DETECTION OF SUBSTRUCTURE IN THE GRAVITATIONALLY LENSED QUASAR MG0414+0534 USING MID-INFRARED AND RADIO VLBI OBSERVATIONS

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ABSTRACT

We present 11.2 μm observations of the gravitationally lensed, radio-loud z_s = 2.64 quasar MG0414+0534, obtained using the Michelle camera on Gemini North. We find a flux ratio anomaly of A2/A1 = 0.93 ± 0.02 for the quasar images A1 and A2. When combined with the 11.7 μm measurements from Minezaki et al., the A2/A1 flux ratio is nearly 5σ from the expected ratio for a model based on the two visible lens galaxies. The mid-IR flux ratio anomaly can be explained by a satellite (substructure), 0.3 northeast of image A2, as can the detailed very long baseline interferometry (VLBI) structures of the jet produced by the quasar. When we combine the mid-IR flux ratios with high-resolution VLBI measurements, we find a best-fit mass between 10^{6.2} and 10^{7.5} M_☉ inside the Einstein radius for a satellite substructure modeled as a singular isothermal sphere at the redshift of the main lens (z_s = 0.96). We are unable to set an interesting limit on the mass to light ratio due to its proximity to the quasar image A2. While the observations used here were technically difficult, surveys of flux anomalies in gravitational lenses with the James Webb Space Telescope will be simple, fast, and should well constrain the abundance of substructure in dark matter halos.

Key words: galaxies: structure – gravitational lensing: strong

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1. INTRODUCTION

The missing satellite problem, where cosmological simulations of cold dark matter (CDM) predict a significantly larger fraction of lower mass satellites around galaxies than is detected, represents a major puzzle in the study of structure formation (Klypin et al. 1999; Moore et al. 1999). In the case of the Milky Way, the Sloan Digital Sky Survey has steadily found additional, faint satellites, but the total numbers are still far lower than the expected abundances of subhalos (e.g., Willman et al. 2005; Belokurov et al. 2007). The simplest solution in the context of CDM models is to suppress star formation in low-mass satellites, probably through heating and baryonic mass loss as the universe re-ionizes to leave a population of dark satellites (e.g., Klypin et al. 1999; Bullock et al. 2000) with assistance from the relative streaming of baryons and dark matter after recombination (Tseliakhovich & Hirata 2010). Locally there is some hope of finding these dark satellites through γ-rays emitted by dark matter annihilation, but the likelihood of detection depends heavily on the properties of dark matter (e.g., Strigari et al. 2008).

Gravitational lensing offers an alternate method to detect subhalos. In some strong lenses (e.g., MG0414+0534, Ros et al. 2000; MG2016+112, Kochanek 2006; HE0435–1223, Kochanek et al. 2006, Fadely & Keeton 2012; B1938+666, Vegetti et al. 2012), satellite galaxies of the primary lens can be detected astrometrically through their effects on the image positions. Potentially, the most massive satellites can also be detected through their effects on time delay ratios (Keeton & Moustakas 2009). But as emphasized by Mao & Schneider (1998) and Metcalf & Zhao (2002), image fluxes are sensitive to perturbations even from very low-mass satellites (≤10^6 M_☉). Moreover, we observe many lenses with “flux ratio anomalies” where the relative image brightnesses cannot be explained by simple, central lens galaxies (see Evans & Witt 2003; Kochanek & Dalal 2004; Congdon & Keeton 2005; Yoo et al. 2006a, 2006b; Kratzer et al. 2011). While current results are consistent with the expectations of CDM (Dalal & Kochanek 2002; Vegetti et al. 2012), there are still too few lenses to precisely test the CDM model using flux ratio anomalies. For this technique, the challenge is that image fluxes can also be affected by extinction and microlensing in the primary lens at the most easily observed wavelengths, although the wavelength dependencies of these three effects can help to disentangle them from each other (e.g., Agol et al. 2009; Muñoz et al. 2011). The microlensing signal by substructures is best isolated at radio or rest-frame mid-infrared (mid-IR, ~4–100 μm) wavelengths, where both extinction and microlensing effects from the lens galaxy are negligible (stars can only magnify sources smaller than ~0.1 pc). Ideally, our observations (3.1 μm in the rest frame) would be at still longer wavelengths, but simulations indicate that microlensing effects should be ≤0.1 mag for our observations (Stalevski et al. 2012; Sluse et al. 2013). The mid-IR images are also unaffected by interstellar scattering, or scintillation, which can further perturb the radio images, although few lenses show the strong radio wavelength-dependent signatures expected from these effects (Kochanek & Dalal 2004). The biggest problem for using radio wavelengths is simply that most quasars are radio-quiet, leaving only a handful of objects to be studied. While mid-IR observations are challenging, they are ideal for searching for substructures in lens galaxies.

Here we present mid-IR observations of the quadruply lensed, radio-loud z_s = 2.64 quasar MG0414+0534, obtained using the Michelle camera on Gemini North. This system is known to be affected by extinction and microlensing in the optical and near-IR (Hewitt et al. 1992; Lawrence et al. 1995; Falco et al. 1997; Schechter & Wambsganss 2002; Bate et al. 2008, 2011; Pooley et al. 2012), but the flux ratio anomaly persists into the...
mid-IR and radio. Our new measurements have slightly higher precision than those by Minezaki et al. (2009) and we then consider more detailed models. This work is an extension of the study in MacLeod et al. (2009), where a companion lens galaxy was detected through the mid-IR flux ratios of the four-image lens H1413+117. Here, we show that the flux ratio anomaly in MG0414+0534 indicates the presence of low-mass substructure in the lens based on models of the individual or combined radio and mid-IR observations of this lens. Our data are described in Section 2, our lens models are presented in Section 3, and our conclusions are in Section 4.

2. FLUX MEASUREMENTS AND ERRORS

We observed MG0414+0534 with the Michelle camera (Roche 2004) on Gemini North at 11.2 μm (F112B21 filter) on 2006 January 2. The observing time was 1 hr, of which 940.8 s were spent on source. The data were processed with the standard Gemini pipeline mireduce. Our analysis starts with the coadded chop and nod subtracted image. These initial images have 16 vertical stripes due to the 16 readout channels. We corrected for the stripes by subtracting the median of each stripe after masking the region containing the quasar images. This procedure also removes any residual sky flux. Figure 1 shows the resulting image.

We fit the four lensed images using a two-dimensional (2D) Gaussian to model the point-spread function (PSF), fixing the relative image positions to those measured from the Hubble Space Telescope (HST) images4 (Falco et al. 1997). Since the sky is so much brighter than the quasar images, we use the standard deviation of the background pixels as an estimate of the errors in the flux of each pixel. The model has nine free parameters: the fluxes of the four images (4), the position of image B (2), the standard deviation of the Gaussian PSF along the two principal directions (2), and the angle of the major axis. We found the best-fit model using non-linear Levenberg–Marquardt optimization. We used a Markov chain Monte Carlo (MCMC) with 106 steps to compute the parameter uncertainties, and ran multiple chains to check the convergence of the best-fit parameters and their uncertainties. We also estimated the errors by simply computing the goodness of fit as a function of the flux of each image, marginalizing over all other variables.

Table 1

| Images | This Work | Minezaki et al. (2009) | Combined |
|--------|-----------|------------------------|----------|
| A2/A1  | 0.926 ± 0.025 | 0.90 ± 0.04 | 0.919 ± 0.021 |
| B/A1   | 0.338 ± 0.017 | 0.36 ± 0.02 | 0.347 ± 0.013 |
| C/A1   | 0.145 ± 0.016 | 0.12 ± 0.03 | 0.139 ± 0.014 |

Figure 1 shows the best-fit model and its residuals, and Figure 2 shows the MCMC and Δχ² estimate for the fluxes (in arbitrary units) and their uncertainties. In order to include any covariances between the image fluxes, we use the actual distribution of flux ratios from the MCMC approach to estimate the flux ratio uncertainties. We calibrated the flux measurements using observations of the standard star Rho Orionis (HR 1698) and the Cohen et al. (1999) flux calibration at 11.2 μm (the interpolated flux is 6.43 Jy). We obtained a total flux of 33.4 ± 1.3 (statistical) ± 3.2 (systematic) mJy at 11.2 μm from aperture photometry, which is lower than the value of 39.2 ± 1.4 mJy in Minezaki et al. (2009). This discrepancy may be due to the fact that our filter has a shorter central wavelength and that the spectral energy distribution is rising toward longer wavelengths. The resulting mid-IR flux ratios are listed in Table 1 along with the mid-IR results from Minezaki et al. (2009), and the combined results. The results agree given their mutual uncertainties and show that the anomaly, while not as strong as in the near-IR (Bate et al. 2008), persists into the mid-IR. This wavelength behavior is a first indication that the anomalous flux ratio in the near-IR is not produced solely by microlensing, as assumed in Bate et al. (2008), but also by substructure in the lens.

3. MODELS

In a multiple-image strong gravitational lens, a close pair of bright images such as A1 and A2 results if the quasar is near a fold caustic created by the main lens galaxy. Their flux ratio is expected to be unity for a smooth lens model (e.g., Keeton et al. 2005), whereas we measure a flux ratio of A2/A1 = 0.93 ± 0.02 for MG0414+0534. Since we are insensitive to extinction or microlensing effects created by the lens galaxy in the mid-IR, the anomalous ratio must be attributed to millilensing by substructure in the lens, as was also argued by Minezaki et al. (2009).

We model the system with LENSMODEL⁵ (Keeton 2001), using the combined mid-IR flux ratios listed in Table 1 (last column) as constraints on our models. We use the measured HST WFPC/WFPC2 positions of the main, central lens galaxy, the secondary lens “X” (Schechter & Moore 1993; Ros et al. 2000), and the image positions from the CASTLES database (Falco et al. 1997). The component positions are listed in Table 2. The main lens galaxy (G1) is modeled as a singular isothermal ellipsoid (SIE) combined with an external shear, as this is the simplest plausible model for a lens. There is considerable evidence in favor of the isothermal profile, and the properties of four-image systems other than time delays are very insensitive to the radial mass distribution (see Kochanek 2006; Koopmans et al. 2009). We include weak priors on the ellipticity of the main lens (1 − b/a = 0 ± 1), and the external shear (γ = 0.05 ± 0.05). The expectation value of 0 for the ellipticity is based on the relatively round isophotes derived from the HST.

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4 http://www.cfa.harvard.edu/castles/

5 http://redfive.rutgers.edu/~keeton/gravlens/
photometry of the lens (Falco et al. 1997; Keeton et al. 1997), Ros et al. (2000) found that the presence of an observed nearby galaxy, object X (Schechter & Moore 1993), hereafter “G2,” in their lens models was essential for reproducing the image astrometry. For G2, we tried two different models: a singular isothermal sphere (SIS) or a pseudo-Jaffe (pJaffe) profile with a scale length $a'$ that is allowed to vary.

Using the mid-IR flux ratios as constraints, we obtain the best-fit two-galaxy models described in Table 3. The models have 17 total constraints (the positions of four lensed images and both lens galaxies, the three flux ratios, plus the priors on the ellipticity $e$ and shear $\gamma$) and 12 free parameters (the mass scale $b_1$, position, ellipticity $e$ and position angle $b_0$ for G1, the amplitude $\gamma$ and position angle $\theta_e$ of the external shear, the mass scale $b_2$ and position for G2, and the source position), plus one more free parameter for the scale length $a'_2$ when using a pJaffe profile. In the table, we describe our best two-galaxy models when using SIE+SIS or SIE+pJaffe profiles. We find a slightly better fit when using an SIS profile for G2, with $\chi^2 = 31.1$ for $\sigma = 5$ degrees of freedom and a best-fit flux ratio $A2/A1 = 1.01$. The discrepancy between the observed and predicted mid-IR flux ratios in our two-galaxy models suggests the presence of substructure along the line of sight or associated with the main lens galaxy at nearly a $5\sigma$ level.

We modeled the substructure by adding a third lens galaxy (G3) with an SIS profile at various positions surrounding the lens and searched for a better fit to the observed flux ratios. Here, we adopt an SIS rather than a pJaffe profile for G2 since the former yielded a better fit among the two-galaxy models. At each position in the grid, the mass scales $b_1, b_2,$ and $b_3$ for galaxies G1, G2, and G3 were allowed to vary, as well as the ellipticity of G1 and the external shear, until a best-fit three-galaxy model was obtained. Here, $\sigma = 6$, since we are holding the positions for G1 and G2 fixed for each model. Figure 3 (left panel) shows the resulting $\Delta\chi^2$ (relative to the two-galaxy model). It can be seen that the addition of substructure improves the two-galaxy model when placed northeast or northwest of image A2, although the range of positions that lead to a similar improvement is more limited northwest of A2. We consider the region northeast of A2 as an approximate location for G3 in our initial three-galaxy model since it ultimately yielded lower $\chi^2$ values than the northwest region. We obtain the best-fit parameters in Table 3, where the coordinates of G3 are treated as free parameters. We find that an SIS with $b_3 \approx 0.0028$ located at $(x_3, y_3) = (−0.91, 1.56)$ leads to the best improvement, with $\Delta\chi^2 = 25$ ($\chi^2/\text{dof} = 3$), although as described in Section 3.1, a similar fit can be achieved if $b_3$ is larger and G3 is slightly farther away from image A2. Assuming the measured redshift of $z_l = 0.96$ for G1 (Tonry & Kochanek 1999), we estimate a best-fit mass of $M_\odot \approx 3 \times 10^7$ and $M_\odot \approx 10^{10}$ enclosed within the Einstein radii of G3 and G2, respectively, based on the mid-IR constraints alone, as compared to $\sim 5 \times 10^7$ and $\sim 10^{10}$ enclosed within the Einstein radii. The statistical significance of finding $\Delta\chi^2 = 25$ for three additional parameters is 0.28 (a 72% confidence level) based on the $F$-test. When G2 is modeled as a pJaffe potential, we find similar results for a three-galaxy model but with $\chi^2/\text{dof} = 5.8$ (and an $F$-test confidence level of 45%). We conclude that G2 is better modeled as an SIS than a pJaffe potential and therefore do not

![Figure 2: MCMC probability distributions for the MG0414+0534 image fluxes (in arbitrary units). The vertical dashed lines show the mean and $1\sigma$ error bars determined from the best-fit Gaussian curve. These are compared to the best-fit flux value and 68% confidence limits (or parameter values at which $\Delta\chi^2 = 1$ from the minimum $\chi^2$) that result from the $\chi^2$ minimization technique (see text), which are shown by vertical dotted lines. The Gaussian widths ($\sigma$) are listed in the top right corners. For the uncertainties reported in Table 1, we instead use the dispersion of flux ratios from the MCMC.](image-url)

### Table 2

| MG0414 Component | HST Position | Rotated 0:1 | Error |
|------------------|-------------|------------|-------|
| A1               | (−0.600, −1.942) | (−0.596, −1.943) | 0.003 |
| A2               | (−0.732, −1.549) | (−0.729, −1.550) | 0.003 |
| B                | (0.000, 0.000) | (0.000, 0.000) | 0.003 |
| C                | (1.342, −1.650) | (1.345, −1.648) | 0.003 |
| G1               | (0.472, −1.277) | (0.474, −1.276) | 0.003 |
| G2 (=X)          | (0.857, 0.180) | (0.857, 0.181) | 0.011 |

**Notes.** The positions are taken from the CASTLES database (Falco et al. 1997) and are relative to image B, where negative R.A. values are eastward of image B. We rotate the positions counterclockwise by 0:1 when adding the radio constraints to our lens models.
list the model parameters for a three-galaxy (SIE+pJaffe+SIS) model here.

3.1. Radio Constraints: 8.4 GHz VLBI Structures

Fortunately, we can further test this model by adding the flux ratios and positions of the components detected in the radio with very long baseline interferometry (VLBI; Ros et al. 2000; Trotter et al. 2000), where each quasar image is resolved into core and jet structures. We added the core components a and b detected in the VLBI maps, and the VLBI jet structures c and d. The radio positions were constrained using the error ellipses shown in Figure 4, which are estimated based on the outermost contours.
The constraints on the positions of the five sources used in our final model are shown in the image plane as error ellipses. Our estimates for the VLBI core components (a and b) and jet structures (c and d) from Ros et al. (2000) are shown as black ellipses. The error circles for the mid-IR positions are shown in gray. The best-fit positions for each component are indicated by the symbols and are consistent with each error ellipse. The larger symbols correspond to the mid-IR image positions, and the smaller, thick gray symbols correspond to VLBI component b.

in Figures 1 and 2 in Ros et al. (2000), and extend to the most distant “clump” in the jet structures. For the c and d components in image C, we set the error ellipses to an arbitrarily large radius since they are not clearly resolved. Note that Trotter et al. (2000) used tighter constraints on the component positions while ours are more conservative, especially along the jet structures, to allow more freedom in the component cross-identifications. We find a better agreement ($\Delta \chi^2 = 3$) between the optical and radio core positions when shifting the HST images counterclockwise by 0.1, which is well within the HST astrometric uncertainties of $\sim 0.5\,\text{mas}$. However, these systematic offsets are along the direction of the physical extent of the jets and could easily be due to inaccurate cross-identification of the VLBI centroids and the systematic problems of VLBI maps in the presence of complex structures, which is why we adopted the error ellipses discussed earlier.

Figure 5 shows the resulting $\chi^2$ improvement when adding a third lens galaxy in the same fashion as before, but including the constraints from all four radio sources (a similar map using the radio constraints only is shown in the right panel of Figure 3). The best-fit mass scale $b_3$ is also shown. The overall results are consistent with those based only on the mid-IR data, but with a narrower region extending to the northeast (145° north of west) for the position of the third galaxy. The parameters for the best three-galaxy model with $(x_3, y_3) = (-0.097, -1.39)$ and $\chi^2 / \text{dof} = 1.6$ are listed in Table 3. We determined the 1σ error in the mass scale for G3 by varying $b_3$ in steps of 0.0001 around the best-fit value of 0.0001 until the $\chi^2$ increased by one on either side of the minimum, while leaving the other lens parameters (including the external shear) allowed to vary. Using this method, we obtained an error of 0.0001 for a third lens at

\[ \text{Offset between the VLBI centroids and best-fit source positions (see the c and d components in image A1), which are often much larger than the VLBI beam size of 2.55 \times 1.13\,\text{mas}. However, these systematic offsets are along the direction of the physical extent of the jets and could easily be due to inaccurate cross-identification of the VLBI centroids and the systematic problems of VLBI maps in the presence of complex structures, which is why we adopted the error ellipses discussed earlier.} \]

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Figure 5. The left panels show the $\Delta \chi^2$ improvement resulting from adding a third lens galaxy as a function of its position, as in Figure 3, but using both the mid-IR and radio constraints on the models. The right panels show the best-fit critical radius for the substructure. The bottom panels give an expanded view of the region indicated by the box in the top-left panel. The positions of two nearby galaxies G4 and G5 seen in the $H$-band image are also indicated.

this location. This corresponds to $10^{7.3\pm0.2} M_\odot$ enclosed within the Einstein radius at $z_l = 0.96$. The statistical significance of this result is $>99\%$ based on the $F$-test. We can also obtain a good fit with $b_3 = 0\.'002$ at $(x_3, y_3) = (-0\.'86, -1\.'54)$ if the position of G3 is set initially closer to image A2. This degeneracy results because the model requires a larger mass for G3 to reproduce the observed flux ratios when G3 is farther from image A2. Given this limitation, we can only constrain the mass scale to $0.002 < b_3 < 0.008$ based on the range of models in Figure 5 that yield a comparable $\chi^2$ improvement, corresponding to masses within the Einstein radius of between $10^{6.2}$ and $10^{7.5} M_\odot$. For simplicity, we adopt the final three-galaxy model listed in Table 3 for the remainder of our analysis.

The critical and caustic curves for our final three-galaxy model are shown in Figure 6. The third galaxy distorts the critical curves near images A1 and A2, bringing their flux ratio back into agreement with the mid-IR data. G3 may be associated with a faint dwarf galaxy or a nonluminous dark matter substructure, as there are no nearby objects detected in the $H$-band image which are coincident with its predicted positions. Unfortunately, in the $H$-band image where we would best be able to detect G3, the estimated position lies almost exactly on the first Airy ring of image A2 (where the image subtraction residuals are high) and in a region with substantial emission from the quasar host galaxy, making it impossible to place useful limits on the mass-to-light ratio of G3.

The orientation of the external shear in our three-galaxy model, indicated in Figure 6, is in the same general direction as another object (G6) found 4\.'4 southwest of image C in the $H$-band image. As pointed out by Falco et al. (1997), G6 is
a possible compact group of galaxies, as it consists of three visible galaxies within 1" of each other. If we assume that G6 and G2 are at the same redshift as G1 and scale the Einstein radii of these objects by their I-band fluxes assuming a standard Faber–Jackson relation ($L \propto \sigma^4$), we can estimate the deflection scale of G6 as $b_6 = b_{G2}(L_6/L_{G2})^{1/2}$, using the fact that $b \propto \sigma^2$ for an SIS. Adopting the I-band magnitudes of G2 (24.769) and G6 (23.16) from Falco et al. (1997), we estimate $b_6 = 0'.34$. The shear caused by G6 is then $\gamma_6 = b_6/2r_6 = 0.03$, where $r_6$ is the angular separation from G1, and the amplitude of any higher order perturbations is $b_6b_{G1}/r_6^2 = 0.013$ (see Kochanek et al. 2006). Since $\gamma_6 < 0.09$, G6 does not appear massive enough to fully explain the external shear in our three-galaxy model, although it likely contributes some shear. The inclusion of G6 as a fourth lens mass yields a best-fit with $b_6 = 0'.21$, a reduction in shear amplitude (0.061), and a minor change in the shear orientation (53.3') with $\chi^2$/dof = 52.6/37 = 1.4.

In an attempt to bring our reduced $\chi^2$ closer to unity, we tried adding a fifth lens galaxy on a grid of positions while optimizing the overall lens properties. We find the best improvement ($\Delta \chi^2 \approx 7$) near image C, extending to a region $\sim 2^\prime$ north of G6. However, the reduced $\chi^2$ does not improve (46/34 = 1.4). We conclude that additional substructures are unlikely to lead to a significant improvement of the fit given the constraints adopted here.

We also checked the significance of G2 in our models since the redshift for G2 has not been measured, and there is a slight chance it lies at a different redshift than G1 and has a smaller gravitational influence than expected. We excluded G2 from our final three-galaxy model and attempted to fit the available mid-IR and VLBI data using just G1 and G3, allowing the mass scales and external shear to vary along with the position and ellipticity of G1. The best fit to the observed lens astrometry was significantly worse with a total $\chi^2$ of 470, which includes a factor of 10 increase in the image position $\chi^2$, a factor of 266 increase in the contribution from the lens (G1) position, and a factor of 3 increase in the contribution from the flux ratios. Therefore, we confirm the earlier result that G2 is essential for reproducing the lens astrometry. The main consequence of G2 lying at a different redshift is that we would incorrectly convert its Einstein radius into a mass.

4. DISCUSSION

Gravitationally lensed quasars are useful astrophysical tools because they allow us to study both the lens mass distribution and the background quasar. Unlike microlensing, where time variability can be used to isolate the effect, the effects of microlensing need to be disentangled from other physics that modify flux ratios. Mid-IR observations are ideal for this purpose because the effects of both microlensing and extinction are negligible or small (Stavelesi et al. 2012; Sluse et al. 2013). The effect of microlensing of the dust torus on our observations can be estimated by comparing the average Einstein radius $R_E$ of stars in the lens galaxy to the dust sublimation radius $R_{\text{sub}}$. For a bolometric luminosity of roughly $1.4 \times 10^{47}$ erg s$^{-1}$, estimated from correcting the total flux in our observations for a total magnification of 38.5 and assuming no extinction, we find a minimum dust radius of $R_{\text{sub}} \sim 5$ pc. This is large compared to the average Einstein radius of $R_E \approx 0.0066$ pc, assuming a typical microlens mass of $0.3 M_\odot$, and thus the microlensing effects should be no larger than 0.003 mag (Refsdal & Stabell 1991). In MacLeod et al. (2009), we used the mid-IR flux ratios for the lens H1413+117 to show that flux ratio anomalies can detect companion lens galaxies, albeit a luminous companion in that system. This technique can also be used for detecting dark subhalos in the lens, down to $10^5 M_\odot$ (Mao & Schneider 1998; Metcalf & Zhao 2002). As shown here and in Minezaki et al. (2009), the quadruply lensed quasar MG0414+0534 exhibits a flux ratio anomaly at mid-IR wavelengths that suggests there is a millilensing substructure in the lens or along the line of sight to the quasar.

When we model either the mid-IR or radio data or both using only two lens galaxies (the primary lens G1 and a secondary lens G2/object X), we are unable to reproduce the observed flux ratios. When we add a third lens G3 near image A2, we obtain a significantly improved fit to the flux ratios. The optimal location of the substructure, roughly 0.3 to the northeast of image A2 and 1.5 east of G1, was determined by adding a third lens on a grid of positions in the lens plane and varying its mass along with the overall lens properties. We are unable to associate the substructure with any source in the H-band image from HST, which suggests the third galaxy is either very faint or nonluminous. The mass of the substructure within the Einstein radius is in the range $10^{6.5}$ to $10^{7.5} M_\odot$ when modeled as an SIS, depending on the precise location of the substructure, and our results are statistically significant at >99% confidence based on the T-test. Our findings are generally consistent with the less detailed models of Minezaki et al. (2009). The anomaly in the mid-IR suggests the presence of a third lens galaxy which we assume is at the redshift of the main lens, although the structure could theoretically lie at some other redshift along the line of sight (Xu et al. 2012; Inoue & Takahashi 2012). There is also evidence for some contribution to the flux ratios from the neighboring galaxy group (G6) in the H-band image.

Besides being relevant to studying the background quasar, the search for subhalos in the lens is also cosmologically important, because it offers the only means of identifying dark, low mass halos other than detection of $\gamma$-ray annihilation signals by Fermi. Sufficiently massive structures can be detected through their perturbations of image positions as seen with object X here,
or in MG2016+112 (Kochanek 2006) and B1938+666 (Vegetti et al. 2012). Lower mass structures can only be detected through flux ratio anomalies, where the challenge is to obtain flux ratios unaffected by absorption or microlensing. The rest frame mid-IR satisfies these requirements but is limited at present by either poor resolution, as in Spitzer observations, or poor sensitivity, as in ground-based measurements. The LBTI mid-IR imaging interferometer (Hinz et al. 2003) on the Large Binocular Telescope is a promising near-term solution, and a complete survey will be trivial with the advent of the James Webb Space Telescope.

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