Discovery of a Fifth Image of the Large Separation Gravitationally
Lensed Quasar SDSS J1004+4112*

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Abstract

We report the discovery of a fifth image in the large separation lensed quasar system SDSS J1004+4112. A faint point source located 0′′2 from the center of the brightest galaxy in the lensing cluster is detected in images taken with the Advanced Camera for Surveys (ACS) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) on the Hubble Space Telescope. The flux ratio between the point source and the brightest lensed component in the ACS image is similar to that in the NICMOS image. The location and brightness of the point source are consistent with lens model predictions for a lensed image. We therefore conclude that the point source is likely to be a fifth image of the source quasar. In addition, the NICMOS image reveals the lensed host galaxy of the source quasar, which can strongly constrain the structure of the lensing critical curves and thereby the mass distribution of the lensing cluster.

Key words: galaxies: quasars: individual (SDSS J1004+4112) — gravitational lensing — Galaxy: structure

1. Introduction

Gravitational lensing is a unique tool for exploring the distribution of matter, particularly that of dark matter. The recently discovered largest separation lensed quasar, SDSS J1004+4112 (Inada et al. 2003; Oguri et al. 2004), has opened a new window for probing dark matter distributions in the universe. The quasar was discovered in the Sloan Digital Sky Survey (SDSS; York et al. 2000; Abazajian et al. 2004), and the lensing hypothesis was confirmed by subsequent observations with the Subaru 8.2-m telescope and the Keck telescope. The system consists of four lensed quasar components (i′ = 18.5, 18.9, 19.4, and 20.1) at z = 1.734 and the maximum separation angle between the lensed images is 14′′62. The lensing object must be a massive object, such as a cluster of galaxies, to produce such a large image separation; indeed, we have identified a z = 0.68 cluster centered among the four lensed images. The discovery of a single, cluster-size lensed quasar among the current SDSS quasars is consistent with the theoretical expectation of lensing based on the cold dark matter model (Oguri et al. 2004; Oguri & Keeton 2004).

SDSS J1004+4112 is unique in the sense that 1) the quadruple images place robust constraints on the innermost region of the lensing cluster, and 2) the lensing cluster is a strong lensing selected cluster of galaxies. These features indicate that the mass modeling of this lens system may offer valuable information on the structure of clusters of galaxies. The first attempt at modeling the system with various parametric models revealed the elongated and complicated mass distribution of the lensing cluster (Oguri et al. 2004). Williams & Saha (2004) recently studied this system using a free-form reconstruction technique and reached similar conclusions. However, important degeneracies between different models remain, and further follow-up observations are required to deter-

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mine the mass distribution more precisely.

Observations using the Hubble Space Telescope (HST) can offer such new data. In particular, high-resolution HST images could be quite effective at detecting lensed images of the quasar host galaxy, arc or arclet images of other lensed sources, and perhaps a central or “odd” image of the lensed quasar system that would be expected theoretically (e.g., Burke 1981; Rusin 2002). A central image is especially useful for providing tight constraints on the central mass distribution of the lensing object. This was indeed demonstrated by the first discovery of a central image in a lensed quasar system; Winn, Rusin, & Kochanek (2004) showed that the central image of PMN J1632–0033 requires $\beta = 1.91 \pm 0.02$ (2σ confidence) when a power-law density profile $\rho(r) \propto r^{-\beta}$ is assumed. Possible central images have also been identified in lensed arc systems, such as CL 0024+1654 (Colley, Tyson, & Turner 1996), MS 2137.3–2353 (Gavazzi et al. 2003), and A1689 (Broadhurst et al. 2005), and they also provide important constraints on mass models (see, e.g., Gavazzi et al. 2003).

In this letter, we present an identification of a fifth image of the lensed quasar with the Advanced Camera for Surveys (ACS; Clampin 2000) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS; Thompson 1992) installed on the HST. In addition, we report unambiguous detection of the lensed host galaxy in the NICMOS image.

2. The ACS Observation

An ACS observation (with the Wide Field Channel) in the F814W filter (≈I-band) was conducted on 2004 April 28, under the program “HST Imaging of Gravitational Lenses” (GO-9744, PI C. Kochanek). The observation consisted of five dithered exposures taken in ACCUM mode. The total exposure time was 405 seconds. The reduced (drizzled and calibrated) images were extracted using the CALACS pipeline (Hack 1999), which includes the PyDrizzle algorithm. We further rejected cosmic rays using the L.A.Cosmic package (van Dokkum 2001) in the drizzled image. A $40'' \times 40''$ subsection of a median of the five dithered images is shown in Figure 1. Following Figure 9 of Oguri et al. (2004), the four lensed components are denoted as “A–D”, and three central bright galaxies of the lensing cluster are denoted as “G1–G3”. The redshifts of galaxies G1–G3 are 0.680, 0.675, and 0.675, respectively (Oguri et al. 2004). The relative positions of components A–D were calculated by a single Gaussian fit, and the flux ratios of components A–D were estimated by fitting the PSF stars produced by the Tiny Tim software (version 6.1a; Krist & Hook 2003), in the drizzled (and cosmic ray rejected) image. The PSF of a quasar was constructed with an $a_0 = -0.5$ power law spectrum in the F814W wavelength region (corresponding to $\sim 3000$ Å in the rest frame). The relative positions derived from the ACS (F814W) are consistent with those derived from the Subaru i′ band image (Oguri et al. 2004) within $\sim 5\sigma$. The four components are all unsaturated, and the AB magnitude of component A in the F814W filter is estimated to be 18.4. The position of component G1 was extracted by the Source Extractor algorithm (Bertin & Arnouts 1996). The results are summarized in Table 1.

3. The NICMOS Observation

The NICMOS imaging observation was also conducted under the same HST program on 2004 October 9. The observation consists of four dithered exposures taken in MULTIACCUM mode, using the F160W filter (≈H-band). The exposure time was 640 sec for two of the exposures and 704 sec for the other two. The calibration was extracted by the CALNICA pipeline, and the central bad columns of each dithered image were corrected by linear interpolation. The combined image is shown in Figure 2. First, we confirm a galaxy near component A (marked as G4 in Figure 2), which may host the star or stars responsible for microlensing of the broad emission line region (Richards et al. 2004). In addition, extended emission is clearly seen around components A, B and C. Although such extensions are also seen in the ACS images (see Figure 1), their existence is much more robust in the NICMOS image. The fact that these extensions are obvious in the F160W (near-infrared) image and faint in the F814W (optical) image, and that the distortions agree with the theoretical critical curves (see Figure 17 of Oguri et al. 2004), demonstrates that the extended flux is due to the lensed host galaxy of the source quasar. These images provide many new constraints on lens models that will significantly improve our ability to determine the mass distribution of the lensing cluster. They do make lens modeling more computationally intensive (because one must account for the intrinsic shape of the host galaxy, and also for the effects of the point spread function), so we defer detailed modeling of the arcs to a subsequent paper.

4. Fifth Image

Of interest is the existence of a point source near the center of G1. The left panel in Figure 3 shows the ACS image of galaxy G1; what appears to be an unresolved source is clearly seen approximately $0''2$ northwest of the center of G1. This feature is neither a bad pixel nor a cosmic ray.
the source is seen in all dithered images. The right panel in Figure 3 displays the image after subtracting the signal from G1 (modeled with the GALFIT package of Peng et al. 2002). Due to the existence of the unresolved source near the center of G1 (the peak flux of this unresolved source is almost the same as that of G1), G1 was slightly over-subtracted. However, we can see a new source, labeled E, in the subtracted image. This object is classified as a point source by the Source Extractor algorithm. The position and brightness of E, based on a single Gaussian fit to the data, are given in Table 1.

We find component E also in the NICMOS image; the left panel in Figure 4 is the NICMOS image of galaxy G1. We subtracted the signal from G1 using the GALFIT package, which is shown in the right panel of Figure 4. We confirm component E in the subtracted image, although G1 was slightly over-subtracted as in the ACS image. Measuring the flux of component E with a single Gaussian fit, we find that the flux ratios between E and A (E/A) in the ACS and NICMOS images are 0.003 and 0.004, respectively. This remarkable agreement of the flux ratios supports the idea that component E is a fifth image of the lensed quasar.

To test this hypothesis, we have refined the lens models presented in Oguri et al. (2004) using the more precise HST data. The models consist of a singular isothermal ellipsoid mass distribution for galaxy G1, and an NFW (Navarro, Frenk, & White 1997) elliptical potential for the cluster. We demand that the models reproduce the relative positions and brightnesses of components A–D (and the relative position of G1), as well as the position of component E; we do not use the brightness of E as a constraint, because we want to see what the models predict. Adopting the same approach as Oguri et al. (2004), we use the lensmodel software (Keeton 2001) for Monte Carlo sampling of the parameter space. There is a wide range of models consistent with the data, indicating that it is not difficult to produce a 5-image lens matching the configuration of components A–E, and that significant model degeneracies remain. More interesting are the model predictions for the flux ratio between the fifth image and component A, shown in Figure 5. The predictions span a remarkable nine orders of magnitude, from $E/A \sim 0.1$ down to $E/A \sim 10^{-10}$, but a significant fraction predict $E/A$ in the range 0.001–0.01, consistent with the observed value. In other words, there are (many) reasonable models that can fit all of the HST data under the hypothesis that E is a fifth image; conversely, the observed properties of E are highly compatible with that hypothesis.

Given the enormous range of model predictions for the brightness of E, it appears that the observed brightness offers strong constraints on the models. We caution that one must be careful in using the brightness of E as a constraint, because its measured flux could be contaminated by improper subtraction of the galaxy or by physical effects such as microlensing or extinction. Nevertheless, the range of predictions is so large that even conservative estimates of systematic uncertainties should still yield very
interesting results. As an example, to test the ability of E to constrain the central density profile of G1, we switch from an isothermal model to a more general power law density profile $\rho(r) \propto r^{-\beta}$ for the galaxy (for computational simplicity, we now assume that the potential, rather than the density, has elliptical symmetry). We find that there is a wide range of models with $1.6 \leq \beta \leq 2.0$ that predict $0.001 \lesssim E/A \lesssim 0.01$. By contrast, all of the models we examined with $\beta \geq 2.1$ predict $E/A \lesssim 10^{-10}$, which grossly contradicts even a conservative reading of the data. In other words, the observed properties of E imply that the galaxy mass distribution cannot be steeper than isothermal (i.e., $\beta \leq 2$). This upper bound is similar to that found by Winn, Rusin, & Kochanek (2004) from the central image in PMN J1632−0033 (specifically, they found $\beta = 1.91 \pm 0.02$). However, SDSS J1004+4112 differs from PMN J1632−0033 in that we do not obtain any lower bound on $\beta$, at least over the range $1.6 \leq \beta \leq 2.0$ that we have explored so far. Apparently the complexity of the SDSS J1004+4112 lens potential, with a cluster in addition to the galaxy, prevents a unique measurement of the value of $\beta$. Nevertheless, it is clear that component E provides important new constraints on the mass distribution of this interesting lens system.

5. Summary

We have presented the HST ACS and NICMOS images of SDSS J1004+4112, which reveal a fifth image of the lensed quasar core. The fifth image offers a unique probe of the mass distribution of the cluster core. Deep spectroscopic observations of component E with large telescopes, such as the Subaru Telescope, offer the best prospect for the final confirmation that it is a lensed quasar image. In the NICMOS image, we also found unambiguous evidence of the lensed host galaxy of the source quasar. These extended images provide strong additional constraints on mass models of the lensing cluster, which are expected to break degeneracies seen in the modeling studies to date. A detailed analysis of lens models including the host galaxy images is underway and will be presented elsewhere.

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Fig. 5. Frequency (fraction of models) of the predicted flux ratio of $E/A$ from two component (central galaxy + cluster component) lens models. The models are constrained by the observed positions and brightnesses of components A–D (and the observed position of G1), and the position of component E. We assume that the scale radius of the NFW component is 40$\arcsec$, but the results are insensitive to the particular value. The gray filled circle represents the observed value of $E/A$ (in ACS) with 50% error.

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