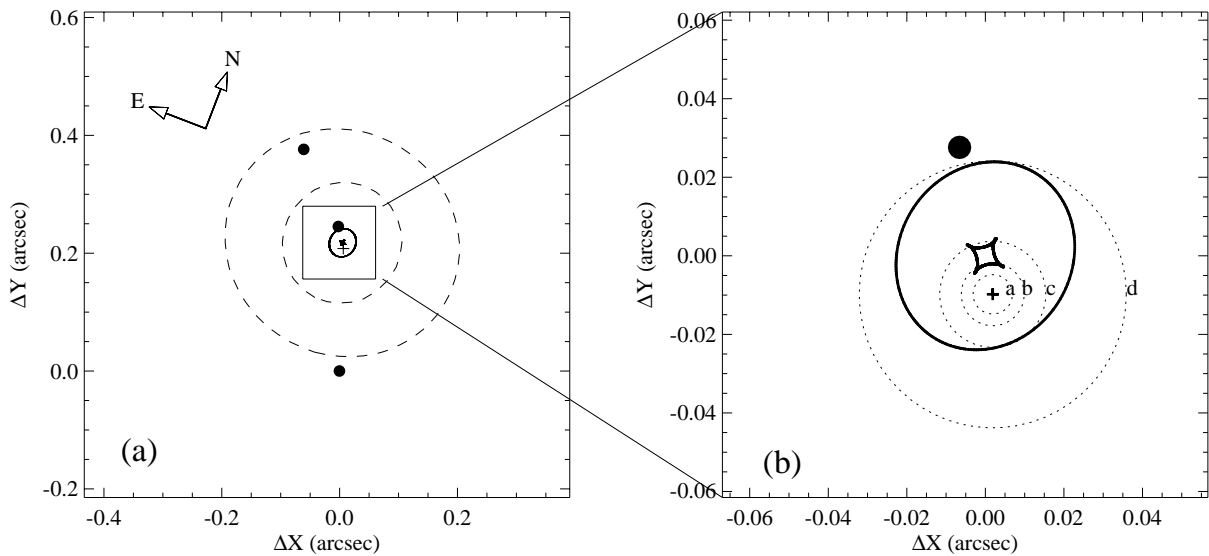


FIG. 5.—Three-image model. (a) Plot showing two critical curves (two outer dashed lines), two caustics (two inner solid lines in the square), the background QSO position (cross), and three lensed images (filled circles). The coordinate origin was taken at the position of the component B. (b) Plot magnifying the square region in (a). The dotted lines show the shapes of four extended sources (i.e., constant surface brightness disks) with different radii. The source radii of a, b, c, and d correspond to those of (a), (b), (c), and (d) in Figs. 7 and 9, respectively. The coordinate origin was taken at the center of the lensing potential.

4.2. Magnification of Extended Sources

The background source is likely to be spatially extended at longer wavelengths. Therefore, it is necessary to understand how the lens distorts and magnifies an extended source as the outer edge of the source approaches/crosses the caustics. For a background source that is a uniform circular disk, the lensed image can be constructed with the methods of Schramm & Kayser (1987). Since the surface brightness is preserved in gravitational lensing, the areal ratio between the source and the images gives the magnification factor.

For the two models, we show how the source crosses the caustics (Figs. 5 and 6) and how the shapes of the lensed

images change (Figs. 7 and 8). The behavior is similar in the two models: as the source size increases, it first forms an arc (Figs. 7b and 8b) and later turns into a ring (Figs. 7c and 8c). In the case of the three-image model, the ring quickly becomes a filled disk as a result of the third image, while the ring is not completely filled in the two-image model even with a source radius of 650 pc (Figs. 7d and 8d). Figure 9 shows how the total magnification factor changes as the source radius increases in the two models.

There are three major differences between the two models in terms of their response to extended sources. First, a much larger source size is required in the two-image model for each transition of the lensed image shape as shown in

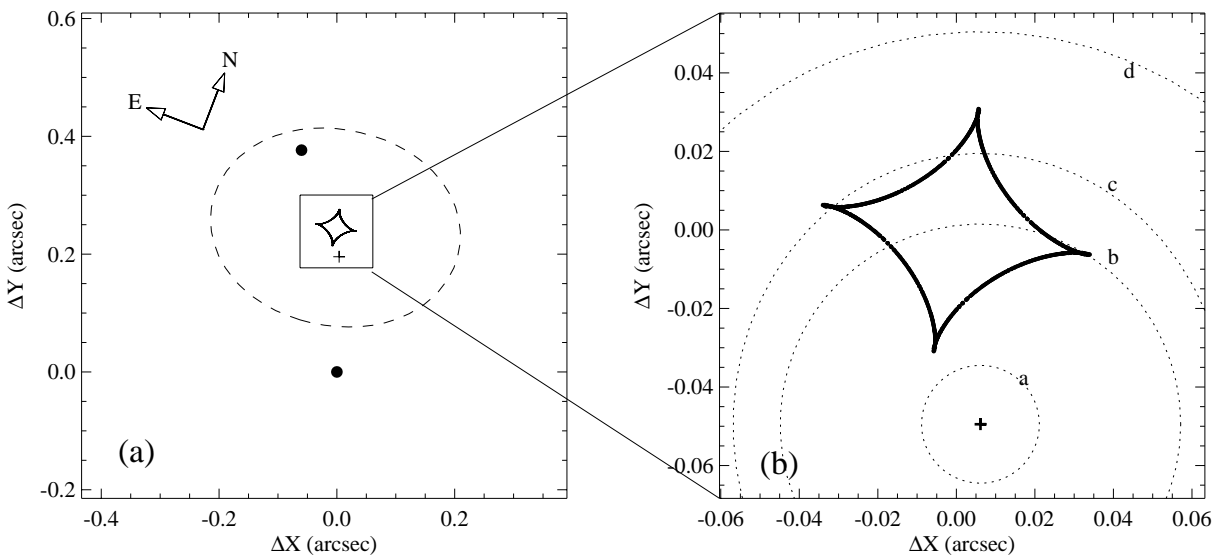


FIG. 6.—Two-image model. (a) Same as Fig. 5, except for the two-image model. Because of the singularity at the core (i.e., $\theta_c = 0$), there is only one caustic and one corresponding critical curve. (b) A plot magnifying the square region in (a). The dotted lines show the shapes of four extended sources (i.e., constant surface brightness disks) with different radii. The source radii of a, b, c, and d correspond to those of (a), (b), (c), and (d) in Figs. 8 and 9, respectively. The coordinate origin was taken at the center of the lensing potential.

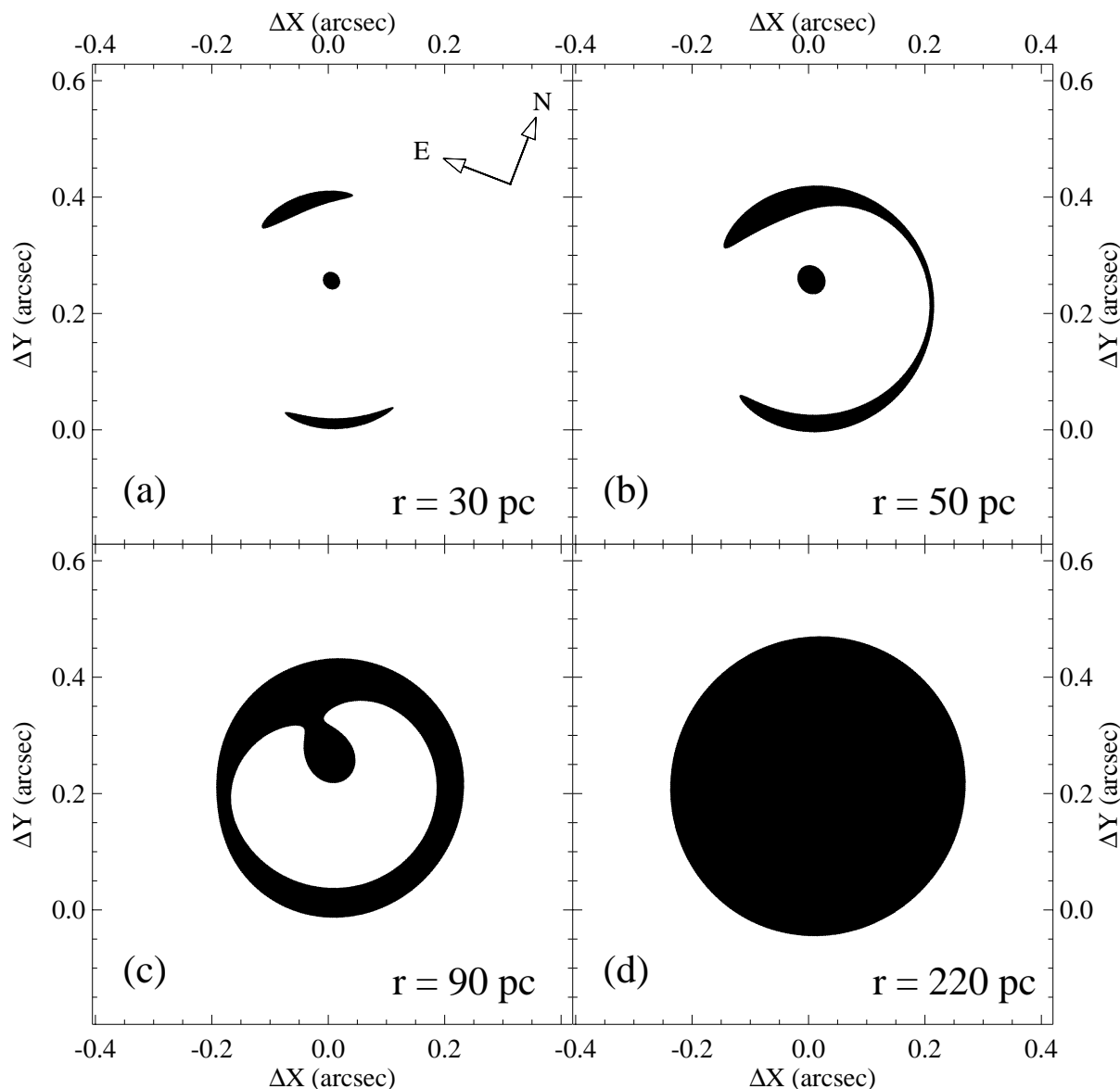


FIG. 7.—Gravitationally lensed images of an extended source produced by the three-image model. The intrinsic source was assumed to be a disk with a constant surface brightness. The radius of the source was assumed to be (a) $0''.005$ (30 pc), (b) $0''.008$ (50 pc), (c) $0''.0135$ (90 pc), and (d) $0''.034$ (220 pc), respectively. The surface brightness of the image is preserved by the gravitational lensing process. The coordinate origin was taken at the position of the component B.

Figure 8. Second, the magnification is much greater in the three-image model. Figure 9 shows that the magnification factor of the three-image model could be as large as ~ 120 when the source radius is 50–90 pc, while that of the two-image model is more than an order of magnitude less (~ 7) for the same radius range. Third, the magnification factor of the two-image model hardly changes with an increasing source size, while the magnification factor of the three-image model is very sensitive to such a change (Fig. 9). In other words, the effects of differential magnification could be significant with the three-image model.

4.3. Differential Reddening

One uncertainty underlying the discussion so far is differential reddening. For example, if the three-image model is correct, the line of sight to component C intersects the lensing galaxy at a point only $\sim 0''.03$ from the galaxy's

center (Fig. 5b). Such an angular separation corresponds to 200–250 pc at a lensing galaxy's redshift of $0.5 < z < 4$. If this is the case, the brightness of component C might be more heavily affected by the reddening in the lensing galaxy than those of the other two components. This would produce observed flux ratios considerably different from the intrinsic ones.

However, the currently available data seem to indicate that differential reddening is not significant in this system. Ibata et al. (1999) noted that the three components have almost identical colors from 1.10 to $2.05 \mu\text{m}$. Our K -band image also does not show any sign of change in the flux ratio or image morphology, which would have resulted if component C brightens significantly at longer wavelengths. The $12.5 \mu\text{m}$ image also seems to be consistent with the K -band image. Therefore, it seems unlikely that the derived models are in serious error due to differential reddening.

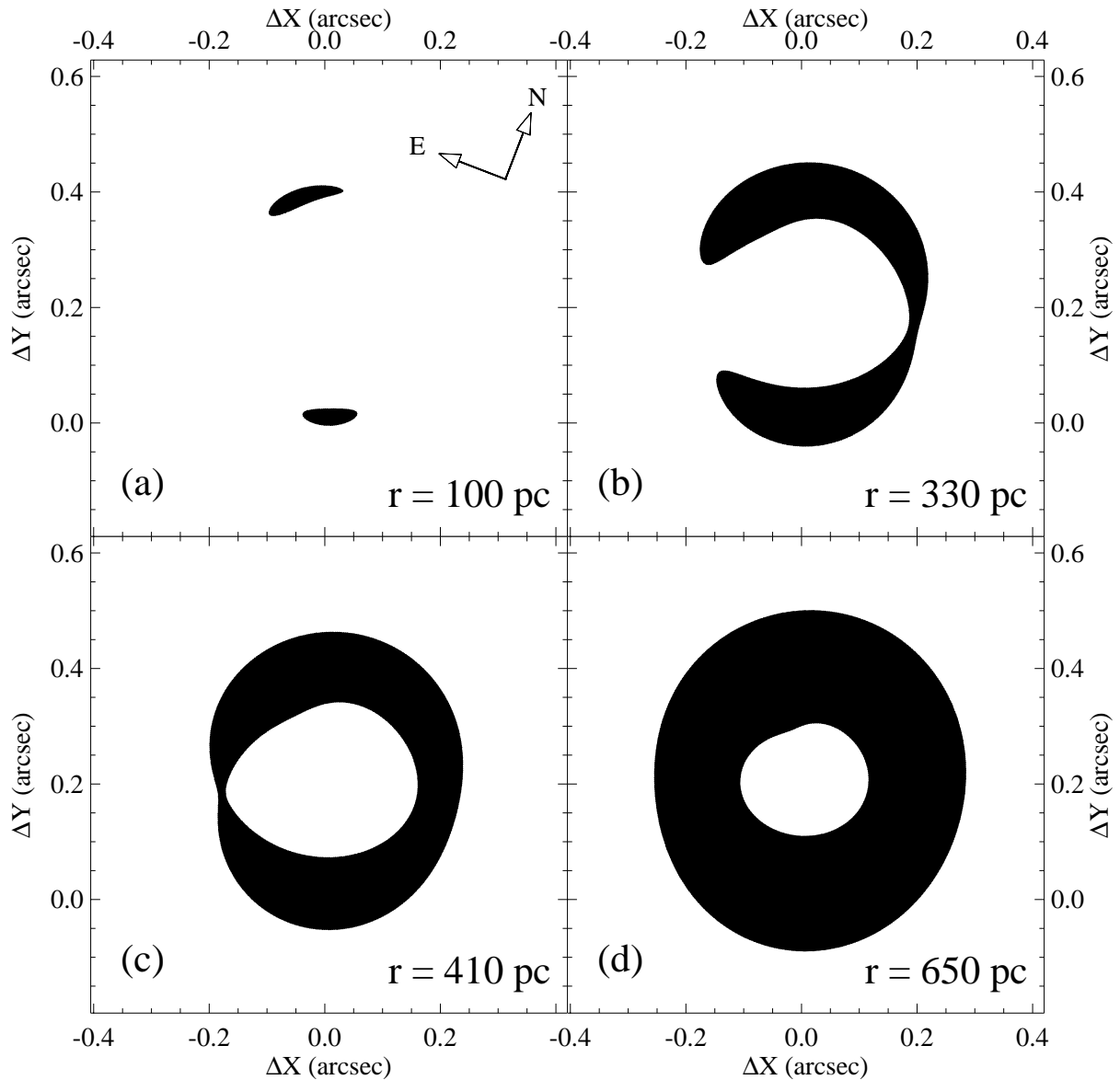


FIG. 8.—Same as Fig. 7, except for the two-image model. The radius of the source was assumed to be (a) $0''.015$ (100 pc), (b) $0''.051$ (330 pc), (c) $0''.063$ (410 pc), and (d) $0''.1$ (650 pc), respectively.

4.4. The Nature of the Third Image

As seen in Figure 9, depending on whether component C is a third lensed image or a lensing galaxy, the magnification factor could be drastically different. Therefore, the nature of component C is a decisive factor when determining the intrinsic properties of APM 08279 + 5255. We list three arguments favoring the idea that component C is a third lensed image rather than the lensing galaxy.

4.4.1. The Large Apparent Brightness of Component C

If component C is the lensing galaxy, then it cannot be an ordinary field galaxy. The small separation between the lensed images ($0''.4$) requires the lensing galaxy to be either a low-mass low-redshift galaxy or a massive high-redshift galaxy in order to not split the lensed images too far apart. However, neither type of galaxy with a normal mass-to-light ratio could produce such a bright apparent magnitude as $K = 14.5$ mag. More quantitatively, inserting $\theta_E = 0''.2$ in equation (2), we obtain possible combinations of the lensing

galaxy redshift and velocity dispersion (z_l, σ_v [km s^{-1}]) as (0.5, 100), (1, 120), (2, 170), and (3, 280). To illustrate how much the lensing galaxy must be overluminous, if we take an L^* galaxy (i.e., $\sigma \sim 200 \text{ km s}^{-1}$) as the lens, it implies that $z_l \sim 2$, but the expected observed K magnitude of such a galaxy would be $K \sim 20$ mag. Therefore, it requires such a lensing galaxy to be overluminous by more than 5 mag. Together with the evidence that component C is pointlike, this would require that component C is a luminous active galactic nucleus (AGN)/QSO nucleus of the lensing galaxy. Although such QSO-AGN/QSO gravitational lensing may happen (Gott & Gunn 1974), the probability for such an event is in general very small.

4.4.2. Dark Ly α Forest Line Cores

The high-resolution Keck HIRES spectrum of APM 08279 + 5255 (Ellison et al. 1999a, 1999b) shows no residual flux in the core of strong Ly α forest lines up to an observed wavelength of 5715 Å. If component C is a lower redshift

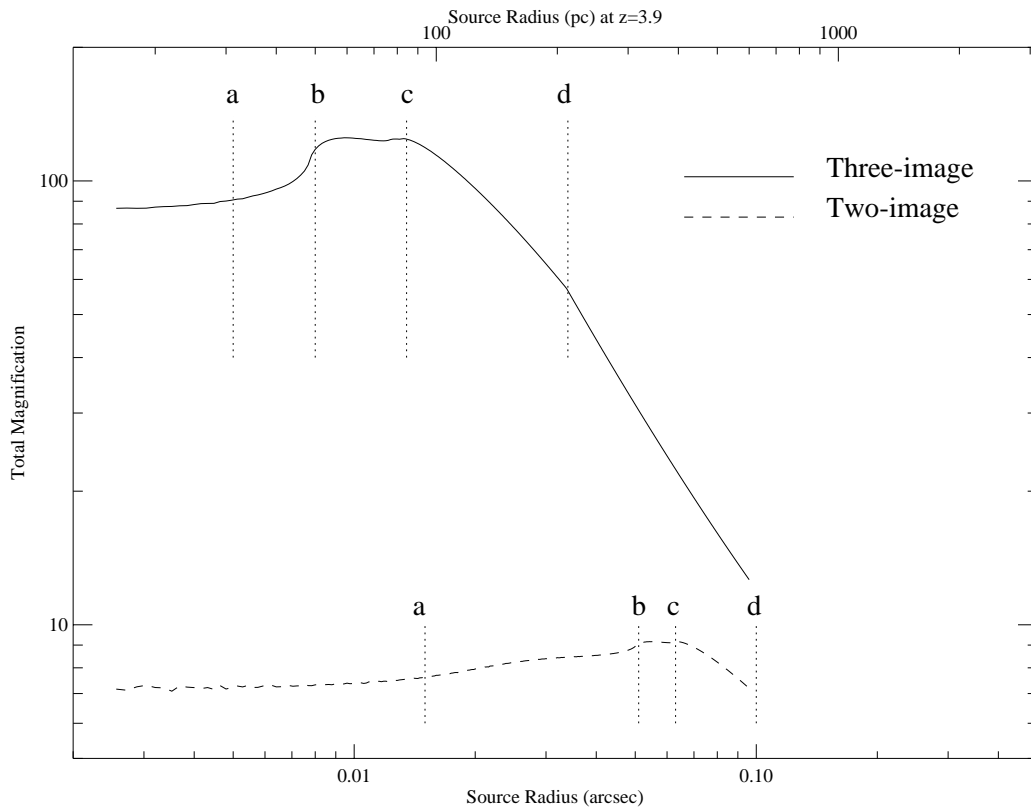


FIG. 9.—Total magnification produced by the lens models as a function of the source radius. The source is assumed to be a disk with a constant surface brightness. The solid curve shows the magnification factor of the three-image model, while the dashed curve shows that of the two-image model. The vertical dotted lines indicate the source radii of (a), (b), (c), and (d) in Figs. 5 and 7 for the three-image model and Figs. 6 and 8 for the two-image model.

AGN/QSO, its continuum flux should be easily detectable in the core of these strong Ly α lines, given the high signal-to-noise ratio of this HIRES spectrum. This means that if component C is an AGN/QSO, its redshift must be larger than 3.7, and it seems rather contrived if a $z = 3.9$ QSO is gravitationally lensed by another QSO system at $z > 3.7$.

4.4.3. Color

As already mentioned in the discussion of differential reddening, components A, B, and C have almost identical colors from 1.1 to 12.5 μm . This is easy to understand if component C is also a lensed image of the same background source.

Based on these arguments, we conclude that component C is a third lensed image of the QSO. Therefore, we investigate the intrinsic properties of APM 08279 + 5255 based on the three-image model, although in the end this question can be settled with spectroscopy of component C. If, however, the two-image model is correct, its consequences are easy to derive because this model is not sensitive to differential magnification; the magnification factor is ~ 7 –10 over the relevant spectral range, and therefore APM 08279 + 5255 must be an extremely luminous object with the intrinsic bolometric luminosity $\sim 5 \times 10^{14} L_{\odot}$. Also, the shape of the intrinsic SED must be close to what is observed.

4.5. Differential Magnification

In this section, we discuss the consequences for differential magnification of our preferred three-image model. Unlike the two-image model, the magnification factor of the

three-image model is sensitive to the source size (Fig. 9). Therefore, the effects of differential magnification must be evaluated before the intrinsic properties of the lensed QSO can be discussed. For the discussions below, references are made with respect to the rest-frame wavelength of APM 08279 + 5255.

4.5.1. Magnification in the Rest-Frame UV/Optical

The fact that three lensed images are completely pointlike in the rest-frame B band (observer's K band) sets the upper limit of ~ 20 pc on the source radius. If the source radius were larger than 20 pc, we should see the effects of image elongation seen in Figure 7a. In the rest-frame UV, the source size is expected to be either comparable to or smaller than that in the rest-frame optical. From Figure 9, it can be seen that the magnification factor corresponding to this range of source size is ~ 90 , which is same as the value derived by Iбата et al. (1999).

4.5.2. Magnification in the Rest-Frame Near-IR

Since the spatial resolution of the rest-frame near-IR (observed 12.5 μm) image is not high enough to detect the morphology of each component, it is not possible to set as stringent a limit on the source radius as in the rest-frame optical. As seen in Figure 7, once the source radius reaches 50 pc, components A and B will connect with each other and form an arc, and this would produce a lower ellipticity in the resultant image (Fig. 10). However, this has not been seen in Figures 3a and 3c. Based on the overall ellipticity of the rest-frame near-IR image, we conclude that the source radius in the rest-frame near-IR (observer's 12.5 μm) must

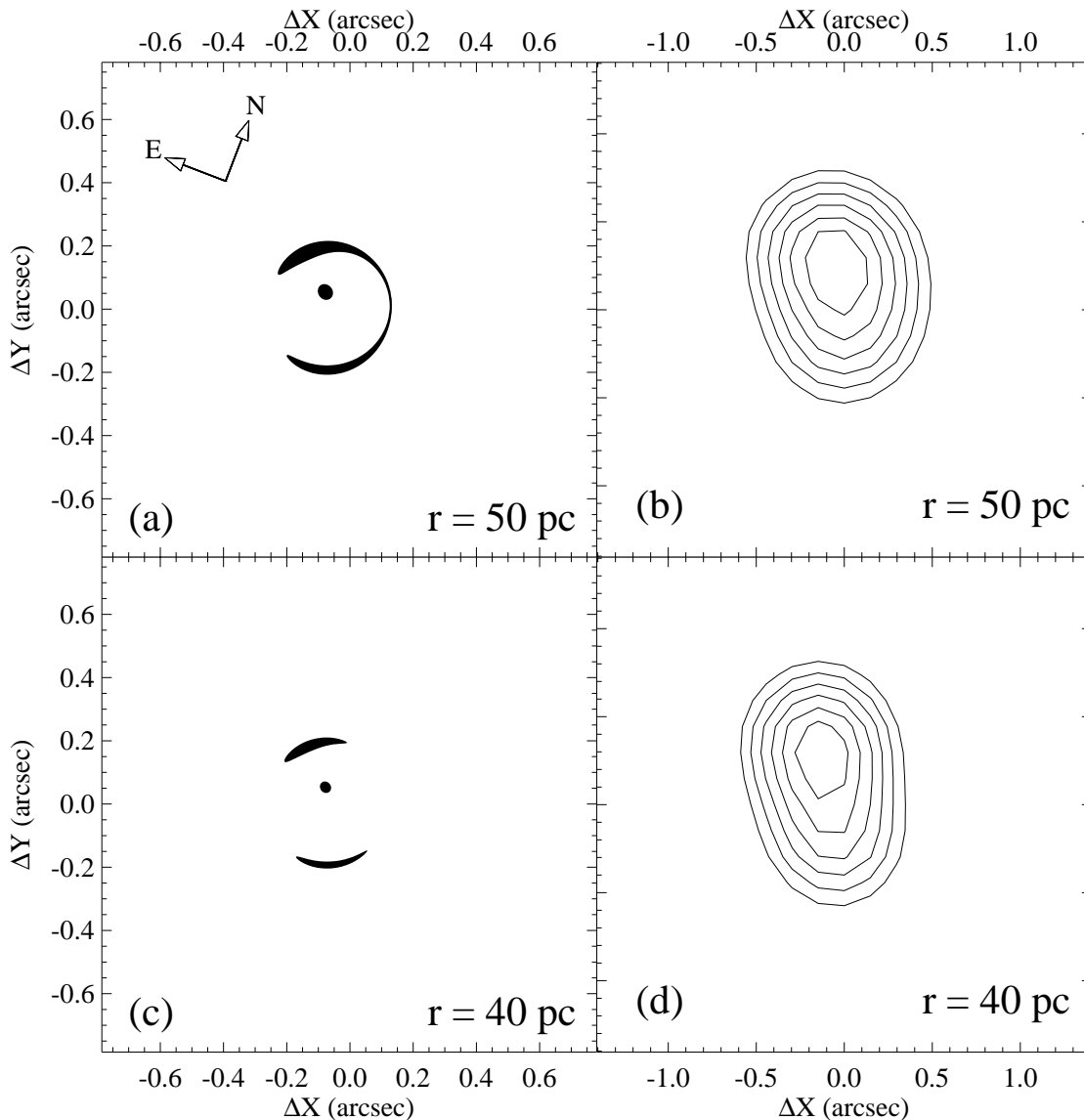


FIG. 10.—(a) Expected lensed image of APM 08279 + 5255 with an intrinsic source radius of $0''.008$ (50 pc) in the three-image model. (b) Contour map of (a) convolved with a Gaussian PSF with an FWHM of $0''.4$ and rebinned to a pixel scale of $0''.08 \text{ pixel}^{-1}$, simulating the LWS $12.5 \mu\text{m}$ image. The contour levels are 40%, 50%, 60%, 70%, 80%, and 90% of the peak level (the sky level is subtracted). (c) Expected lensed image with an intrinsic source radius of $0''.006$ (40 pc) in the three-image model. (d) Contour map of the image (c) convolved with a Gaussian PSF with an FWHM of $0''.4$. The contour levels are 40%, 50%, 60%, 70%, 80%, and 90% of the peak level (the sky level is subtracted). The difference of ellipticity between (b) and (d) is clearly noticeable.

be less than 50 pc, which corresponds to a magnification factor of 90–120 (Fig. 9).

4.5.3. Magnification in the Rest-Frame Mid-IR

There exists no high-resolution spatial information in the rest-frame mid-IR (observer's far-IR) which can be used to determine the magnification factor directly. However, it is possible to put constraints on the magnification factor based on the rest-frame mid-IR luminosity.

With the assumption that the mid-IR emitting region is intrinsically a circular disk on the sky with a constant specific intensity, the mid-IR SED can be modeled with the following expression:

$$f_{\nu_{\text{obs}}} = m Q_{\text{em}}(v_e) B_{\nu_e}(T_d) (1 + z_s)^{-3} \pi \left(\frac{r}{D_s} \right)^2. \quad (3)$$

Here m is the magnification factor, Q_{em} is the dust emissivity, B_{ν_e} is the Planck function evaluated at the emitted

frequency, T_d is the dust temperature, z_s is the redshift of the background source, and r is the intrinsic radius of the emitting region. The Planck function is evaluated at the emitted frequency (B_{ν_e}), while the observed flux density is expressed at the observed frequency [$f_{\nu_{\text{obs}}}$; $\nu_e = \nu_{\text{obs}}(1 + z_s)$].

As the dust temperature, we adopt the CO gas temperature of 200 K derived by Downes et al. (1999) from the ratio of the CO (4–3) and (9–8) lines. If this 200 K region is strongly magnified, the dust global temperature could be much lower than 200 K, but it does not affect our discussion here because dust at a temperature significantly below 200 K would not provide a significant flux in the rest-frame mid-IR.

Only specific combinations of m and r are allowed by the lens model (Fig. 9). For each allowed combination, the corresponding value of Q_{em} is determined such that equation (3) reproduces the observed *IRAS* $100 \mu\text{m}$ flux. Since $100 \mu\text{m}$ is close to the peak of a 200 K blackbody at a redshift of

3.91, the value of Q_{em} essentially scales the total energy output of such a blackbody. Therefore, its value can be regarded as equivalent to that of the Planck-averaged dust emissivity (Draine & Lee 1984).

As long as the dust emissivity Q_{em} is larger than ~ 0.03 , it is always possible to find a set of a source radius and a magnification factor which reproduces the observed 100 μm flux. However, the emissivity cannot be smaller than this because the intrinsic source size would become larger than $0''.3$, which would produce a gravitationally magnified image with a diameter $\sim 1''$, roughly the upper limit on the millimeter source size set by Downes et al. (1999). A Planck-averaged emissivity of 0.03 is similar to that of astronomical silicate grains with a radius 0.1 μm at 200 K as found by Draine & Lee (1984).

Depending on the dust emissivity, the magnification factor in the mid-IR could be anywhere between 4 ($Q_{\text{em}} = 0.03$) and 120 ($Q_{\text{em}} = 1$), which corresponds to the source radius of 1.8 kpc and 60 pc, respectively. The case of $Q_{\text{em}} = 1$ corresponds to an optically thick source of temperature 200 K. The source radius of the 200 K component becomes larger with a smaller dust emissivity because dust grains can be heated to 200 K at a farther distance from the central source.

4.5.4. Magnification in the Rest-Frame Far-IR/Submillimeter

The range of possible magnification factors in the rest-frame far-IR/submillimeter is the same as that in the mid-IR (i.e., 4–120). However, it cannot exceed the magnification factor in the mid-IR since the far-IR/submillimeter-emitting region is expected to be larger than the mid-IR-emitting region. The magnification factor could be exactly the same in the rest-frame mid-IR and far-IR/submillimeter if the emission from the 200 K component also dominates in the latter wavelength regime.

Table 4 summarizes the derived magnification factors at different wave bands and the corresponding source sizes. It can be seen that the effects of differential magnification are negligible through the rest-frame UV, optical, and near-IR, while they could potentially be significant in the rest-frame mid-IR/far-IR/submillimeter.

4.6. Intrinsic Properties

4.6.1. Spectral Energy Distribution

From the rest frame visible to near-IR, the magnification factors are estimated to be ~ 100 , and the intrinsic SED, basically unaffected by differential magnification, is extremely flat ($f_{\nu} \propto \nu^{-1}$, Fig. 11). On the other hand, in the rest-frame mid-IR/far-IR/submillimeter, the exact magnification factors are not known. Therefore, we derive instead the possible range of the intrinsic SED allowed by the model.

The allowed range can be calculated based on the fact that the lens model requires the magnification factor to be 4–120 in the rest-frame mid-IR/far-IR/submillimeter. In

Figure 11, we empirically fit the observed SED with the following expression:

$$f_{\nu_{\text{obs}}} \propto B_{\nu_e}(T_d = 200 \text{ K})(1 - e^{-\tau_{\nu_e}}), \quad (4)$$

where τ_{ν_e} is the optical depth parametrized as

$$\tau_{\nu_e} = \left(\frac{\nu_e}{\nu_0}\right)^2. \quad (5)$$

Here ν_0 is set to be 1.5 THz (i.e., 200 μm). The possible range of the intrinsic SED (Fig. 11, *shaded area*) is determined by demagnifying the observed SED fit by factors between 4 and 120. The upper limit corresponds to the case in which the dust emissivity is low (0.03) and therefore the 200 K dust region is large, resulting in a small magnification factor, while the lower limit corresponds to the case in which the dust emissivity is unity (i.e., blackbody) and therefore the 200 K region is small, resulting in a large magnification factor.

As seen in Figure 11, in principle the intrinsic SED of APM 08279+5255 could strongly peak at $\lambda_{\text{rest}} \sim 20 \mu\text{m}$. However, such an SED is unlikely. If the SED strongly peaks in the rest-frame mid-IR, the dust covering factor around the central energy source must be large. However, as can be seen in Figure 11, the intrinsic SED is extremely flat at $\lambda_{\text{rest}} < 2 \mu\text{m}$, which means that our line of sight to the central QSO is relatively dust-free. Therefore, if the SED strongly peaks in the mid-IR, it must mean that we are looking into a heavily dust-enshrouded QSO through a relatively transparent hole, which seems unlikely. We believe it more likely that the intrinsic SED is relatively flat up to $\lambda_{\text{rest}} = 20 \mu\text{m}$ and drops at longer wavelengths (Fig. 11, *dark shaded region*).

4.6.2. Bolometric Luminosity

If we assume that the intrinsic SED is flat up to the rest-frame mid-IR, the characteristic magnification factor of APM 08279+5255 can be taken as ~ 100 . Therefore, the intrinsic bolometric luminosity is estimated to be $5 \times 10^{13} L_{\odot}$. The IR luminosity at $\lambda > 10 \mu\text{m}$ is $1 \times 10^{13} L_{\odot}$. Because most of the luminosity is coming out at shorter wavelengths, we can determine the luminosities without knowing the precise shape of the rest-frame far-IR/submillimeter SED.

4.6.3. Dust Properties

Figure 11 shows that the mid-IR/far-IR/submillimeter SED of APM 08279+5255 is roughly consistent with those of lower redshift IR-luminous galaxies/QSOs. However, since we cannot constrain the intrinsic SED at $\lambda_{\text{rest}} > 100 \mu\text{m}$ to better than a factor of 10, it is not possible to set meaningful limits on intrinsic properties of this object such as the mass and temperature of dust.

The main sources of uncertainty are the dust emissivity and the effects of differential magnification. As seen in equation (3), the magnification factor is inversely proportional to the dust emissivity. Since the dust emissivity is not well known even in the local universe, this introduces a large uncertainty in the magnification factor and therefore in the intrinsic luminosity of the dust emission. In addition, there is a possibility that the magnification factor may systematically decrease at longer wavelengths because cooler regions have larger spatial extent (Eisenhardt 1996; Blain 1999). If this is the case, there may exist a cold (e.g., 50 K) massive dust component which is not seen in the observed spectrum

TABLE 4
MAGNIFICATION FACTORS FOR THE THREE-IMAGE MODEL

Parameter	UV/Optical	Near-IR	Mid-IR/Far-IR/ Submillimeter
Magnification	90	90–120	4–120
Source radius (pc).....	<20	<50	60–1800

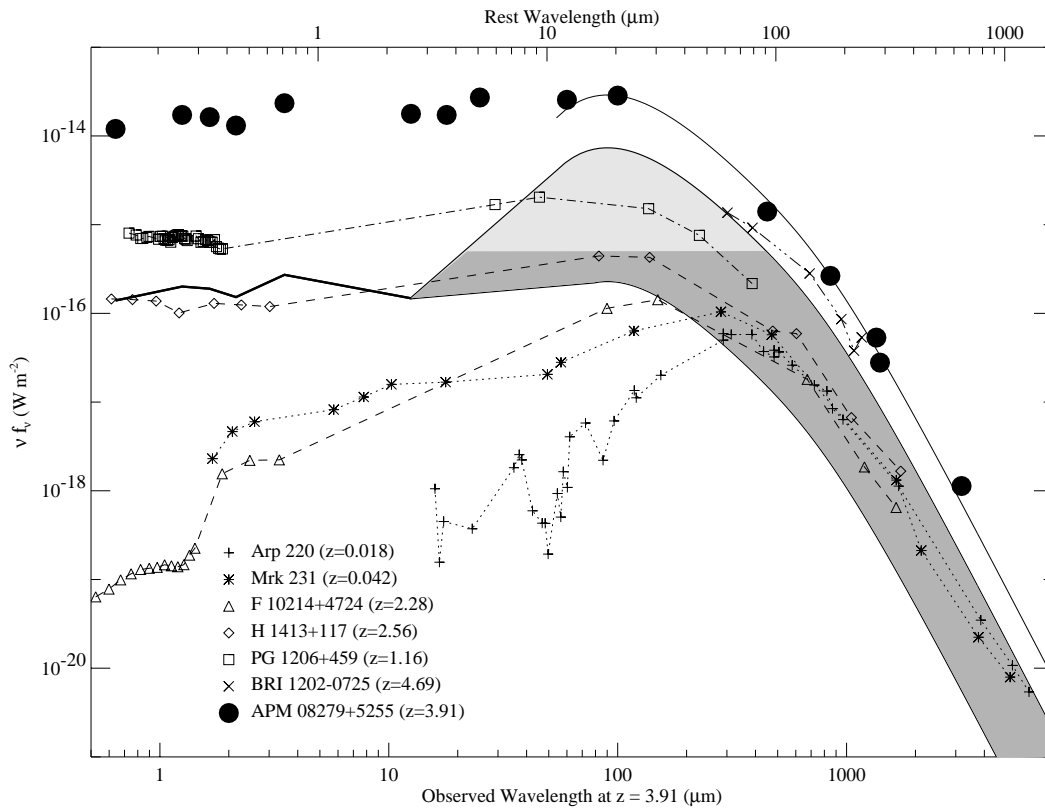


FIG. 11.—Comparison of the SEDs of various ultraluminous/hyperluminous galaxies/QSOs. All the SEDs are shifted to a redshift of 3.91. The SED of H1413 + 117 (Cloverleaf QSO) is downscaled by a magnification factor of 10 (see Kneib et al. 1998 for the most recent discussion of the magnification factor). The SED of F10214 + 4724 is downscaled by a factor of 100 at $\lambda_{\text{rest}} < 0.3 \mu\text{m}$ (Eisenhardt et al. 1996), 50 at $0.3 \mu\text{m} < \lambda_{\text{rest}} < 1 \mu\text{m}$ (Evans et al. 1999), and 30 at $\lambda_{\text{rest}} > 10 \mu\text{m}$ (Eisenhardt et al. 1996). The SED of APM 08279 + 5255 was downscaled by a factor of 86 at $\lambda_{\text{rest}} < 1 \mu\text{m}$ and 120 at $\lambda_{\text{rest}} = 2.6 \mu\text{m}$. The shaded area shows the allowed range for the intrinsic SED of APM 08279 + 5255 at $\lambda_{\text{rest}} > 2.6 \mu\text{m}$. The area was determined by demagnifying the empirical fit to the observed SED (solid line connecting filled circles) by factors of 4 and 120. The intrinsic SED is probably flat up to $\lambda_{\text{rest}} = 20 \mu\text{m}$ (dark shaded area; see text). The SED data were taken from Barvainis et al. (1995), Benford et al. (1999), Downes et al. (1999), Iбата et al. (1999), Irwin et al. (1998), Isaak et al. (1994), Klaas et al. (1997), Lewis et al. (1998), Neugebauer et al. (1987), Rigopoulou, Lawrence, & Rowan-Robinson (1996), Sakamoto et al. (1999), Sanders et al. (1988), Soifer et al. (1999), and the NED database.

because of its small magnification factor. Because of these uncertainties, a self-consistent model can be constructed with a broad range of dust masses (10^6 – $10^9 M_{\odot}$) and temperatures (50–200 K).

Figure 11 also illustrates the difficulty of determining dust properties without knowing the exact shape of the mid-IR/far-IR/submillimeter SED. For example, one noticeable feature in the figure is that most of the objects have comparable submillimeter luminosities in spite of the large spread in the bolometric luminosity. This strongly suggests that the dust distribution in these objects are “matter-bounded” (cf. Barvainis et al. 1995): in other words, these objects are likely to have comparable dust masses, and the difference in the IR ($> 10 \mu\text{m}$) luminosities is caused by the difference in dust temperature (from 50 K [ultraluminous IR galaxies] to 200 K [PG 1206 + 459] for the dust component dominating the rest-frame submillimeter emission). On the other hand, the large submillimeter luminosity of BRI 1202 – 0725 indicates that even if the dust temperature is at 200 K, its dust mass is still as large as those of local ultraluminous IR galaxies and could be larger by an order of magnitude if the dust temperature is low (e.g., 50 K). The fact that the allowed IR/submillimeter SED range for APM 08279 + 5255 is broadly consistent with the SEDs of such a variety of objects indicates that with the currently available data little can be said about the dust mass and temperature of APM 08279 + 5255.

4.7. The Lensing Galaxy

If the three-image model is correct, there is no observational image that can be associated with the lensing galaxy. The redshift of the lensing galaxy is not determined by the model because the redshift of the lens enters only through the Einstein radius, and the same Einstein radius can be produced by a distant massive galaxy or a nearby low-mass galaxy.

The derived core radius of $0''.2$ corresponds to a physical length of 1.3–1.6 kpc at a redshift of $0.5 < z < 4$. A galaxy with a core radius of this size must be a large elliptical-type galaxy with a velocity dispersion σ_v of $\sim 300 \text{ km s}^{-1}$. To be compatible with the derived small Einstein radius, the lensing galaxy must be at a high redshift, probably $z \sim 3$, although at the moment there is no observational evidence to support this hypothesis. The mass of such a lensing galaxy is calculated to be $\sim 2 \times 10^{11} L_{\odot}$ within the Einstein radius of $0''.29$. Such a galaxy would not have been detected by any observations to date of this system.

5. SUMMARY AND CONCLUSIONS

We have obtained high-resolution images of APM 08279 + 5255 in the K band (FWHM $\sim 0''.15$) and at $12.5 \mu\text{m}$ (FWHM $\sim 0''.4$). We have constructed a gravitational lens model using the K -band image and determined the magnification factors at longer wavelengths based on the

12.5 μm image and other existing data. The basic conclusions are as follows.

1. APM 08279+5255 consists of three components, which are distributed over $\sim 0''.4$. The third image (component C) is bright ($K = 14.5$ mag) and compact (FWHM $\sim 0''.15$).

2. Component C could be either a third lensed image (three-image model) or the luminous QSO/AGN nucleus of the lensing galaxy (two-image model). If the three-image model is correct, the magnification factor is high (~ 100) and the effects of differential magnification could be significant. If the two-image model is correct, the magnification factor is low (~ 10) and the effects of differential magnification are negligible. The three-image model is preferred by a number of observational arguments, and therefore we adopt this model to deduce the intrinsic properties.

3. The derived magnification factors for APM 08279+5255 are 90, 90–120, and 4–120 in the rest-frame UV/optical, near-IR, and mid-IR/far-IR/submillimeter, respectively. The corresponding intrinsic source radii are less than 20 pc, less than 50 pc, and 60–1800 pc.

4. By assuming that the intrinsic SED is flat up to $\lambda_{\text{rest}} < 20 \mu\text{m}$, we estimate an overall magnification factor of ~ 100 . From this, the intrinsic bolometric luminosity of APM

08279+5255 is derived to be $5 \times 10^{13} L_{\odot}$. Its intrinsic IR luminosity is $1 \times 10^{13} L_{\odot}$. Therefore, APM 08279+5255 is intrinsically luminous, but it is not the most luminous object known.

5. With the currently available data, neither the dust mass nor the dust temperature can be determined because of the uncertainties associated with the dust emissivity and the possible effects of differential magnification.

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