The Extragalactic Lens VLBI Imaging Survey (ELVIS): Investigating Galaxy Cores and Black Holes with Gravitational Lens Central Images

by

Edward R. Boyce

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

July 2006

© Edward R. Boyce, MMVI. All rights reserved.

The author hereby grants to MIT permission to reproduce and distribute publicly paper and electronic copies of this thesis document in whole or in part.

Author .................................................................
Department of Physics
July 5, 2006

Certified by ..............................................................
Jacqueline N. Hewitt
Professor of Physics
Director, Kavli Institute for Astrophysics and Space Research
Thesis Supervisor

Accepted by .............................................................
Thomas Greytak
Professor of Physics
Associate Department Head for Education
The Extragalactic Lens VLBI Imaging Survey (ELVIS): 
Investigating Galaxy Cores and Black Holes with 
Gravitational Lens Central Images
by
Edward R. Boyce

Submitted to the Department of Physics
on July 5, 2006, in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Abstract
This thesis describes the Extragalactic Lens VLBI Imaging Survey (ELVIS), a search for central images in gravitational lenses. We present the first four ELVIS targets, for which we have radio VLBI observations with resolutions of a few milli-arcseconds and sensitivities of \(15 - 38\) mJy. For PMN J1838-3427, CLASS B0739+366 and CLASS B0445+123 we have not detected any central images, but have set stringent upper limits on their flux densities. For CLASS B2319+051 we have made a tentative detection of a third radio source, which may be either a central image or radio emission from the lens galaxy.

Using the upper limits on the central image flux densities, we gain new information about the matter distributions in the lens galaxies of these systems. We fit a broken power law model for the matter profile, and constrain the allowed break radii and inner index of this model. To demagnify the central images to the observed level the matter profiles must be slightly shallower than or steeper than isothermal, which is consistent with previous studies of early type galaxy profiles. The presence of a super-massive black hole weakens the constraints somewhat, but the profiles are still close to isothermal. Relative to previous work, we reduce the maximum sizes of shallow cores by factors of 2 to 3, and raise the indices of \(\rho \propto r^{-\gamma}\) central cusps by \(\gamma = 0.05 - 0.35\). If we take the source in B2319+051 to be a central image, then we select a narrow band of allowed break radii and inner indices, finding that a constant density core has size 150-380 pc, and a pure power law has index \(\gamma = 1.5 - 1.67\). Our constraints still allow sufficiently shallow profiles that some super-massive black holes may form central image pairs rather than eliminating the central image, and these image pairs may be detected with future instruments.

Thesis Supervisor: Jacqueline N. Hewitt
Title: Professor of Physics
Director, Kavli Institute for Astrophysics and Space Research
Acknowledgments

Jacqueline Hewitt has been a wonderful mentor, introducing me to the world of central images and guiding me through this project. She has been invaluable as a source of knowledge, inspiration and discipline during my graduate career.

Steven Myers has been an excellent co-supervisor, providing direction to the observing program, and a valuable perspective on its interpretation. He also gave me the chance to spend an enriching and informative year in Socorro.

Josh Winn has been a very helpful collaborator, and almost a third supervisor. I have benefited from his experience in lensing and radio imaging, his skill in writing and his focus on results.

These three people also deserve many thanks for writing an unreasonable number of job references without complaint.

The lensing analysis in this thesis builds on work by Chuck Keeton, David Rusin, Judd Bowman, Jim Kiger and Sheperd Doeleman. I acknowledge their role in developing the methods I have used and their collaboration in the wider central image effort.

Paul Schechter and Saul Rappaport have been an able thesis committee, giving useful advice and feedback on my research program.

I appreciate the expertise and camaraderie of my fellow students, who have helped me overcome obstacles academic, technical and emotional. I thank everyone for providing such a wonderful community, particularly Adam Bolton, Kristin Burgess, John Fregeau, Donglai Gong, Jake Hartman, Adrienne Juett, Justin Kasper, Miriam Krauss and Matthew Muterspaugh.

The scientific staff of the National Radio Astronomy Observatory have taught me a lot about interferometry, and I’m particularly grateful to Walter Brisken, Amy Mioduszewski, Loránt Sjouwerman, Greg Taylor and Joan Wrobel. I also thank the many NRAO operators, analysts and technicians who kept the instruments running and helped to collect all the data in this project.

My family have been a great source of support during the last five years. Many thanks to Mum, Dad, Georgia and Joseph for encouraging me through the bleak times and celebrating my successes.

This thesis has used data from the Very Long Baseline Array (VLBA) and High Sensitivity Array (HSA) of the National Radio Astronomy Observatory (NRAO). The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Support for my research has been provided by NSF grant AST 00-71181, an NRAO pre-doctoral fellowship, and two MIT teaching assistantships.
Contents

List of Figures 7

List of Tables 9

1 Introduction 10
1.1 Galaxy Cores 10
1.2 Central Images 11
1.3 Super-Massive Black Holes 12
1.4 Outline of this Thesis 15

2 ELVIS 17
2.1 Asymmetric Lenses 17
2.2 Radio Lenses 17
2.3 The Sample 19

3 Observations of J1838–3427, B0739+366 and B0445+123: Central Image Upper Limits 21
3.1 Observing Methods 21
3.2 Bright Image Observations 22
3.2.1 J1838 22
3.2.2 B0739+366 25
3.2.3 B0445 29
3.3 Central Image Limits in J1838, B0739, B0445 29
3.4 Scintillation in J1838 31

4 Mass Models of J1838–3427, B0739+366 and B0445+123 with no Black Hole 38
4.1 Properties of the Central Images 41

5 Mass Models of J1838–3427, B0739+366 and B0445+123 with a Black Hole 48

6 B2319+051: A Possible Central Image 53
6.1 Observations 53
6.2 A Possible Central Image 55
6.3 Mass Models 61
6.3.1 A Lens Galaxy Detection .......................... 63
6.3.2 Detection of the Central Image ..................... 67
6.3.3 A Spurious or Unrelated Third Radio Source ......... 70

7 Conclusions ........................................ 73
7.1 Combination of Galaxy Models .......................... 73
7.2 Comparison with Other Central-Image Modelling ............. 73
7.3 Implications for SMBH Images .......................... 77
7.4 Future Work ........................................ 79
List of Figures

1-1 VLA images of MG 1131+0456. ........................................ 13
1-2 5 GHZ MERLIN image of PMN J1632–0033. .......................... 14

2-1 Image magnifications as a function of source position. .............. 18

3-1 Radio map of the two images of gravitational lens PMN J1838–3427. 23
3-2 Radio map of J1838 image A and image B. .......................... 25
3-3 Radio map of the two images of gravitational lens CLASS B0739+366. 26
3-4 Radio map of B0739 image A and image B, from the third epoch. ... 27
3-5 Radio map of B0739 image A and image B, from the first epoch. ... 27
3-6 Radio map of the two images of gravitational lens CLASS B0445+123. 30
3-7 Radio map of B0445+123 image A and image B. .................... 31
3-8 Radio map of the central image search region for J1838. .......... 32
3-9 Histogram of surface brightness values for all pixels within the central-
image search region for J1838. ......................................... 33
3-10 Radio map of the central image search region for B0739. .......... 34
3-11 Histogram of surface brightness values for all pixels within the central-
image search region for B0739. ......................................... 35
3-12 Radio map of the central image search region for B0445. .......... 36
3-13 Histogram of surface brightness values for all pixels within the central-
image search region for B0445. ......................................... 37

4-1 Models for the lens galaxy of J1838. ................................. 41
4-2 Models for the lens galaxy of B0739. ................................. 42
4-3 Models for the lens galaxy of B0445. ................................. 43
4-4 Central image flux density as a function of break radius for the lens
galaxy in J1838. ......................................................... 44
4-5 Central image flux density as a function of inner index for the lens
galaxy in J1838. ......................................................... 44
4-6 Central image flux density as a function of break radius for the lens
galaxy in B0739. ......................................................... 45
4-7 Central image flux density as a function of inner index for the lens
galaxy in B0739. ......................................................... 46
4-8 Central image flux density as a function of break radius for the lens
galaxy in B0445. ......................................................... 47
4-9 Central image flux density as a function of inner index for the lens galaxy in B0445. .................................................. 47
5-1 Models for the lens galaxy of J1838, including a super-massive black hole. ................................................................. 50
5-2 Models for the lens galaxy of B0739, including a super-massive black hole. ................................................................. 51
5-3 Models for the lens galaxy of B0445, including a super-massive black hole. ................................................................. 52

6-1 Radio map of the two bright images of gravitational lens CLASS B2319+051. 54
6-2 Radio map of B2319 image A. ............................................................. 55
6-3 Radio map of B2319 image B. ............................................................. 56
6-4 B2319 central image region, after imaging at the locations of the two bright images. .......................................................... 57
6-5 The irregular beam of the B2319 HSA observations. ...................... 58
6-6 B2319 central image region, after imaging at the locations of the two bright images and within the upper box. ...................... 59
6-7 B2319 central image region, after imaging at the locations of the two bright images and within the upper box, applying a 50 MA taper. ... 60
6-8 B2319 central image region, after imaging at the locations of the two bright images and within the lower box. ...................... 61
6-9 Radio map of B2319 image C. ............................................................. 62
6-10 The irregular beam of the B2319 HSA observations. ...................... 63
6-11 Histogram of surface brightness values for off-source pixels within the B2319 map of image C. ............................................ 64
6-12 Models for the lens galaxy of B2319, assuming the third radio source is a low-luminosity AGN in the lens galaxy. ...................... 67
6-13 Models for the lens galaxy of B2319, assuming the third radio source is a central image. .................................................. 70
6-14 Models for the lens galaxy of B2319, assuming the third radio source is a central image, and including a super-massive black hole. .... 71
6-15 Constraints on the lens galaxy of B2319 from the bright images, assuming an isothermal profile. .................................... 72

7-1 Histogram of predicted central image magnifications from Keeton (2003), with limits on magnifications for the first four ELVIS targets. .... 74
## List of Tables

2. Details of the individual observing epochs for J1838.
3. Details of the individual observing epochs for B0739.
4. The flux densities and separations of sub-images A1 and A2 in B0739.
5. Details of the B0445 observation.
6. Limits on the bright image to central image magnification ratio in J1838, B0739 and B0445.
7. Constraints on the lens models for J1838, B0739 and B0445.
8. The best fit values of the lens model parameters in the isothermal case, for J1838, B0739 and B0445.
9. Distances from the lens galaxy to the bright image B and the central image for the three lenses J1838, B0739 and B0445.
10. The Einstein radii and velocity dispersions for the singular isothermal sphere models, and inferred black hole masses.
11. Details of the B2319 observation.
12. Constraints on the lens models for B2319, assuming that the third radio source is a faint AGN in the lens galaxy.
13. The best fit values of the lens model parameters in the isothermal case for B2319, assuming the third radio source is a faint AGN in the lens galaxy.
14. The Einstein radius and velocity dispersion for the singular isothermal sphere model, and inferred black hole masses, for B2319.
15. Constraints on the lens models for B2319, assuming that the third radio source is the central image.
16. The best fit values of the lens model parameters for a fairly shallow core in the B2319 lens galaxy, and taking the third radio source to be a central image.
17. Core image magnification constraints for the four lenses in our sample.
18. The maximum break radii of broken power law density profiles with a flat inner core.
19. The minimum power law indices of pure power law density profiles.
7.4 The Einstein radii (in the isothermal model) and break radii limits (in the flat core models) for our four lenses.
Chapter 1
Introduction

1.1 Galaxy Cores

The central regions of galaxies ($r < 1$ kpc) are a topic of great interest, but one for which it is difficult to compare the results of observations and theoretical simulations. The observational difficulty is especially severe for galaxies at cosmological distances. The Extragalactic Lens VLBI Imaging Survey (ELVIS) is motivated mainly by the desire to measure (or place interesting constraints on) the central matter distribution in galaxies at significant redshift, by searching for central images of gravitational lenses.

On the theoretical side, cosmological dark matter simulations produce dark matter halos with a universal density profile that goes as $\rho \propto r^{-3}$ at large radii and $\rho \propto r^{-1}$ at small radii (Navarro et al. 1997):

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}.$$

Others have proposed slightly modified forms in which the inner profile goes as $\rho \propto r^{-1.5}$ while maintaining the $\rho \propto r^{-3}$ profile at large radii (Moore et al. 1999). The transition occurs at a scale radius $r_s$, typically 10-30 kpc for halos of galactic mass. The main difficulty with interpreting the results for galaxy interiors is that on scales $\sim 10$ kpc and smaller, the baryonic component is expected to modify the dark matter halo significantly. Adiabatic contraction (Blumenthal et al. 1986) and similar models (Sellwood & McGaugh 2005) model the contraction of dark matter under the gravitation of a baryonic disk or bulge. The total matter profile steepens and becomes close to isothermal ($\rho \propto r^{-2}$) on scales of a few kpc (Kazantzidis et al. 2006). Similar results are found from hydrodynamic simulations that use cooling, gas dynamics, star formation and gravitation to model the dark matter and baryons within individual halos. The baryonic matter dissipates energy and collects at the halo center, becoming the dominant component inside radii $1.5 - 5$ kpc (Gnedin et al. 2004; Macciò et al. 2006). The dark matter contracts inwards under the gravitational influence of the baryons, again giving a total matter profile that is close to isothermal. At present the smallest scales probed by the hydrodynamic simulations are $0.3 - 1$ kpc.
On the observational side, the density distributions of massive galaxies can be directly probed through dynamical studies, at least in the nearby universe. Gerhard et al. (2001) have modelled the dynamics of a sample of large early-type galaxies, using photometry and kinematic line profiles. The dark matter fraction is only 10-40% within the effective radius $R_e$, while the rotation curves are flat on scales larger than $0.2R_e$, indicating an isothermal density profile on these scales. Typically $R_e = 4 - 10$ kpc (Kronawitter et al. 2000), so these results agree with the simulations described above. The density profile of an early type galaxy is isothermal at radii of a few kpc, and baryons represent most of the mass inside this radius.

Projected surface brightness profiles of nearby galaxies ($z = 0.002 - 0.005$) have been observed with the Hubble Space Telescope (Lauer et al. 1995). The angular resolution is 0.1', which corresponds to a physical size of ~10 pc for the typical galaxy in this sample. The surface brightness profiles are well fit by a broken power law, with steep outer exponents, shallower inner exponents, and break radii between 10 and 1000 pc. Based on their inner profiles $I(R) \propto R^{-3}$ the galaxies can be classified into two populations: steep cusps with $\beta \sim 1$ and flatter cores with $\beta = 0 - 0.3$. A surface density power law $\Sigma(R) \propto R^{-\beta}$ corresponds to a density power law $\rho(r) \propto r^{-\gamma}$, where $\gamma = \beta + 1$. Thus the luminous matter in a cuspy galaxy has an isothermal distribution ($\Sigma(R) \propto R^{-1}$) to within ~10 pc of the galaxy's center, while the luminous matter in a core galaxy breaks to a shallower profile at some radius $< 1$ kpc. This is a good approximation to the total mass profile, as the stars seem to represent most of the mass at these radii.

### 1.2 Central Images

Gravitational lenses provide information on the mass profiles of more distant (and therefore younger) galaxies. For a lens galaxy at $z = 0.3 - 1.0$, the relative positions and fluxes of the bright lensed images of a background source constrain the matter profile interior to a few kpc from the lens galaxy center. Detailed studies of ~20 gravitational lenses find that the early type lens galaxies have density profiles which are very close to isothermal on these scales (Rusin et al. 2003; Koopmans et al. 2006). Distant early-type galaxies have similar profiles to those nearby: they are isothermal at galactic radii of a few kpc.

But what about the central few hundred parsecs? Here, too, gravitational lenses can help, through the properties of the "central image." In theory, a non-singular galactic profile produces an odd number of images (Dyer & Roeder 1980; Burke 1981). One image forms near the center of the lens galaxy, where it is expected to be highly demagnified by the large surface density at that position (Narasimha et al. 1986). Due to the demagnification, the faint central image is rarely observed, leaving two or four bright images. In cases where the density profile has a central cusp that is stronger than isothermal ($\rho \sim r^{-\gamma}$ with $\gamma \geq 2$), no central image is produced even in theory. Based on the surface-brightness profiles of nearby early-type galaxies measured with HST, Keeton (2003) predicted the distribution of core image magnifications. He found a broad distribution, from $10^{-4.5} - 10^{-1}$, with a most probable magnification of
approximately $10^{-2.5}$.

While they are hard to observe, central images probe the inner 10–100 pc of very distant galaxies. At optical wavelengths, the central image will be confused with, if not overwhelmed by, starlight from the foreground galaxy. At radio wavelengths the quasar can be much brighter than the foreground object, but few central images have been observed even in the radio regime. Large demagnifications by lensing are necessary, which constrains the matter distribution in the foreground lens galaxies. Constant density cores must be smaller than 200–300 pc (Wallington & Narayan 1993; Evans & Hunter 2002) and power law matter profiles must be nearly isothermal, or steeper (Rusin & Ma 2001; Evans & Hunter 2002).

There are two good galaxy lens central image candidates. Chen & Hewitt (1993) detected a radio source at the center of the ring in the lens MG 1131+0456 (Figure 1-1). Subsequent modelling of the lens galaxy as a cored power law determined that this was probably a central image, as the range of core radii and power law indices which fit the shape of the ring also generated a central image with the observed flux density (Chen et al. 1995). Winn et al. (2003, 2004b) have confirmed the existence of a central image produced by an isolated lens galaxy in the lens PMN J1632-0033, using radio observations (Figure 1-2). We discuss these objects and their matter profiles further in Chapter 7.

There are also two cases of odd images which are not the central images of a galaxy lens. Inada et al. (2005) found a central image generated by the combined profile of a cluster and a massive galaxy, using the Sloan Digital Sky Survey and the Hubble Space Telescope. The mass modelling here is dependent on both the galaxy and the cluster profile. The lens APM08279+5255 has a third image (Ibata et al. 1999), but extended CO(1-0) radio emission from the source quasar indicated that this lens has a “naked cusp” configuration (Lewis et al. 2002). The highly elongated projected profile of an edge-on lens galaxy creates a cusp in the tangential caustic, and this source quasar lies near this cusp, giving three collinear bright images. The third image here is not a central image, and does not give any information on the lens galaxy central profile.

1.3 Super-Massive Black Holes

Most galaxies host a super-massive black hole (SMBH) whose mass correlates closely with the properties of the central stellar bulge (Kormendy & Richstone 1995; Magorrian et al. 1998). In the local universe (within 100 Mpc, $z < 0.02$) there is a particularly tight correlation between the black hole mass and the spheroid’s velocity, the $M_{\text{BH}} - \sigma$ relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002). The stellar velocity dispersion is measured from narrow stellar or nebular lines such as [OIII] λ5007, $^1$ Mgb λ5175, Fe λ5270 and the CaII λλ8498, 8542, 8662 triplet (Greene & Ho 2006; Shields et al. 2006b; Woo et al. 2006). Local estimates of the black hole mass rely on the kinematics of stars, masers or gas orbiting the SMBH (see review by Ferrarese & Ford (2005)).

$^1$All wavelengths in this section are in Å.
Figure 1-1: Very Large Array (VLA) images of MG 1131+0456, at 5 GHz (top left), 8.4 GHZ (top right), 15 GHz (lower left) and 22 GHz (lower right), from Chen et al. (1995), reproduced by permission of the AAS. The background source has a steep spectrum lobe which is lensed into a ring (prominent at low frequencies) and a flatter spectrum nucleus which is lensed into two bright point images (prominent at higher frequencies). Component D is the central image, clearly visible at 8.4 GHz, marginally detected at 5 GHz, and below the sensitivity limit at the higher frequencies.

In the more distant universe ($z \gtrsim 0.03$) it is not possible to resolve a black hole’s sphere of influence, and mass estimates can only be made in bright active galactic nuclei (AGN) with less direct methods. The kinematics of the broad-line region within AGN are inferred from the widths of broad emission lines such Hβ $\lambda$4861 and MgII $\lambda$2798. The size of the broad-line region within an AGN is measured using either the reverberation method, in which the delays between variations in the
Figure 1-2: 5 GHZ Multi-Element Radio Linked Interferometric Network (MERLIN) image of PMN J1632-0033 from Winn et al. (2003), reproduced by permission of the AAS. This is a single galaxy lens which has a confirmed central image (labelled C), with a flux density 250 times smaller than that of the bright image (labelled A).

The tightness of the local $M_{\text{BH}} - \sigma$ relation suggests that super-massive black holes and stellar bulges evolve together, with various feedback processes maintaining the
correlation between these components. In galaxy mergers, accretion onto the SMBH produces a quasar, and outflow from this quasar heats the gas in the merged galaxy, inhibiting further black hole growth and halting star formation. The black hole's quasar activity regulates both the spheroidal stellar mass and the black hole mass, reproducing the local $M_{\text{BH}} - \sigma$ relation (Di Matteo et al. 2005) and the slope of the local $M_{\text{BH}} - \sigma$ relation for $0 < z < 6$ (Robertson et al. 2006). These models also suggest that the SMBH plays a critical role in the formation of quasars and galaxies in general (Hopkins et al. 2006).

Gravitational lens central images can measure the black hole mass in an independent fashion, offering a useful check on the determination of black hole masses at $z \sim 0.5$. A SMBH in the lens galaxy affects the central image: it can destroy the central image, or split the central image into two images, one of which is directly attributable to the black hole (Mao et al. 2001; Bowman et al. 2004). In the latter case, the properties of the central-image pair could allow for the measurement of the black hole mass in an ordinary galaxy at significant redshift (Rusin et al. 2005). Given the critical role of SMBHs in galaxy formation outlined above, it would be useful to measure their masses in non-active galaxies at redshifts $z > 0.03$, and using a method independent of assumptions about the structure and kinematics of the AGN.

Keeton (2003)'s results on central image detectability were not strongly affected by the addition of a black hole: the magnification of the central image was strongly affected only when the central image was already most demagnified by the smooth galaxy profile. Rusin & Ma (2001) found that their constraints on the density profiles of two CLASS lenses were somewhat weaker when an SMBH was included. So the inclusion of a black hole has only a minor effect on the use of central images to constrain galaxy profiles. We return to this point in Chapter 5.

However the nature of the galaxy profile is relevant to eventual detection and use of SMBH images. Rusin et al. (2005) find that black hole images are more likely to be detected for shallower profiles. They consider single power laws for the density profile $\rho \propto r^{-\gamma}$ and find that an SMBH image is four times less likely to be detected in a galaxy with $\gamma = 1.95$ than in one with $\gamma = 1.75$. Bowman et al. (2004) examined cored isothermal models and found that smaller core radii make SMBH images less detectable: the cusp in the lens galaxy profile from the black hole eliminates both central images. The cross-section for forming the central image pair is maximized when the core radius is $\sim 0.001 - 0.1$, times the Einstein radius in their cored isothermal sphere models (see, for example, Figure 6 of Bowman et al. (2004)). The cross-section increases and the peak moves to lower core radii as the black hole mass decreases.

1.4 Outline of this Thesis

This thesis presents the first four objects in the Extragalactic Lens VLBI Imaging Survey (ELVIS), which aims to detect central images or set upper limits on their flux densities, and constrain galaxy profiles with either the central images or upper limits. In Chapter 2 we describe the survey and motivate the selection criteria and
observing methods. In Chapter 3 we explain the observing methods and present the measurements for three lenses for which we set an upper limit on the central image flux density. In Chapter 4 we look at the implications of these non-detections for the lens galaxy profiles and constrain a broken power law lens model. In Chapter 5 we investigate the implications of adding a super-massive black hole to the lens galaxy in each of these three systems. In Chapter 6 we present a tentative detection of a third radio source in the gravitational lens CLASS B2319+051. We then model the lens galaxy for the three scenarios: taking this source to be a faint AGN in the lens galaxy itself; taking the source to be the central image; and taking it to be an unrelated radio source. In Chapter 7 we summarize our results and compare them with previous central image modelling. We discuss the implications of our work for future searches for images produced by super-massive black holes, and describe our plans for continuing the survey.
Chapter 2

ELVIS

The Extragalactic Lens VLBI Imaging Survey (ELVIS) involves sensitive, high-angular-resolution radio observations of many of the known cases of gravitational lensing of a radio-loud quasar. The traditional reasons to conduct such observations are to confirm cases of gravitational lensing, and to observe correspondences between lensed radio jets in order to refine models of the lens galaxy. ELVIS is the first survey (to our knowledge) motivated by the search for central images. As such, our highest-priority targets are those that are most favorable for central-image hunting: radio-loud, asymmetric two-image lenses.

2.1 Asymmetric Lenses

The asymmetric two-image lenses (those with a large magnification ratio between the two bright quasar images) are best for central image searching because for those systems, the mean magnification of the central image is generally the largest, for a given lens galaxy (Mao et al. 2001; Bowman et al. 2004). A highly asymmetric system, in which there are two bright images with a large magnification ratio, forms when the angular separation between the lens galaxy and the unlensed source is nearly as large as possible, while still being close enough to produce multiple images. This results in a central image that is as distant as possible from the lens galaxy center, where the surface density is lessened and the demagnification is reduced. A more symmetric lens, with two bright images at a small magnification ratio or a ring of four bright images, occurs when the lens galaxy and the source are closer together. The central image forms closer to the galaxy center, where the surface density is larger and the degree of demagnification is consequently greater. Figure 2-1 illustrates this situation for a broken power law lens galaxy profile.

2.2 Radio Lenses

Observing at radio wavelengths is desirable to avoid extinction by dust within the interstellar medium of the lens galaxy. Attenuation by plasma effects is also possible, but can be minimized by observing at a high enough radio frequency (typically ≥
Figure 2-1: Image magnifications as a function of source position for a broken power law lens model with external shear. The model is one of those considered for the lens J1838 in Chapter 4, and has an isothermal outer slope ($\rho \propto r^{-2}$), a shallower inner slope with $\rho \propto r^{-0.9}$ and a break radius $r_b = 0'04$. The long-dashed lines show the magnifications of the bright images A and B, which form at the light travel time minimum and saddle point, respectively. The short-dashed lines show the two additional bright images which form when the source and the lens are closely aligned. The solid line shows the central image C, which forms at the central maximum of the light travel time. When the source and the lens are closely aligned, the central image is highly demagnified and the bright images form as pair of similarly magnified bright images, or a ring of four bright images if the source lies inside the tangential caustic. As the source is moved further from the lens galaxy, the central image becomes less demagnified and the magnification ratio of image A to image B increases. At sufficiently large separation the source crosses the radial caustic, eliminating images B and C and leaving only image A. Clearly central images will be most easily detected in asymmetric lenses: those with two bright images at a large magnification ratio.

Moreover, an optical image could easily be lost in the starlight of the lens galaxy, while even a demagnified radio image will be brighter than a typical radio-quiet lens galaxy. The angular separation between the central image and the other images, or the lens galaxy center, is likely to be 100 mas or less, so at the widely used radio frequencies of 1-10 GHz, very-long-baseline interferometry (VLBI) is needed. The search for central images is a task that is well-matched to recent advances in VLBI technologies. New high-bandwidth recorders and digital back-ends have increased typical data rates by a factor of 4 in recent years, with even greater improvements expected in the next few years. The effect is a considerable sensitivity boost for those experiments that can take advantage of the increased bandwidth.
The European VLBI Network now routinely records at 1 Gb s\(^{-1}\). The U.S. National Radio Astronomy Observatory does not yet generally deploy recorders with bandwidths this wide, but it recently began devoting approximately 300 hours per year to simultaneous observing with the 10-station Very Long Baseline Array (VLBA) and several other large antennas such as the phased Very Large Array (VLA), Arecibo, the Green Bank Telescope, and the Effelsberg telescope. The thermal noise level with this “High Sensitivity Array” (HSA) is often 10-20 times lower than a traditional VLBA observation of similar duration. Gravitational lens central image searches are perfect projects for sensitive observations with heterogeneous arrays. The search for a faint central image in an otherwise blank region is a problem limited mainly by the thermal noise level, rather than the need for complete coverage of the Fourier plane. The typical radio lens field has two or four bright, compact sources (the bright images of the lensed quasar), and no extended structure. The bright images provide in-beam phase calibration sources. The simplicity of the source structure (multiple, isolated point sources) makes it easier to calibrate and image the data from the heterogeneous array.

2.3 The Sample

For the reasons given above, the first ELVIS targets are radio-loud quasars lensed by a single galaxy to produce two bright images with a flux ratio exceeding 5:1. Two lenses that fit this description, PMN J1632-0033 (Winn et al. 2002) and CLASS B1030+074 (Xanthopoulos et al. 1998), have already been the subjects of sensitive VLBI observations by other groups. In the former case, good evidence for a central image was found (Winn et al. 2004b), with a flux density 250 times less than that of the brightest image A.

ELVIS includes long-duration VLBA observations, or shorter-duration HSA observations, of the 6 other known radio lenses meeting these criteria. It also includes B1152+199, which has a bright image flux density ratio of 3:1, but has a central radio source. While this source has a steeper spectral index than the two bright lens images and is suspected not to be a lens image, we thought it worthy of further investigation. Table 2.1 provides a brief description of these systems.

The gravitational lens PMN J1838–3427 was discovered by Winn et al. (2000), as part of a survey for radio-loud gravitational lenses in the southern sky. Our other targets were discovered in the CLASS survey (Browne et al. 2003; Myers et al. 2003).

This thesis includes PMN J1838–3427, CLASS B0739+366, CLASS B0445+123 and CLASS B2319+051, hereafter referred to as J1838, B0739, B0445 and B2319. The observations and modelling for J1838 have been accepted for publication in the Astrophysical Journal (Boyce et al. 2006).

The last three lenses are not included in this thesis. The observations of B1152+199 and B0631+519 have only recently been obtained, and there has not been time to analyze these systems. An incorrect sky position was supplied for the correlation of the original B0850+054 observations, and these data were not useable. A HSA reobservation of this target may be scheduled in the second half of 2006, and we are
Table 2.1: Properties of the lenses in the Extragalactic Lens VLBI Imaging Survey (ELVIS). The first four lenses (above line) are included in this thesis and the last three (below line) will be published at a later date. The flux density of the brightest image, $S_A$, the separation of the two bright images and their flux density ratio, $S_A/S_B$ are taken from earlier 5 GHz VLBA observations for the first 5 lenses, from 5 GHz MERLIN observations for B0850+054, and from 8.4 GHz VLA observations for B1152+199. Data taken from the references cited, some redshifts taken from McKean et al. (2004). The lens galaxy redshift in J1838–3427 has not been measured; Winn et al. (2000) estimate $z_L = 0.36 \pm 0.08$ based on the lens galaxy’s photometric properties.

<table>
<thead>
<tr>
<th>Target</th>
<th>$S_A$</th>
<th>$S_A/S_B$</th>
<th>Separation</th>
<th>$z_L$</th>
<th>$z_S$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMN J1838–3427</td>
<td>145</td>
<td>14</td>
<td>1&quot;00</td>
<td>0.36?</td>
<td>2.78</td>
<td>Winn et al. (2000)</td>
</tr>
<tr>
<td>CLASS B0739+366</td>
<td>31</td>
<td>6</td>
<td>0&quot;54</td>
<td>-</td>
<td>-</td>
<td>Marlow et al. (2001)</td>
</tr>
<tr>
<td>CLASS B0445+123</td>
<td>17</td>
<td>6</td>
<td>1&quot;34</td>
<td>0.558</td>
<td>-</td>
<td>Argo et al. (2003)</td>
</tr>
<tr>
<td>CLASS B2319+051</td>
<td>40</td>
<td>5</td>
<td>1&quot;36</td>
<td>0.624</td>
<td>-</td>
<td>Rusin et al. (2001b)</td>
</tr>
<tr>
<td>CLASS B0631+519</td>
<td>46</td>
<td>9</td>
<td>1&quot;16</td>
<td>0.620</td>
<td>-</td>
<td>York et al. (2005)</td>
</tr>
<tr>
<td>CLASS B0850+054</td>
<td>49</td>
<td>6</td>
<td>0&quot;68</td>
<td>0.588</td>
<td>-</td>
<td>Biggs et al. (2003a)</td>
</tr>
<tr>
<td>CLASS B1152+199</td>
<td>52</td>
<td>3</td>
<td>1&quot;56</td>
<td>0.439</td>
<td>1.109</td>
<td>Myers et al. (1999)</td>
</tr>
</tbody>
</table>

pursuing other avenues for observing this target.
Chapter 3

Observations of J1838–3427, B0739+366 and B0445+123: Central Image Upper Limits

3.1 Observing Methods

We observed J1838 and B0739 with the ten antennas of the NRAO Very Long Baseline Array (VLBA, Napier (1994)) over multiple epochs, while we observed B0445 and B2319 with the High Sensitivity Array (HSA) in a single short epoch.

We observed J1838 with the ten antennas of the VLBA, on 6 different epochs between 2000 October and 2001 March. At each epoch, the duration of the observation was 5 hours. We observed right circular polarization with a central frequency of 8.415 GHz. We used 2 bit sampling at 16 Msamples s\(^{-1}\) for each of 8 channels, giving a total data rate of 256 Mb s\(^{-1}\). Data from antennas that were observing at an elevation of less than 10 degrees were excluded (this included all of the data from the Brewster antenna). In addition, the North Liberty antenna was not in use for two epochs, and was excluded from a third epoch for which its data were very noisy and degraded the image. Thus, 3 epochs used 9 antennas and 3 epochs used 8 antennas. In each observation, the time on J1838 was 4.5 hours and the estimated thermal noise limit (based on the collecting area and receiver characteristics) was \(\sim 70 \mu\text{Jy beam}^{-1}\).

We observed B0739 with the ten antennas of the VLBA, on 10 epochs in February and March 2005. At each epoch, the observation spanned 8 hours. We observed dual circular polarization with a central frequency of 4.987 GHz. We used 2 bit sampling at 16 Msamples s\(^{-1}\) for each of 4 channels, giving a total data rate of 128 Mb s\(^{-1}\). The Mauna Kea antenna was not in use for the Feb 4 and Feb 5 epochs due to a heavy blizzard, the Owens Valley antenna was not in use for the 2005 Feb 17 epoch due to maintenance and the Pie Town antenna was excluded from the Mar 19 epoch, as its data from this epoch were very noisy and degraded the image. The bright image A of B0739 has a flux density \(\sim 15 \text{ mJy}\), too faint for self-calibration with the VLBA, and so phase-referencing was necessary. 3 minute observations of B0739 were alternated with 2 minute observations of the calibration source J0752+3730, at a separation of
2.2. In each epoch the time on B0739 was 4.4 hours and the thermal noise estimated from the collecting area and receiver characteristics was $\sim 50 \mu$ Jy beam$^{-1}$.

We observed B0445 with the High Sensitivity Array (HSA) for one epoch on June 10 2005, spanning 3 hours. Our observations included the ten antennas of the Very Long Baseline Array, the Arecibo telescope, the Green Bank telescope and the phased Very Large Array. We observed dual circular polarization with a central frequency of 8.417 GHz. We used 2 bit sampling at 16 Msamples s$^{-1}$ for each of 8 channels, giving a total data rate of 256 Mb s$^{-1}$. At 20 minute intervals we observed the calibration source J0449+1121, at a distance of 1'1 from B0445, in order to measure the phase delays between individual VLA antennas and combine the individual antennas into a phased array. The time on B0445 was 2.2 hours, and the thermal noise estimated from the collecting area and receiver characteristics was 10 $\mu$Jy beam$^{-1}$.

For each epoch the data were amplitude calibrated in AIPS, following standard procedures. The amplitudes should be accurate to within 5% (Wrobel & Ulvestad 2005). For B0739, the earth orientation parameter correlation bug was corrected using the standard patch (Walker et al. 2005). This bug was not relevant to the other targets, which did not rely on phase referencing and did not need accurate absolute positions.

In J1838 and B0445 the bright image A of the gravitational lens was bright enough to allow self-calibration. The initial phase solution was derived from a fringe fit to a point-source model centered at the location of image A, using a solution interval of 2 minutes for J1838 and 3 minutes for B0445. For B0739 the bright image A has a flux density $\sim 15$ mJy, too faint for self-calibration. An initial phase solution was determined for the calibration source J0752+3730 and then transferred to B0739.

The gravitational lens was then reduced with between 7 and 13 self-calibration cycles, each cycle consisting of imaging, phase-only self-calibration with a 0.5-1.5 minute solution interval, imaging, and phase and amplitude self-calibration with a 15 minute solution interval. CLEAN components were only included within two small regions, one at the location of each bright image. For each new cycle, smaller CLEAN components were included.

### 3.2 Bright Image Observations

#### 3.2.1 J1838

For J1838, the brightest image A appeared as a point source of flux density $\sim 210$ mJy, with $\sim 10$ mJy of extended emission to the west, while image B appeared as a point source, varying between 9 and 18 mJy. Maps from the first epoch are shown in Figure 3-2, while details of each observing run are presented in Table 3.1. The single epoch 5 GHz VLBA map of Winn et al. (2000) shows two bright point sources at the same positions, with diffuse emission to the west of image A. The fraction of the total image A flux density in this extended component is $\sim 10\%$ at 5 GHz and $\sim 5\%$ at 8.4 GHz, so the extended emission has a steeper spectral index than the point source.

The flux densities of the two bright images varied between the epochs, and the
Figure 3-1: Radio map of the two images of gravitational lens PMN J1838-3427 (labelled A and B), made with the VLBA at 8.4 GHz. Data are from the first epoch. The restoring beam (40 x 20 mas) was chosen to be much larger than the naturally weighted beam in order to show both images on a single map. Contours begin at 1.5 mJy beam\(^{-1}\) and increase by factors of 2. The absolute J2000 radio positions were not determined from our observations; they were assumed from earlier VLA imaging. The cross (labelled G) marks the location of the lens galaxy; it is offset from the bright quasar image A by \(-0\degree.085 \pm 0\degree.006\) in right ascension and by \(-0\degree.911 \pm 0\degree.006\) in declination, based on HST/WFPC2 imaging (Winn et al. 2000). The dot labelled S shows the location of the source for an isothermal sphere model (see Table 4.1). The box shows the central image search region.
<table>
<thead>
<tr>
<th>Date</th>
<th>Image A point source (mJy)</th>
<th>flux density total (mJy)</th>
<th>Image B flux density (mJy)</th>
<th>R.A.ₐ-R.A.ᵦ</th>
<th>dec.ₐ-dec.ᵦ</th>
<th>Blank field rms ($\mu$Jy beam⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 Oct 07</td>
<td>206.8</td>
<td>219.2</td>
<td>9.3</td>
<td>0''09747</td>
<td>0''99130</td>
<td>86</td>
</tr>
<tr>
<td>2000 Oct 30</td>
<td>204.3</td>
<td>213.4</td>
<td>16.2</td>
<td>0''09747</td>
<td>0''99125</td>
<td>88</td>
</tr>
<tr>
<td>2000 Dec 17</td>
<td>222.4</td>
<td>232.3</td>
<td>12.8</td>
<td>0''09746</td>
<td>0''99122</td>
<td>95</td>
</tr>
<tr>
<td>2000 Dec 18</td>
<td>202.7</td>
<td>214.4</td>
<td>12.3</td>
<td>0''09747</td>
<td>0''99121</td>
<td>98</td>
</tr>
<tr>
<td>2000 Dec 22</td>
<td>209.7</td>
<td>209.7</td>
<td>13.4</td>
<td>0''09745</td>
<td>0''99118</td>
<td>93</td>
</tr>
<tr>
<td>2001 Mar 24</td>
<td>207.5</td>
<td>219.5</td>
<td>18.3</td>
<td>0''09744</td>
<td>0''99111</td>
<td>79</td>
</tr>
</tbody>
</table>

Table 3.1: Details of the individual observing epochs for J1838. The beam size varied slightly between epochs, with average values of $3.5 \times 1.3$ mas, and the position angle was always within 1° of zero. All epochs excluded the Brewster antenna due to low elevations. The December epochs lacked the North Liberty VLBA antenna, December 17 and December 18 substituted a single Very Large Array (VLA) antenna for the Pie Town VLBA antenna.
Figure 3-2: Radio map of J1838 image A (left) and image B (right). Both maps were made from the first epoch of VLBA imaging at 8.4 GHz. Coordinate offsets are from the phase center at (J2000) 18°34'28.95'', -34°27'41.60''. Contours begin at 300 $\mu$Jy beam$^{-1}$ and increase by factors of 2 (the blank field rms near image B was 86 $\mu$Jy beam$^{-1}$). The synthesized beam of 3.6 x 1.1 mas at a position angle of 0°7 is shown at the lower left. Note the extended emission to the west of the main point source in image A.

ratio of these flux densities also varied. The image A to image B flux density ratio in our maps varies from 12 to 24, with an average of 15. This ratio averaged 14.6 in VLA observations and 10.6 in the previous 5 GHz VLBA observations (Winn et al. 2000). The lens image B appears to undergo large variations in intensity. The two likely explanations are intrinsic source variation, and interstellar scintillation (see Section 3.4).

3.2.2 B0739+366

For B0739, the eight epochs that included the Mauna Kea antenna resolve image A into two point sources A1 and A2 1.7 mas apart, with flux densities $\sim$ 9 mJy and $\sim$ 6 mJy (see Figure 3-4). In the two epochs that lacked the Mauna Kea antenna, the angular resolution was poorer and the beam’s major axis was more closely aligned with the line joining the two sub-images A1 and A2. For these two observations A1 and A2 were blended together into a single extended component of flux density $\sim$ 15 mJy (see Figure 3-5). In all epochs, image B was seen as a point source of flux density $\sim$ 2 mJy.

The total flux densities of the bright images varied between the epochs, and the ratio of these flux densities also varied slightly. The total image A flux to image B flux density ratio in our maps varies between 5.9 and 7.7, with an average of 6.5. This ratio averaged 6.0 in previous VLA observations and was 5.0 in a previous 5 GHz VLBA snapshot (Marlow et al. 2001). The variations in intensity are not huge, and may
Figure 3-3: Radio map of the two images of gravitational lens CLASS B0739+366 (labelled A and B), made with the VLBA at 5 GHz. Data are from the third epoch. The restoring beam (40 × 20 mas) was chosen to be much larger than the naturally weighted beam in order to show both images on a single map. Contours begin at 0.25 mJy beam⁻¹ and increase by factors of 2. The J2000 positions are derived from phase referencing in these observations. The cross (labelled G) marks the location of the lens galaxy; it is offset from the bright quasar image A by 0''1840 ± 0''010 in right ascension and by −0''4324 ± 0''010 in declination, based on HST/NICMOS imaging (Marlow et al. 2001). The dot labelled S shows the location of the source for an isothermal sphere model (see Table 4.1). The box shows the central image search region.
Figure 3-4: Radio map of B0739 image A (left) and image B (right). Both maps were made from the third epoch of VLBA imaging at 5 GHz. Coordinate offsets are from the phase center at (J2000) 07h42m51s16.85, +36°34'43.638. Contours begin at 165 µJy beam\(^{-1}\) and increase by factors of 2 (the blank field rms near image B was 48 µJy beam\(^{-1}\)). The synthesized beam of 3.2 × 1.8 mas at a position angle of \(-95\degree\) is shown at the lower left. This observation included Mauna Kea and image A is barely resolved into two components.

Figure 3-5: Radio map of B0739 image A (left) and image B (right). Both maps were made from the first epoch of VLBA imaging at 5 GHz. Coordinate offsets are from the phase center at (J2000) 07h42m51s16.85, +36°34'43.638. Contours begin at 165 µJy beam\(^{-1}\) and increase by factors of 2 (the blank field rms near image B was 51 µJy beam\(^{-1}\)). The synthesized beam of 3.7 × 2.4 mas at a position angle of \(70\degree\) is shown at the lower left. This observation did not include Mauna Kea and image A is seen as a single extended component.
### Table 3.2: Details of the individual observing epochs for B0739.

<table>
<thead>
<tr>
<th>Date</th>
<th>Image A flux density (mJy)</th>
<th>Image B flux density (mJy)</th>
<th>R.A. (<em>{A1})-R.A. (</em>{A2}) (mas)</th>
<th>dec. (<em>{A1})-dec. (</em>{A2}) (mas)</th>
<th>Blank field rms (μJy beam(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 Feb 04</td>
<td>15.5</td>
<td>2.2</td>
<td>0''22547</td>
<td>-0''.48930</td>
<td>51</td>
</tr>
<tr>
<td>2005 Feb 05</td>
<td>17.6</td>
<td>3.0</td>
<td>0''22535</td>
<td>-0''.48938</td>
<td>56</td>
</tr>
<tr>
<td>2005 Feb 11</td>
<td>14.0</td>
<td>2.0</td>
<td>0''22554</td>
<td>-0''.48931</td>
<td>48</td>
</tr>
<tr>
<td>2005 Feb 17</td>
<td>14.6</td>
<td>2.3</td>
<td>0''22555</td>
<td>-0''.48926</td>
<td>50</td>
</tr>
<tr>
<td>2005 Feb 18</td>
<td>14.5</td>
<td>2.1</td>
<td>0''22546</td>
<td>-0''.48920</td>
<td>47</td>
</tr>
<tr>
<td>2005 Feb 26</td>
<td>12.3</td>
<td>2.0</td>
<td>0''22555</td>
<td>-0''.48915</td>
<td>41</td>
</tr>
<tr>
<td>2005 Mar 10</td>
<td>13.9</td>
<td>2.2</td>
<td>0''22551</td>
<td>-0''.48913</td>
<td>41</td>
</tr>
<tr>
<td>2005 Mar 12</td>
<td>14.8</td>
<td>2.5</td>
<td>0''22564</td>
<td>-0''.48925</td>
<td>47</td>
</tr>
<tr>
<td>2005 Mar 19</td>
<td>16.9</td>
<td>2.2</td>
<td>0''22558</td>
<td>-0''.48921</td>
<td>56</td>
</tr>
<tr>
<td>2005 Mar 20</td>
<td>15.7</td>
<td>2.6</td>
<td>0''22551</td>
<td>-0''.48934</td>
<td>56</td>
</tr>
</tbody>
</table>

Table 3.2: Details of the individual observing epochs for B0739. All dates UT, the last three epochs began between 23:00 and 0:00 UT one day earlier than the listed date. The Pie Town antenna was not used for the Mar 19 epoch and the Owens Valley antenna was not used for the Feb 17 epoch. The Feb 04 and Feb 05 epochs lacked the Mauna Kea antenna, making the beam larger and aligning its major axis with the line joining A1 and A2. For these two epochs a single extended image A was resolved, for the remaining eight epochs image A was split into point sources, A1 and A2. This table includes the total image A flux density and the offset between image B and the flux-weighted centroid of image A. Table 3.3 presents data on A1 and A2 for the last eight epochs.

### Table 3.3: The flux densities and separations of sub-images A1 and A2 in B0739.

<table>
<thead>
<tr>
<th>Date</th>
<th>Flux Density A1 (mJy)</th>
<th>Flux Density A2 (mJy)</th>
<th>Total (mJy)</th>
<th>R.A. (<em>{A1})-R.A. (</em>{A2}) (mas)</th>
<th>dec. (<em>{A1})-dec. (</em>{A2}) (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 Feb 11</td>
<td>8.5</td>
<td>5.5</td>
<td>14.0</td>
<td>-1.52</td>
<td>-0.79</td>
</tr>
<tr>
<td>2005 Feb 17</td>
<td>9.2</td>
<td>5.3</td>
<td>14.5</td>
<td>-1.57</td>
<td>-0.79</td>
</tr>
<tr>
<td>2005 Feb 18</td>
<td>9.2</td>
<td>5.3</td>
<td>14.5</td>
<td>-1.59</td>
<td>-0.79</td>
</tr>
<tr>
<td>2005 Feb 26</td>
<td>7.0</td>
<td>5.2</td>
<td>12.2</td>
<td>-1.52</td>
<td>-0.90</td>
</tr>
<tr>
<td>2005 Mar 10</td>
<td>8.9</td>
<td>5.0</td>
<td>13.9</td>
<td>-1.55</td>
<td>-0.84</td>
</tr>
<tr>
<td>2005 Mar 12</td>
<td>8.8</td>
<td>6.1</td>
<td>14.8</td>
<td>-1.59</td>
<td>-0.79</td>
</tr>
<tr>
<td>2005 Mar 19</td>
<td>10.0</td>
<td>6.9</td>
<td>16.9</td>
<td>-1.59</td>
<td>-0.85</td>
</tr>
<tr>
<td>2005 Mar 20</td>
<td>9.9</td>
<td>5.8</td>
<td>15.7</td>
<td>-1.55</td>
<td>-0.87</td>
</tr>
</tbody>
</table>

Table 3.3: The flux densities and separations of sub-images A1 and A2 in B0739, for the eight epochs which included Mauna Kea and resolved these two sub-images. The beam size was \(~ 3.2 \times 1.7\) mas, with a position angle of \(~ -9^\circ\). Given that the separation of the two components is comparable to the minor axis of the beam, the decomposition of flux density between these components is probably not accurate and we do not ascribe any significance to the variations.
be due to intrinsic source variation, substructure in the lensing galaxy or interstellar scintillation.

In an earlier 1.7 GHz observation, Marlow et al. (2001) detected weak extended emission 50 mas to the east of image A, and corresponding parity reversed weak emission west of image B. Our combined 5 GHz observations did not detect these features even though the noise was three times lower. The extended emission clearly has a steep spectral index.

### 3.2.3 B0445

For B0445, the brightest image A appeared as a point source of flux density $\sim 14$ mJy, with $\sim 1$ mJy of extended emission to the east, while image B appeared as a point source of $\sim 3$ mJy. Maps are shown in Figure 3-7, while details of the observations are presented in Table 3.4. The beam is more irregular for this observation, as it had a duration of only 2.5 hours and the array was heterogeneous.

With only one epoch, we have no information on variability of the bright images for this lens. A 5 GHz VLBA snapshot in 2001 found flux densities of 16.6 mJy for image A and 2.7 mJy for image B (Argo et al. 2003). These are similar to the values we present in Table 3.4, although our image A flux is lower by $\sim 10\%$. This is likely due to intrinsic variation, or possibly due to resolving out some extended emission to the east: the earlier observations found image A to be a point source.

### 3.3 Central Image Limits in J1838, B0739, B0445

For these three lenses, no additional sources of radiation were seen in any epoch. In each case, we examined a large region between the location of the lens galaxy and the bright image B, where a central image would be expected.\(^1\) We extended this region slightly to the other side of the lens galaxy to allow for the uncertainty in the optical position. For J1838 and B0739 the multiple epoch maps were co-added, and the blank

---

\(^1\)Gravitational lens images form at extrema of the time delay surface, which is a combination of the geometric delay and the lens galaxy potential determined by its density profile. The central image forms near the lens galaxy potential maximum. The geometric delay shifts the overall maximum towards the saddle point image B, on the opposite side of the lens galaxy from the source. The central image will thus form between the lens galaxy and image B, the fainter of the two bright images.
Figure 3-6: Radio map of the two images of gravitational lens CLASS B0445+123 (labelled A and B), made with the VLBA at 5 GHz. The restoring beam (50 × 50 mas) was chosen to be much larger than the naturally weighted beam in order to show both images on a single map. Contours begin at 1.5 mJy beam⁻¹ and increase by factors of 2. The J2000 radio positions were not determined from our observations; they were assumed from earlier VLA imaging. The cross (labelled G) marks the location of the lens galaxy; it is offset from the bright quasar image A by 0′930 ± 0′004 in right ascension and by 0′360 ± 0′004 in declination, based on HST/WFPC2 imaging (Falco, E. E., private communication). The dot labelled S shows the location of the source for an isothermal sphere model (see Table 4.1). The box shows the central image search region.

Field noise decreased by ~ \sqrt{6} and ~ \sqrt{10}, respectively. For each lens the central-image search region remained blank (see Figures 3-8, 3-10, 3-12. The distributions of surface brightness in the pixels of the final maps are roughly Gaussian (see Figures 3-9, 3-11 and 3-13).

We note that the rms noise is equal to the expected thermal noise for B0739,
Figure 3-7: Radio map of B0445+123 image A (left) and image B (right). Both maps were made using the High Sensitivity Array (HSA) at 8.4 GHz. Coordinate offsets are from the approximate location of the bright image A at (J2000) 04\textdegree 48\textquoteleft 21.9898, +12\textdegree 27\textquoteleft 55\textquoteleft 40.9. Contours begin at 60 \( \mu \)Jy beam\(^{-1}\) and increase by factors of 2 (the blank field rms near image B was 18 \( \mu \)Jy beam\(^{-1}\)). The synthesized beam of 2.3 \( \times \) 0.8 mas (position angle 28\textdegree 5) is shown at the lower left. Note the extended emission to the east of the main point source in image A.

showing that we can reach the expected thermal noise limit with VLBA observations of a source at mid-northern latitudes. For J1838 the noise is within 20-30\% of the thermal limit, with the excess being due to the southerly declination of the target. In B0445 the noise is considerably higher than the thermal limit of \( \sim 10 \) \( \mu \)Jy beam\(^{-1}\), by a factor of \( \sim 1.8 \). There are no obvious sidelobes and the excess of 1.8 is due to the uniform weighting which yielded good images with the heterogeneous array.

To quote an upper limit to the central image flux density in each lens, we considered directly the surface brightness distribution and took the 99th percentile to be the 99\% limit on the central image flux density. The central image flux density upper limits, and the corresponding 99\% limits on the magnification ratio are given in Table 3.5. The previous 99\% limits on the magnification ratio (based on the flux density of image A and the rms noise in earlier VLBA maps) are presented for comparison.

3.4 Scintillation in J1838

In J1838, we found the flux densities \( S_A \) and \( S_B \) of the two bright quasar images to vary from epoch to epoch. The ratio \( S_A/S_B \) also varied significantly, demonstrating that the variations are not due only to inconsistencies in the flux density scale. Image B showed a higher fractional variation than image A (Table 3.1). This is similar to what was observed by Winn et al. (2004a), who monitored this object for 4 months with the Australia Telescope Compact Array (ATCA) at 9 GHz. Over the course of
Figure 3-8: Radio map of the central image search region for J1838, from the combined VLBA 8.4 GHz map of all six epochs. The wedge at right shows the grey scale in $\mu$Jy beam$^{-1}$. The J2000 radio positions were not determined from phase referencing; they were assumed from earlier VLA imaging. The cross (labelled G) marks the location of the lens galaxy detected using HST/WFPC2. Its position is based on the offset from the bright quasar images in the WFPC2 images. Image B is obvious near the bottom of the map. We searched for the central image in the boxed area, between the lens galaxy and image B.

<table>
<thead>
<tr>
<th>Target</th>
<th>$S_A$ (mJy)</th>
<th>$S_C$ Limit ($\mu$Jy)</th>
<th>$S_A/S_C$ Limit</th>
<th>Old $S_A/S_C$ Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1838</td>
<td>208.3</td>
<td>83</td>
<td>2500</td>
<td>330</td>
<td>Winn et al. (2000)</td>
</tr>
<tr>
<td>B0739</td>
<td>15.0</td>
<td>38</td>
<td>400</td>
<td>113</td>
<td>Marlow et al. (2001)</td>
</tr>
<tr>
<td>B0445</td>
<td>13.8</td>
<td>43</td>
<td>320</td>
<td>42</td>
<td>Argo et al. (2003)</td>
</tr>
</tbody>
</table>

Table 3.5: Limits on the bright image to central image magnification ratio in J1838, B0739 and B0445. We measure the flux density of the brightest image ($S_A$) and quote an upper limit on the flux density of the central image ($S_C$) based on the flux density from the measured distribution of pixels in the blank central image search region. The old limits on $S_A/S_C$ are taken from the flux density of $A$ and the rms noise measured from the VLBA maps in the appropriate reference.
Figure 3-9: Histogram of surface brightness values for all pixels within the central-image search region for J1838. The pixel size is 0.2 mas, which is smaller than the typical beam size of 3.5 × 1.3 mas. The distribution of surface brightness is approximately Gaussian, with a mean of −0.4 μJy beam⁻¹ and a standard deviation of 38 μJy beam⁻¹.

the campaign, the fractional variation in the flux density of image A was 4%, and that of image B was 8%.

The lens is located at a low galactic latitude (b_H = −12°5), and may undergo scintillation due to the Milky Way’s interstellar medium. The root-mean-squared amplitude due to scintillation is inversely proportional to the angular size of the source (Walker 1998, 2001), while the angular size of each lens image is proportional to $S^{1/2}$, since gravitational lensing conserves surface brightness. Thus the rms amplitude of scintillation variations is proportional to $S^{-1/2}$, and the fainter image B would be more affected by interstellar scintillation than image A. In contrast, intrinsic variability should produce the same fractional variation in each component (though the variations would appear with time lags due to the geometric and Shapiro delays). The greater fractional variation of image B that was observed with ATCA, and in our own observations, supports the scintillation hypothesis.

The central image, if it exists, has a much smaller flux density and angular size than either of the bright images. Taking $S_A/S_C > 2500$, scintillation would cause fractional variations in $S_C$ of order unity. No central radio source was seen in any individual observation. Scintillation, if present, did not magnify the central image.
above the detection limit for any single epoch (∼200 μJy). In what follows, we use the blank field of the combined map to define our upper limit on the central image flux density, but we note that scintillation could be a major source of systematic error in this determination.

Our other targets are located at higher galactic latitude: \( b_\parallel = +25^\circ.5, -20^\circ.3, -50^\circ.8 \) for B0739, B0445 and B2319, respectively. Further away from the galactic plane, these targets are presumably less affected by scintillation, and B0739 does show less variation in the flux densities of images A and B between epochs than J1838 (Table 3.2). However scintillation may introduce a systematic error into the flux density limits for these targets as well.
Figure 3-11: Histogram of surface brightness values for all pixels within the central-image search region for B0739. The pixel size is 0.2 mas, which is smaller than the typical beam size of $3.5 \times 1.3$ mas. The distribution of surface brightness is approximately Gaussian, with a mean of $-0.5 \, \mu$Jy beam$^{-1}$ and a standard deviation of $15 \, \mu$Jy beam$^{-1}$.
Figure 3-12: Radio map of the central image search region for B0445, from the HSA 8.4 GHz map. The wedge at right shows the grey scale in $\mu$Jy beam$^{-1}$. The J2000 radio positions were not determined from phase referencing; they were assumed from earlier VLA imaging. The cross (labelled G) marks the location of the lens galaxy detected using HST/NICMOS. Its position is based on the offset from the bright quasar images in the NICMOS images. Image B is obvious near the upper left of the map. We searched for the central image in the boxed area, between the lens galaxy and image B.
Figure 3-13: Histogram of surface brightness values for all pixels within the central-image search region for B0445. The pixel size is 0.2 mas, which is smaller than the beam size of $2.3 \times 0.8$ mas. The distribution of surface brightness is approximately Gaussian, with a mean of $-0.1 \, \mu\text{Jy beam}^{-1}$ and a standard deviation of $18 \, \mu\text{Jy beam}^{-1}$. 
Chapter 4

Mass Models of J1838–3427, B0739+366 and B0445+123 with no Black Hole

With these new and more stringent upper limits on the flux densities of the central images in J1838, B0739 and B0445, we can restrict the possibilities for the central density profile of the lens galaxies. A simple and realistic model for the mass distribution of a massive galaxy is a broken power law (see Section 1). We adopt the broken power law density profile of Muñoz et al. (2001), in which the surface density and the deflection angle are given by analytic expressions. This profile varies as $\rho \propto r^{-n}$ at large radii, and as $\rho \propto r^{-\gamma}$ at small radii, with a break at radius $r_b$:

$$\rho(r) = \rho_0 \frac{1}{r^{\gamma} (1 + r^2/r_b^2)^{(n-\gamma)/2}}. \quad (4.1)$$

Since galactic profiles are approximately isothermal on scales of a few kpc (see Section 1) and we have few constraints, we apply the method used by Winn et al. (2003) in the analysis of PMN J1632–0033 and fix the outer power law to be isothermal ($n = 2$). We then explore the constraints on the break radius $r_b$ and inner power law index $\gamma$. In the limit of a pure isothermal sphere, the central image vanishes; thus, as $r_b$ goes to zero or as $\gamma$ goes to 2, the central image flux density approaches zero. We use a spherical galaxy model, and account for non-sphericity in the profile with an external shear at an arbitrary position angle. The 10 free parameters of our model are the positions of the lens galaxy and the source, $(x_G, y_G, x_S, y_S)$, the source flux density ($S_s$), the mass parameter ($b = (2\pi r_b \rho_0)/(\Sigma_{cr})$) $^1$ the shear and its position angle $(\sigma, \theta_s)$, the break radius ($r_b$) and the inner power law index ($\gamma$).

The data provide 9 observables: the two sky coordinates for each of the lens galaxy, bright image A and bright image B; the flux densities for image A and image B ($S_A, S_B$); and an upper limit on the flux density of the central image C ($S_C$).

$^1$The quantity $\Sigma_{cr} = (c^2/4\pi G)(D_S/(D_L D_{LS}))$ is the critical surface density for lensing. The quantities $D_L$, $D_S$ and $D_{LS}$ are the angular diameter distances from the observer to the lens, from the observer to the source and from the lens to the source, respectively.
Table 4.1: Constraints on the lens models for J1838, B0739 and B0445. All positions are offsets from image A. Galaxy postions are from HST photometry, other constraints are from VLBA or HSA data.

The galaxy coordinates and their uncertainties were taken from the Hubble Space Telescope images: the Wide Field Planetary Camera 2 (WFPC2) photometry of Winn et al. (2000) for J1838, the Near Infrared Camera Multi-Object Spectrograph (NICMOS) photometry of Marlow et al. (2001) for B0739 and unpublished NICMOS photometry for B0445 (Falco, E. E., private communication). For J1838 and B0739 the radio coordinates and flux densities for images A and B were measured in each of the VLBA maps and the mean values of these observables were taken as model constraints. For B0445 we used the measured values in the single HSA map. For J1838 and B0445, we considered only the bright peak of image A, and ignored the diffuse emission seen only near this image, as we consider only the point source magnifications. In B0739, the two sub-components of image A are only 1\'7 apart, and in the less magnified image B and central image the corresponding sub-components would be closer together and appear as a single source. Thus the total flux of image A, and the weighted average position of images A1 and A2 was used in the lens modelling. Since both the positions and fluxes of the bright images may be perturbed by substructure in the lens galaxy, we adopted errors of 3 mas in the positions and 20\% in the flux densities (following Mao & Schneider (1998); Keeton & Kochanek (1998); Kochanek et al. (2004)). The constraint on $S_C$ was taken from the rms noise in a large region between the lens galaxy position and image B in the combined VLBA or HSA image. For each system, the distribution of surface brightness in the pixels of this blank region was approximately Gaussian (see Figures 3-9, 3-11, and 3-13), with a mean near zero. We took this to be a null detection of the central image with 1 $\sigma$ error set by the rms noise of the map, and set $S_C = 0 \mu$Jy for the modelling. These constraints are summarized in Table 4.1. All of the observables were assumed to obey Gaussian statistics, and 1 $\sigma$ error bars are quoted.

We model the lenses with the *gravlens* package by Keeton (2001). For the conversion from angular units to physical units, we assume a $\Lambda$CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3, \Omega_\Lambda = 0.7$. With 10 free parameters and 9 measurements, one would expect a one-dimensional locus of allowed points in parameter...
Table 4.2: The best fit values of the lens model parameters in the isothermal case (when \( r_b = 0 \) or \( \gamma = 2 \)) for J1838, B0739 and B0445.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>J1838</th>
<th>B0739</th>
<th>B0445</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b = \theta_E )</td>
<td>0\textquoteleft 528</td>
<td>0\textquoteleft 268</td>
<td>0\textquoteleft 711</td>
</tr>
<tr>
<td>( x_G )</td>
<td>-0\textquoteleft 0850</td>
<td>0\textquoteleft 1840</td>
<td>0\textquoteleft 9300</td>
</tr>
<tr>
<td>( y_G )</td>
<td>-0\textquoteleft 9109</td>
<td>-0\textquoteleft 4324</td>
<td>0\textquoteleft 3600</td>
</tr>
<tr>
<td>( x_S )</td>
<td>-0\textquoteleft 0187</td>
<td>0\textquoteleft 0734</td>
<td>0\textquoteleft 6891</td>
</tr>
<tr>
<td>( y_S )</td>
<td>-0\textquoteleft 4747</td>
<td>-0\textquoteleft 2708</td>
<td>0\textquoteleft 1338</td>
</tr>
<tr>
<td>( S_S )</td>
<td>80.3 mJy</td>
<td>6.54 mJy</td>
<td>3.54 mJy</td>
</tr>
<tr>
<td>( s )</td>
<td>0.0649</td>
<td>0.0848</td>
<td>0.126</td>
</tr>
<tr>
<td>( \theta_s )</td>
<td>-18\textquoteleft 1</td>
<td>75\textquoteleft 6</td>
<td>-28\textquoteleft 5</td>
</tr>
</tbody>
</table>

space. In fact, because the observable \( S_C \) is an upper limit, the data define a one-dimensional boundary between an allowed region and a disallowed region in parameter space. In Figures 4-1, 4-2 and 4-3, we plot the projection of this plane in the \( r_b, \gamma \) parameter space that characterizes the inner density profile. Values of the other parameters are given in Table 4.2 for the isothermal case \( (r_b = 2 \text{ or } \gamma = 0) \), and these values change by \(< 20\% \) over the region of \( r_b, \gamma \) parameter space we investigated.

In each lens, the model fits the data perfectly for a sufficiently small break radius \( r_b \) or sufficiently steep inner index \( \gamma \). As \( r_b \) increases or \( \gamma \) decreases, the fits become progressively worse and \( \chi^2 \) becomes large. Most of the disagreement is due to an unacceptably large \( S_C \). The 95\% confidence region \( (\chi^2 < 5.99 \text{ for two free parameters, cf. Bevington \& Robinson (2003)}) \) lies below and to the right of the solid line. In all three cases, the absence of the central image implies that the matter distribution is nearly isothermal: a flat core with \( \gamma = 0 \) must be very small \( (r_b \lesssim 3\text{mas for J1838 and B0739, } r_b \lesssim 30\text{mas for B0445}) \), and a large core with \( r_b = 100\text{mas} \) has a steep inner profile \( (\gamma \gtrsim 1.9 \text{ for J1838, } \gamma \gtrsim 1.8 \text{ for B0739 and } \gamma \gtrsim 1.5 \text{ for B0445}) \).

We note that J1838 has a stronger limit on the flux density ratio of the brightest image A to the central image C, \( S_A/S_C \) (since image A is brighter in this system), and the limits on the shallowness of the central profile are correspondingly stronger. B0445 and B0739 have similar limits on \( S_A/S_C \), but the isothermal case Einstein radius is \( \sim 2.5 \) times larger in B0445. The lens galaxy is more massive in B0445 than in B0739 and all lensing scales are correspondingly larger, including the limiting break radii.

For comparison, Figures 4-1, 4-2 and 4-3 include the regions of parameter space allowed by the less stringent observational constraints of Winn et al. (2000); Marlow et al. (2001); Argo et al. (2003). The new data reduce the maximum size of a flat core by a factor of 2-3, and increase the minimum inner index of a large core by \( \sim 0.05 \) for J1838 and B0739, and by a factor of \( \sim 0.35 \) for B0445.
Figure 4-1: Models for the lens galaxy of J1838, using the new data presented in this paper (solid curve) and the previous data from Winn et al. (2000) (dashed curve). The matter profile is isothermal ($\rho \propto r^{-2}$) at large radius, and goes as $\rho \propto r^{-\gamma}$ at small radius, with the break at radius $r_b$. The inner power law index and break radius are allowed to vary. The curves mark the $\chi^2 = 5.99$ boundary between the allowed region (below and to the right) and the disallowed region (above and to the left). The solid straight line marks the minimum allowed index ($\gamma > 1.93$) in the limit of a pure power law, equivalent to $r_b = \infty$. The break radius in parsecs is calculated for $z_L = 0.36$, a redshift consistent with the lens galaxy photometry.

4.1 Properties of the Central Images

As well as setting limits from the overall $\chi^2$, we investigate the properties of the central images produced. Figures 4-4 through 4-9 show the variation of the central image flux density $S_C$ along certain cuts in parameter space. For each lens we show $S_C$ as a function of break radius $r_b$ when the inner index is fixed at $\gamma = 0$ (a flat core model) and as a function of $\gamma$ when we fix $r_b$ to a large value $^2$ (a central cusp model). In each case the central image flux density starts at zero for the isothermal case ($r_b = 0$ or $\gamma = 2$), and then rises as the core grows or the inner power law becomes shallower.

When we cross the 99% limit on $S_C$, the optimal model decreases the the intrinsic (unlensed) source flux density, keeping $S_C$ from growing at the expense of decreasing $S_B$, the flux density of the bright image B. The discrepancy between the modeled and observed values of $S_B$ is less disfavored than further increases in $S_C$. The growth in $S_C$ levels off and becomes irregular: this is particularly evident for B0739 (Figures 4-6 and 4-7).

The central image forms between the lens galaxy and the bright image B, at the location of the central maximum. For all break radii and inner indices investigated

$^2$10 times the 95% limit on $r_b$ in the flat core model.
Figure 4-2: Models for the lens galaxy of B0739, using the new data presented in this paper (solid line) and the previous data from Marlow et al. (2001) (dashed line). The matter profile is isothermal ($\rho \propto r^{-2}$) at large radius, and goes as $\rho \propto r^{-\gamma}$ at small radius, with the break at radius $r_b$. The inner power law index and break radius are allowed to vary. The lines mark the $\chi^2 = 5.99$ boundary between the allowed region (below and to the right) and the disallowed region (above and to the left). The solid straight line marks the minimum allowed index ($\gamma > 1.84$) in the limit of a pure power law, equivalent to $r_b = \infty$. The break radius in parsecs is calculated for a typical lens redshift of $z_L = 0.5$.

there is a small distance of 4–35 mas between the measured lens galaxy position and the modelled central image position. In each case the bright image B is tens or hundreds of mas further from the lens galaxy (see Table 4.3), so there should not be any confusion between the central image and the bright image B in VLBI observations, which have an angular resolution of $\sim 1$ mas.
Figure 4-3: Models for the lens galaxy of B0445, using the new data presented in this paper (solid line) and the previous data from Argo et al. (2003) (dashed line). The matter profile is isothermal ($\rho \propto r^{-2}$) at large radius, and goes as $\rho \propto r^{-\gamma}$ at small radius, with the break at radius $r_b$. The inner power law index and break radius are allowed to vary. The lines mark the $\chi^2 = 5.99$ boundary between the allowed region (below and to the right) and the disallowed region (above and to the left). The solid straight line marks the minimum allowed index ($\gamma > 1.67$) in the limit of a pure power law, equivalent to $r_b = \infty$. The break radius in parsecs is calculated for the measured lens redshift of $z_L = 0.5583$.

<table>
<thead>
<tr>
<th>Target</th>
<th>Maximum Modelled C-G Distance</th>
<th>Measured B-G Distance</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1838</td>
<td>4</td>
<td>81</td>
<td>Winn et al. (2000)</td>
</tr>
<tr>
<td>B0739</td>
<td>21</td>
<td>70</td>
<td>Marlow et al. (2001)</td>
</tr>
<tr>
<td>B0445</td>
<td>34</td>
<td>340</td>
<td>Falco (private comm.)</td>
</tr>
</tbody>
</table>

Table 4.3: Distances from the lens galaxy to the central image C and bright image B for the three lenses J1838, B0739 and B0445. The distance from the lens galaxy to the bright image B has been determined from optical observations given in the reference. The distance to the central image C is the largest allowed distance from the lens models plotted in Figures 4-4 through 4-9, and the modelled separation of the lens galaxy and the central image is often smaller by a factor of a few. Bright image B is always at least 50 mas farther from the lens galaxy than the central image and will be resolved at VLBI resolutions of $\sim 1$ mas.
Figure 4-4: The central image flux density $S_C$ as a function of break radius $r_b$ in the lens galaxy of J1838, for a model with a constant density core (inner index $\gamma = 0$). This corresponds to a vertical slice along the left edge of Figure 4-1, but now plotting $S_C$ rather than $\chi^2$. The core image is infinitely demagnified and has zero flux density when $r_b = 0$ (the isothermal model). As $r_b$ increases the central image flux density rises, accounting for most of the disagreement between the observations and the model. The dashed line marks 83 $\mu$Jy, the 99% upper limit on $S_C$.

Figure 4-5: The central image flux density $S_C$ as a function of inner index $\gamma$ in the lens galaxy of J1838, for a model with a large central cusp (break radius $r_b = 0''0131$). This corresponds to a horizontal slice towards the top of Figure 4-1, but now plotting $S_C$ rather than $\chi^2$. The core image is infinitely demagnified and has zero flux density when $\gamma = 2$ (the isothermal model). As $\gamma$ decreases the central image flux density rises, accounting for most of the disagreement between the observations and the model. The dashed line marks 83 $\mu$Jy, the 99% upper limit on $S_C$. 
Figure 4-6: The central image flux density $S_C$ as a function of break radius $r_b$ in the lens galaxy of J1838, for a model with a constant density core (inner index $\gamma = 0$). This corresponds to a vertical slice along the left edge of Figure 4-2, but now plotting $S_C$ rather than $\chi^2$. The core image is infinitely demagnified and has zero flux density when $r_b = 0$ (the isothermal model). As $r_b$ increases the central image flux density rises, accounting for most of the disagreement between the observations and the model. The dashed line marks 38 $\mu$Jy, the 99% upper limit on $S_C$. Note that for large $r_b$ the central image C and the bright image B come close to merging, so the optimal model is found by varying both $S_B$ and $S_C$. $S_C$ does not increase smoothly as $r_b$ increases.
Figure 4-7: The central image flux density $S_C$ as a function of inner index $\gamma$ in the lens galaxy of B0739, for a model with a large central cusp (break radius $r_b = 0''0348$). This corresponds to a horizontal slice towards the top of Figure 4-2, but now plotting $S_C$ rather than $\chi^2$. The core image is infinitely demagnified and has zero flux density when $\gamma = 2$ (the isothermal model). As $\gamma$ decreases the central image flux density rises, accounting for most of the disagreement between the observations and the model. The dashed line marks 38 $\mu$Jy, the 99% upper limit on $S_C$. Note that for small $\gamma$ the central image C and the bright image B come close to merging, so the optimal model is found by varying both $S_B$ and $S_C$. $S_C$ does not increase smoothly as $\gamma$ decreases.
Figure 4-8: The central image flux density $S_C$ as a function of break radius $r_b$ in the lens galaxy of B0445, for a model with a constant density core (inner index $\gamma = 0$). This corresponds to a vertical slice along the left edge of Figure 4-3, but now plotting $S_C$ rather than $\chi^2$. The core image is infinitely demagnified and has zero flux density when $r_b = 0$ (the isothermal model). As $r_b$ increases the central image flux density rises, accounting for most of the disagreement between the observations and the model. The dashed line marks 43 $\mu$Jy, the 99% upper limit on $S_C$.

Figure 4-9: The central image flux density $S_C$ as a function of inner index $\gamma$ in the lens galaxy of B0445, for a model with a large central cusp (break radius $r_b = 0'267$). This corresponds to a horizontal slice towards the top of Figure 4-3, but now plotting $S_C$ rather than $\chi^2$. The core image is infinitely demagnified and has zero flux density when $\gamma = 2$ (the isothermal model). As $\gamma$ decreases the central image flux density rises, accounting for most of the disagreement between the observations and the model. The dashed line marks 43 $\mu$Jy, the 99% upper limit on $S_C$. 

47
Chapter 5

Mass Models of J1838–3427, B0739+366 and B0445+123 with a Black Hole

Most elliptical galaxies host super-massive black holes at their centers (Kormendy & Richstone 1995; Magorrian et al. 1998): this additional point mass steepens the overall central profile and may demagnify the central image (Mao et al. 2001). A realistic galaxy model should include a central black hole. As seen in the previous section, even an interesting smooth profile is underconstrained. To avoid adding extra degrees of freedom to the model, we add a black hole with a fixed mass given by the $M_{\text{BH}} - \sigma$ relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002), and determine the resulting effect.

For an early-type lens galaxy, most of the mass will be in the bulge component and so the total mass responsible for the lensing is a good estimate of the overall velocity dispersion. To estimate $\sigma$, we determine the best-fitting value of the Einstein radius using a model consisting of an isothermal sphere and external shear, and then use the relation $\theta_E = 4\pi(D_{LS}/D_S)(\sigma^2/c^2)$. For the broken power law model, the mass normalization parameter $b = (2\pi b\rho_0)/(\Sigma_c)$ is equivalent to $\theta_E$ and this parameter varies by 20% over the allowed region in the broken power law models, and by < 10% over most of this region, so the isothermal $\theta_E$ is a good estimate of the true velocity dispersion even if the true density profile is not exactly isothermal.

Given this estimate for $\sigma$, we calculate the black hole mass $M_{\text{bh}}$ using the relation from Tremaine et al. (2002),

$$M_{\text{bh}} = (1.35 \times 10^8 M_\odot) \left(\frac{\sigma}{200 \text{ km s}^{-1}}\right)^{4.02}.$$

(5.1)

The scatter in the $M_{\text{BH}} - \sigma$ relation is 0.3 dex (Tremaine et al. 2002), so a plausible range for the black hole mass is within a factor of two of this predicted value. The black hole masses are presented in Table 5.1.

We rerun the calculations from Section 4, but this time include a point mass fixed at the center of the lens galaxy. For each lens, we consider a black hole with a mass
<table>
<thead>
<tr>
<th>Target</th>
<th>$\theta_E$ (km s$^{-1}$)</th>
<th>$\sigma$</th>
<th>$M_{\text{bh}}$ ($10^8 M_\odot$)</th>
<th>$M_{\text{bh}}$ range ($10^8 M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMN J1838–3427</td>
<td>0''523</td>
<td>154</td>
<td>0.47</td>
<td>0.25 – 1</td>
</tr>
<tr>
<td>CLASS B0739+366</td>
<td>0''268</td>
<td>129</td>
<td>0.23</td>
<td>0.12 – 0.5</td>
</tr>
<tr>
<td>CLASS B0445+123</td>
<td>0''711</td>
<td>217</td>
<td>1.9</td>
<td>1 – 4</td>
</tr>
</tbody>
</table>

Table 5.1: The Einstein radii and velocity dispersions for the singular isothermal sphere models, and inferred black hole masses. For J1838, we assume a lens redshift $z_L = 0.36$, consistent with the lens galaxy photometric properties. For B0739, neither redshift is known, we assume typical values of $z_L = 0.5$, $z_S = 1.5$, and for B0445 the source redshift is unknown, we assume $z_S = 1.5$.

in the center of the expected range, and a black hole with a mass at the top of the expected range. The black hole either eliminates the central image completely, leaving only the two bright images, or creates two faint central images, the core and SMBH images, for a total of four images. The allowed regions, again defined by $\chi^2 < 5.99$, are shown in Figures 5-1, 5-2 and 5-3. Below and to the right of the allowed lines there are no central images, or both the core and SMBH images are sufficiently faint that they would not have been detected in our observations. The long-dashed line is for the black hole in the center of the mass range, the short-dashed line is for the black hole at the top of the mass range.

We note that each of our systems relies on at least one estimated redshift, either for the lens galaxy or the source quasar, which introduces an additional uncertainty into the black hole masses. However the relevant quantity for lensing is not the black hole's mass but its Einstein radius,

$$\theta_{\text{bh}} = \sqrt{\frac{4GM_{\text{bh}}}{c^2} \frac{D_{LS}}{D_L D_S}}, \tag{5.2}$$

which is less affected by changing redshift than $M_{\text{bh}}$. For example, when modelling B0739 we assumed redshifts $z_L = 0.5$, $z_S = 1.5$, and the central black hole mass and Einstein radius predicted from the $M - \sigma$ relation are $M_{\text{bh}} = 2.3 \times 10^7 M_\odot$, $\theta_{\text{bh}} = 9.2$ mas. Given the scatter in the $M - \sigma$ relation, these quantities could be anywhere in the range $M_{\text{bh}} = 1.1 - 5 \times 10^7 M_\odot$, $\theta_{\text{bh}} = 6.4 - 13.5$ mas. If we change the redshifts to $z_L = 1.0$, $z_S = 1.5$, the predicted black hole mass increases to $M_{\text{bh}} = 1.3 \times 10^8 M_\odot$ (a factor of 5), but the predicted Einstein radius increases only to $\theta_{\text{bh}} = 12.3$ mas (a factor of 1.3). If we change the redshifts to $z_S = 0.3$, $z_L = 4.0$ the predicted black hole mass decreases to $M_{\text{bh}} = 1.05 \times 10^7 M_\odot$ (a factor of 2.2) while the predicted Einstein radius decreases only to $\theta_{\text{bh}} = 8.8$ mas (a factor of 1.05). The deviations in the black hole Einstein radius from varying the redshift are quite small, and given that the dispersion in the $M - \sigma$ relationship already allows for a wide range of black hole masses and Einstein radii at any redshift, our general results will not depend greatly on the assumed redshifts.

The separation of the core and SMBH images is $2 - 5$ mas for J1838, and $4 - 8$ mas.
Figure 5-1: Models for the lens galaxy of J1838. The matter profile is isothermal \((\rho \propto r^{-2})\) at large radius, and varies as \(\rho \propto r^{-\gamma}\) at small radius, with the break at radius \(r_b\). To the smooth matter profile we add no black hole (solid line), a \(5 \times 10^7 M_\odot\) black hole (long-dashed line), or a \(10^8 M_\odot\) black hole (short-dashed line). These black hole masses are the central and largest values expected, given the velocity dispersion of the galaxy. The inner power law index and break radius are allowed to vary. The lines mark the \(\chi^2 = 5.99\) boundary between the allowed region (below and to the right) and the disallowed region (above and to the left). The break radius in parsecs and the black hole Einstein radius are calculated for a lens galaxy redshift \(z_L = 0.36\), consistent with its photometric properties, and the measured source redshift \(z_s = 2.78\). When no black hole is present, a central image always forms within the parameter ranges plotted. In the allowed region, the central image is below our detection limit. When a black hole is present, the central image is either eliminated or split into a core image and SMBH images. In the allowed region, either there are no central images or both central images have flux densities below our detection limit.

for B0739, so these might appear as a single unresolved component if aligned with the long axis of the beam. The core image flux density is greater than the SMBH image flux density by a factor of \(15 - 270\), so the core image flux density makes a much larger contribution to \(\chi^2\). For models near the boundary of the allowed region, combining both central images into a single unresolved component would raise \(\chi^2\) by \(< 0.6\) for J1838 and \(< 0.25\) for B0739 (usually much less), and the allowed region would be only slightly more constrained.

The SMBH allows the galaxy profile to be shallower, to some extent. For fairly flat cores \((\gamma \lesssim 1.2)\) the maximum break radius increases by a factor of \(5 - 30\%\) for B0739 and B0445, and by a factor of 1.5-3 for J1838, depending on the black hole mass. For larger, cuspy cores, the minimum inner slope is reduced by \(0.05 - 0.2\), depending on the black hole mass. While the central smooth profile remains close to isothermal, it
Figure 5-2: Models for the lens galaxy of B0739. The matter profile is isothermal \((\rho \propto r^{-2})\) at large radius, and varies as \(\rho \propto r^{-\gamma}\) at small radius, with the break at radius \(r_b\). To the smooth matter profile we add no black hole (solid line), a \(2.3 \times 10^7 M_\odot\) black hole (long-dashed line), or a \(5 \times 10^7 M_\odot\) black hole (short-dashed line). These black hole masses are the central and largest values expected, given the velocity dispersion of the galaxy. The inner power law index and break radius are allowed to vary. The lines mark the \(\chi^2 = 5.99\) boundary between the allowed region (below and to the right) and the disallowed region (above and to the left). The break radius in parsecs and the black hole Einstein radius are calculated for assumed lens and source redshifts \(z_L = 0.5\) and \(z_S = 1.5\). When no black hole is present, a central image always forms within the parameter ranges plotted. In the allowed region, the central image is below our detection limit. When a black hole is present, the central image is either eliminated or split into a core image and SMBH images. In the allowed region, either there are no central images or both central images have flux densities below our detection limit.

is allowed to be somewhat flatter. The cusp in the profile from the black hole makes the central mass profile sufficiently steep even if the smooth component is shallower.
Figure 5-3: Models for the lens galaxy of B0445. The matter profile is isothermal ($\rho \propto r^{-2}$) at large radius, and varies as $\rho \propto r^{-\gamma}$ at small radius, with the break at radius $r_b$. To the smooth matter profile we add no black hole (solid line), a $2 \times 10^8 M_\odot$ black hole (long-dashed line), or a $4 \times 10^8 M_\odot$ black hole (short-dashed line). These black hole masses are the central and largest values expected, given the velocity dispersion of the galaxy. The inner power law index and break radius are allowed to vary. The lines mark the $\chi^2 = 5.99$ boundary between the allowed region (below and to the right) and the disallowed region (above and to the left). The break radius in parsecs and the black hole Einstein radius are calculated for the measured lens redshift $z_L = 0.5583$ and an assumed source redshift $z_S = 1.5$. When no black hole is present, a central image always forms within the parameter ranges plotted. In the allowed region, the central image is below our detection limit. When a black hole is present, the central image is either eliminated or split into a core image and SMBH images. In the allowed region, either there are no central images or both central images have flux densities below our detection limit.
Chapter 6

B2319+051: A Possible Central Image

6.1 Observations

We observed B2319 with the High Sensitivity Array (HSA) for one epoch on December 9 2005, spanning 2.5 hours. Our observations included the ten antennas of the Very Long Baseline Array, the Arecibo telescope, the Green Bank telescope, the Effelsberg telescope and the phased Very Large Array. We observed dual circular polarization with a central frequency of 4.987 GHz. We used 2 bit sampling at 16 Msamples s$^{-1}$ for each of 8 channels, giving a total data rate of 256 Mb s$^{-1}$. At 20 minute intervals we observed the calibration source J2230+1100, at a distance of 6:0 from B2319, in order to measure the phase delays between individual VLA antennas and combine the individual antennas into a phased array. The time on B2319 was 2.0 hours (including 1.0 hours with Arecibo), and the thermal noise estimated from the collecting area and receiver characteristics was 10 $\mu$Jy beam$^{-1}$.

The data were amplitude calibrated in AIPS, following standard procedures. The gravitational lens was then reduced with self-calibration cycles, each cycle consisting of imaging, phase-only self-calibration with a 0.5-1.5 minute solution interval, imaging, and phase and amplitude self-calibration with a 15 minute solution interval. CLEAN components were only included within two small regions, one at the location of each bright image. For each new cycle, smaller CLEAN components were included.

For B2319+051, the total flux density in image A was $\sim$ 38 mJy and the total flux density in image B was $\sim$ 7 mJy. Each image was split into two point source components. The parities of these sub-images within image A and image B were reversed, and the flux density ratios between the separate components in image A and image B were the same, as expected for gravitational lensing. With only one epoch, we cannot comment on any variability in the bright images.

Substructure within the bright images is a common phenomenon. For example, in 9 of the 22 lenses in CLASS (Browne et al. 2003) each bright image contains compact sub-components separated by tens or hundreds of milliarcseconds (Biggs et al. 2003b, 2004; Ellithorpe 1995; King et al. 1997; Koopmans et al. 1999; Patnaik
Figure 6-1: Radio map of the two bright images of gravitational lens CLASS B2319+051, made with MERLIN at 5 GHz (Rusin et al. 2001b), reproduced by permission of the AAS. Coordinate offsets are from the position of image A at (J2000) 23h21m40s0, +05°27'37.2. Contours start at 0.424 mJy beam\(^{-1}\) and increase by factors of 2. The synthesized beam of 91 × 48 mas (position angle 21°9) is shown at the lower left. The black dot (labelled 3) marks the location of the third radio source detected in our HSA observations.

et al. 1995; Rusin et al. 2001b,a, 2002; York et al. 2005). Additionally, some lenses show substructure only in the brightest, most magnified image, including the three lenses discussed in Chapter 3. A separation of 10 mas corresponds to \(\sim 100\) pc at \(z = 1.5\), so the compact sub-components in the lensed quasars have separations similar to the knots in the jets of nearby quasars such as M87 (Hines et al. 1989).

\(^{1}\)the lensing magnification means that the actual separations are smaller than those observed by a factor of a few
Figure 6-2: Radio map of B2319 image A, made using the High Sensitivity Array (HSA) at 5 GHz. Coordinate offsets are from the position of sub-image A1 at (J2000) 23°21′40″.3015, +05°27′37″.2252. Contours begin at 150 μJy beam⁻¹ and increase by factors of 2. The synthesized beam of 4.2 × 1.6 mas (position angle 32°7) is shown at the lower left. Images A and B are each comprised of two sub-images and these show classic parity reversal.

<table>
<thead>
<tr>
<th>Image</th>
<th>Flux density (mJy)</th>
<th>Rel. R.A.</th>
<th>Rel. dec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>28.8</td>
<td>0″0000</td>
<td>0″0000</td>
</tr>
<tr>
<td>A2</td>
<td>8.2</td>
<td>-0″0203</td>
<td>-0″0038</td>
</tr>
<tr>
<td>B1</td>
<td>5.5</td>
<td>0″0113</td>
<td>-1″3640</td>
</tr>
<tr>
<td>B2</td>
<td>1.6</td>
<td>0″0188</td>
<td>-1″3641</td>
</tr>
</tbody>
</table>

Table 6.1: Details of the HSA observation of B2319. The beam was 4.3 × 1.5 mas, with a position angle of 34°1. The off-source noise in the field near image B was 37 μJy beam⁻¹.

6.2 A Possible Central Image

When a large map was made covering the region between image B and the lens galaxy in B2319, there was some evidence of a faint third radio image. The observation included only 2.2 hours on source, and most of the sensitivity came from the 1.1 hours on source that included Arecibo. With such short scans of a near-equatorial source, and a very heterogeneous array, the uv-coverage was poor and the beam was very diffuse. When the only deconvolved sources were at the locations of the known bright images, there was some flux spread out in the pattern of the beam, about 0′4 away from image B (Figures 6-4 and 6-5). This flux was present far from image B, and was not present in the directions of images A and B, so it seems to represent a
third source rather than a sidelobe of one of the bright images.

We repeated the final imaging step, but now deconvolved within a large box covering the spread out flux. This yielded a weak detection of a third source, although it appeared as several sources at different locations (Figure 6-6), suggesting that the emission was diffuse and over-resolved by the array. We tested for this by repeating the imaging, but applying a Gaussian taper of 50 MA to the u-v data. This reduced the weights given to the longer baselines, emphasizing structure on larger angular scales. The resulting map (Figure 6-7) still shows emission, although the position of the peak brightness has shifted. This is characteristic of diffuse emission. Deconvolving in another box of the same size but closer to image B did not reveal any source (Figure 6-8). The absence of any source in this comparison blank region suggests that the source is real, but the spread out, spotty nature of the source suggests that it is diffuse.

To produce a better map of the third source, we started with the dataset that had been self-calibrated on the two bright images, and conducted 5 additional cycles of imaging and self-calibration, considering components at the locations of the two bright images and the region where the third source had its peak brightness in the untapered map. Each cycle consisted of imaging, phase-only self-calibration with a 1.5 minute solution interval, imaging, and phase and amplitude self-calibration with a 15 minute solution interval, with no tapering applied to the u-v data. For each of the three
Figure 6-4: The region of B2319 where a central image might be expected, after imaging and self-calibration at the locations of the two bright images. Image B is obvious near the bottom of the map. There appears to be additional emission within the upper box, spread out in the pattern of the beam. (see also Figure 6-5). The wedge at right shows the grayscale in $\mu$Jy beam$^{-1}$, and the synthesized beam of 4.3 $\times$ 1.5 mas (position angle 34°1) is shown at the lower left. The same grayscale and beam are used in the Figures 6-6 and 6-8. The absolute radio positions were not measured in our observations, they were assumed from earlier phase-referenced VLBA observations in Rusin et al. (2001b). The cross marks the location of the lens galaxy, but its position is highly uncertain. The lensed quasar images have not been detected in optical / near-infrared imaging, so the lens galaxy absolute position was determined by Rusin et al. (2001b) from reference stars in wide field Keck images, with a 0′.45 uncertainty in each co-ordinate.
Figure 6-5: The irregular beam of the B2319 HSA observations for the imaging over two large fields, as shown in Figures 6-4, 6-6 and 6-8. The wedge at right shows the grayscale as a fraction of the peak beam strength. Note that the beam shape matches the shape of the diffuse emission seen northeast of image B.

fields, all CLEAN components were included down to the first negative component. The resultant maps of the bright images have already been presented as Figure 6-2 and 6-3, the new map of the third source is shown as Figure 6-9. The third source has a total flux density of 96 $\mu$Jy, and the off-source noise is 24 $\mu$Jy beam$^{-1}$. The noise expected for this field from the receiver characteristics and thermal properties is $\sim 10$ $\mu$Jy beam$^{-1}$.

The third source is split into two components, which may well be an imaging artifact (the two components have the same separation and position angle as the central peak and a bright sidelobe, see Figure 6-10). If this source is a central image, it is 400 times fainter than the bright image A, so the separation of the sub-images would be $1/\sqrt{400} = 1/20$ times the sub-image separation in A, approximately 1 mas, and the central image should appear as a point source.

At such a low level relative to the noise, and given that it may be over-resolved,
Figure 6-6: The region of B2319 where a central image might be expected, after imaging and self-calibration at the locations of the two bright images, followed by imaging at the locations of the bright images and within the upper box. Image B is obvious near the bottom of the map. There is a faint source within the upper box, although it seems to be over-resolved.

The third source detection is clearly very tentative. Follow-up observations at multiple frequencies are required to distinguish whether the third source is a central image, based on its surface brightness and spectral index. We discuss a proposed program of follow-up observations in Section 7.4.
Figure 6-7: The region of B2319 where a central image might be expected, after imaging and self-calibration at the locations of the two bright images, followed by imaging at the locations of the bright images and within the upper box. The wedge at right shows the grayscale in $\mu$Jy beam$^{-1}$, and the synthesized beam of $4.0 \times 1.9$ mas (position angle $28^\circ 3$) is shown at the lower left. A taper of 50 MA was applied to the uv data, emphasizing larger spatial scales. Image B is obvious near the bottom of the map. The faint source is still present in the upper box, although it still appears over-resolved, and the position of the peak brightness has shifted. This suggests that the emission is diffuse.
Figure 6-8: The region of B2319 where a central image might be expected, after imaging and self-calibration at the locations of the two bright images, followed by imaging at the locations of the bright images and within the lower box. Image B is obvious near the bottom of the map. There is no emission in the lower box.

6.3 Mass Models

There are three possible avenues for modelling this lens, depending on the nature of the third radio source. It may be emission from the foreground lensing galaxy, providing an accurate position for the foreground galaxy, and an upper limit on the flux density of a central image. We can repeat a similar analysis to Chapter 4, constraining the deviation of the mass profile from an isothermal profile. If we confirm
the third source as a central image, then we can constrain mass models much better. A valid mass model must produce a central image with the observed flux density rather than simply satisfying an upper limit. If follow-up observations do not confirm the source and it turns out to be an imaging artifact, we have an upper limit on the central image flux density, but very little information on the position of the foreground lens galaxy. We discuss each possibility below.

We briefly consider the effect of a super-massive black hole for the first two models. Taking the third image to be a detection of a lens galaxy, the black hole slightly weakens the constraints on the deviation from isothermal, as was seen for the other 3 targets in Chapter 5. Taking the third image to be the central (core) image, the black hole must produce a central image pair, and we predict the flux density ratio of the core and SMBH images.

Figure 6-9: Radio map of B2319 image C. The wedge at right shows the grey scale in \( \mu \text{Jy beam}^{-1} \). Coordinate offsets are from the position of the third source, 0\'059 east and 0\'946 south of image A. All contours are at 75 \( \mu \text{Jy beam}^{-1} \) (the blank field rms near image C was 24 \( \mu \text{Jy beam}^{-1} \)). The synthesized beam of 4.2 \( \times \) 1.6 mas (position angle 32\'7) is shown at the lower left.
Figure 6-10: The irregular beam of the HSA observations for the imaging of the three sources, as shown in Figures 6-2, 6-3 and 6-9. The wedge at right shows the grey scale as a fraction of the peak beam strength. Note that the beam shape matches the substructure seen in the third image.

This system has been observed with Keck and the Hubble Space Telescope NICMOS, but the quasar images were not detected in any of these optical or near-infrared observations. The lens galaxy absolute position was determined by Rusin et al. (2001b) from reference stars in wide field Keck images, with a 0′.45 uncertainty in each co-ordinate. If we assume the third radio source is the lens galaxy, then we have a good position for this object from the HSA data. In the other two cases the lens galaxy position is not measured from the data, although it must be close to the central image in the case that we take the third radio source to be this image.

6.3.1 A Lens Galaxy Detection

If the third source is confirmed but has a different spectral index and/or surface brightness to the bright images, we would likely conclude that the radio source resides in the foreground lens galaxy. At a redshift of 0.624, the 96 μ Jy flux density corresponds to a 5 GHz luminosity of \( L = 1.6 \times 10^{23} \) W Hz\(^{-1}\). The radio flux is almost certainly due to nuclear activity in the foreground galaxy, \(^2\) and will be spread

\(^2\)The 1.5 GHz luminosity of a non-active galaxy rarely exceeds \(5 \times 10^{22}\), e.g. Figure 3 of Condon (1992). For a non-inverted spectrum the 5 GHz luminosity is even less, and an AGN is needed to generate a 5 GHz luminosity of \(1.6 \times 10^{23}\) W Hz\(^{-1}\).
Figure 6-11: Histogram of surface brightness values for off-source pixels within the B2319 map of image C. The pixel size is 0.4 mas, which is smaller than the beam size of 4.2 \times 1.6 mas. The distribution of surface brightness is somewhat irregular, with a mean of 2 \mu Jy beam^{-1} and a standard deviation of 24 \mu Jy beam^{-1}.

out around the lens galaxy center. This emission is fairly diffuse, but still fixes the lens galaxy position to an accuracy of \sim 30 mas, which allows us to repeat the mass modelling of Chapter 4.

We again consider the broken power-law model of Muñoz et al. (2001)

\[ \rho(r) = \frac{\rho_0}{r^n (1 + r^2/r_b^2)^{(n-\gamma)/2}}. \]  

(6.1)

fixing the outer index to the isothermal value of \( n = 2 \) and varying the break radius \( r_b \) and the inner index \( \gamma \) to explore the allowed deviation from isothermality. We use two point sources to generate the two sub-images in bright images A and B. Our models have 13 free parameters: the positions of the lens galaxy and the two sources \((x_G, y_G, x_{S1}, y_{S1}, x_{S2}, y_{S2})\), the source flux densities \((S_{S1}, S_{S2})\), the mass parameter \((b = (2\pi r_b \rho_0)/(\Sigma_{cr}))\), the shear and its position angle \((\sigma, \theta_s)\), the break radius \((r_b)\) and the inner power law index \((\gamma)\).

The data provide 15 observables when we take the third source to be the lens galaxy: two sky coordinates for each of the lens galaxy, bright sub-images A1, A2, B1 and B2; flux densities for bright sub-images A1, A2, B1 and B2 \((S_{A1}, S_{A2}, S_{B1}, S_{B1})\); and an upper limit on the flux density of the central image C \((S_C)\). The galaxy co-ordinates were taken to be those of the third radio source and we assumed a large
Table 6.2: Constraints on the lens models for B2319, assuming that the third radio source is a faint AGN in the lens galaxy, giving the lens galaxy position and an upper limit on the central image flux density. Sub-images C1 and C2 are too close to be resolved by the HSA, so the combined central image is treated as a single radio source with a flux density limit. All positions are offsets from sub-image A1.

<table>
<thead>
<tr>
<th>Observable</th>
<th>B2319</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.A.A1</td>
<td>0'000 ± 0'003</td>
</tr>
<tr>
<td>decl.A1</td>
<td>0'000 ± 0'003</td>
</tr>
<tr>
<td>R.A.A2</td>
<td>-0'0203 ± 0'003</td>
</tr>
<tr>
<td>decl.A2</td>
<td>-0'037 ± 0'003</td>
</tr>
<tr>
<td>R.A.B1</td>
<td>0'0113 ± 0'003</td>
</tr>
<tr>
<td>decl.B1</td>
<td>-1'3640 ± 0'003</td>
</tr>
<tr>
<td>R.A.B2</td>
<td>0'0188 ± 0'003</td>
</tr>
<tr>
<td>decl.B2</td>
<td>-1'3641 ± 0'003</td>
</tr>
<tr>
<td>S_A1</td>
<td>29.8 mJy</td>
</tr>
<tr>
<td>S_A2</td>
<td>8.1 mJy</td>
</tr>
<tr>
<td>S_B1</td>
<td>5.7 mJy</td>
</tr>
<tr>
<td>S_B2</td>
<td>1.6 mJy</td>
</tr>
<tr>
<td>S_C</td>
<td>0.000 ± 0.024 mJy</td>
</tr>
<tr>
<td>R.A.G</td>
<td>0'060 ± 0'030</td>
</tr>
<tr>
<td>decl.G</td>
<td>-0'946 ± 0'030</td>
</tr>
</tbody>
</table>

uncertainty of 30 mas. We measured the positions and flux densities of the bright sub-images from the HSA maps, again adopting errors of 3 mas in the positions and 20% in the flux densities to account for substructure. Since image C is at least 400 times fainter than image A, the separation of its subimages will be < 1 mas, < 1/√400 = 1/20 the separation of subimages A1 and A2. Image C would thus appear as a single unresolved source, and we obtain an upper limit on its flux density from the distribution of surface brightness in the blank region near the third radio source 6-11, where the mean is near zero. We took this to be a null detection of the central image with 1 σ error set by the rms noise of 24 μJy, and set $S_C = 0 \mu Jy$ for the modelling. These constraints are summarized in Table 6.2. All of the observables were assumed to obey Gaussian statistics, and 1 σ error bars are quoted.

Again we model B2319+051 with Keeton (2001)’s gravlens package. Our model has 13 free parameters and 15 observables (one of which is an upper limit), for 2 degrees of freedom. We convert to physical units using the lens redshift $z_L = 0.624$ and a ΛCDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.3, \Omega_A = 0.7$. As with the three lenses analyzed in Chapter 4, we find an allowed and disallowed region when we project the models into the $r_b, \gamma$ parameter space that describes the central mass profile (see Figure 6-12). The isothermal model ($r_b = 0$ or $\gamma = 2$) is included in the allowed region, and values of the other parameters for this model are given in Table 6.3.

The model fits the data well ($\chi^2 = 1.22$ for 2 degrees of freedom) for a sufficiently
Table 6.3: The best fit values of the lens model parameters in the isothermal case (when \( r_b = 0 \) or \( \gamma = 2 \)) for B2319, assuming the third radio source is a faint AGN in the lens galaxy. This model has \( \chi^2 = 1.22 \), the minimum value achieved.

<table>
<thead>
<tr>
<th>Target</th>
<th>( \theta_E )</th>
<th>( \sigma ) (km s(^{-1}))</th>
<th>( M_{bh} ) (10(^8 M_\odot))</th>
<th>( M_{bh} ) range (10(^8 M_\odot))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLASS B2319+051</td>
<td>( 0'711 )</td>
<td>230</td>
<td>2.4</td>
<td>1.2 – 5</td>
</tr>
</tbody>
</table>

Table 6.4: The Einstein radius and velocity dispersion for the singular isothermal sphere model, and inferred black hole masses, for B2319. The source redshift is unknown, we assume \( z_s = 1.5 \).

small break radius \( r_b \) or sufficiently steep inner index \( \gamma \). As \( r_b \) increases or \( \gamma \) decreases, the fits become progressively worse and \( \chi^2 \) becomes large. Most of the disagreement is due to an unacceptably large \( S_C \). The 95% confidence region, defined by \( \Delta \chi^2 < 5.99 \), lies below and to the right of the solid line. Taking the third radio source to be the lens galaxy and assuming the central image is absent at the rms noise levels of our maps implies that matter distribution is nearly isothermal: a flat core with \( \gamma = 0 \) must be very small (\( r_b \lesssim 30 \text{mas} \)), and a large core with \( r_b = 100 \text{mas} \) has a steep inner profile (\( \gamma \gtrsim 1.4 \)).

We also consider the effect of a super-massive black hole in this case. As in Chapter 5, we use the velocity dispersion of the isothermal sphere model and the \( M_{BH} - \sigma \) relation to estimate a plausible range of black hole masses, presented in Table 6.4. We reran the lensing model calculations, with a fixed point mass at the center of the lensing galaxy. We considered a mass of \( 2.5 \times 10^8 M_\odot \), in the center of the allowed range, and \( 5 \times 10^8 M_\odot \), at the top of the allowed range.

The SMBH allows the galaxy profile to be shallower, to some extent. For fairly flat cores (\( \gamma \lesssim 1.2 \)) the maximum break radius increases by 5-70\%, and for larger, cuspy cores, the minimum inner slope is reduced by 0.2 – 0.4, depending on the black hole mass. The effect is larger for this lens than for B0739 and B0445, which may be due to this lens being the most massive (see Tables 5.1 and 6.4), meaning that it has
Figure 6-12: Models for the lens galaxy of B2319, assuming the third radio source is a low-luminosity AGN in the lens galaxy. The matter profile is isothermal ($\rho \propto r^{-2}$) at large radius, and varies as $\rho \propto r^{-\gamma}$ at small radius, with the break at radius $r_b$. To the smooth matter profile we add no black hole (solid line), a $2.5 \times 10^8 M_\odot$ black hole (long-dashed line), or a $5 \times 10^8 M_\odot$ black hole (short-dashed line). These black hole masses are the central and largest values expected, given the velocity dispersion of the galaxy. The inner power law index and break radius are allowed to vary. The lines mark the $\Delta \chi^2 = 5.99$ boundary between the allowed region (below and to the right) and the disallowed region (above and to the left). The break radius in parsecs and the black hole Einstein radius are calculated for the measured lens redshift $z_L = 0.624$ and an assumed source redshift $z_s = 1.5$. When no black hole is present, a central image always forms within the parameter ranges plotted. In the allowed region, the central image is below our detection limit. When a black hole is present, the central image is either eliminated or split into a core image and SMBH images. In the allowed region, either there are no central images or both central images have flux densities below our detection limit.

6.3.2 Detection of the Central Image

We now consider the case that the third radio source is the central image and investigate the constraints on the broken power law model. The description of the model and the 13 free parameters remain the same as those considered in the previous section. In this instance we again have 15 observables. The bright sub-image positions and flux densities are measured from the HSA maps as in the previous section, with the same assumed errors. Two sky co-ordinates and a flux density are also measured from the HSA maps for image C. We take the two sub-images C1 and C2 to be blended into a single combined source, and place this at the peak found in the HSA map after

the largest super-massive black hole.
Table 6.5: Constraints on the lens models for B2319, assuming that the third radio source is the central image, giving the position and flux density of this image. The first twelve constraints are identical to the lens galaxy case (Table 6.2). Sub-images C1 and C2 are too close to be resolved by the HSA, so the combined central image is treated as a single radio source with the measured flux density. All positions are offsets from sub-image A1.

<table>
<thead>
<tr>
<th>Observable</th>
<th>B2319</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.A. - A1</td>
<td>0°000 ± 0°003</td>
</tr>
<tr>
<td>decl. A1</td>
<td>0°000 ± 0°003</td>
</tr>
<tr>
<td>R.A. - A2</td>
<td>-0°0203 ± 0°003</td>
</tr>
<tr>
<td>decl. A2</td>
<td>-0°0037 ± 0°003</td>
</tr>
<tr>
<td>R.A. - B1</td>
<td>0°0113 ± 0°003</td>
</tr>
<tr>
<td>decl. B1</td>
<td>-1°3640 ± 0°003</td>
</tr>
<tr>
<td>R.A. - B2</td>
<td>0°0188 ± 0°003</td>
</tr>
<tr>
<td>decl. B2</td>
<td>-1°3641 ± 0°003</td>
</tr>
<tr>
<td>S_A1</td>
<td>29.8 mJy</td>
</tr>
<tr>
<td>S_A2</td>
<td>8.1 mJy</td>
</tr>
<tr>
<td>S_B1</td>
<td>5.7 mJy</td>
</tr>
<tr>
<td>S_B2</td>
<td>1.6 mJy</td>
</tr>
<tr>
<td>R.A. - C</td>
<td>0°0604 ± 0°003</td>
</tr>
<tr>
<td>decl. C</td>
<td>-0°9459 ± 0°003</td>
</tr>
<tr>
<td>S_C</td>
<td>0.096 ± 0.024 mJy</td>
</tr>
</tbody>
</table>

self-calibration. The position error is again assumed to be 3 mas due to substructure. For the flux density the measurement error from the HSA map is 25%, and we take this to be the error on our combined image C flux density. As we now assume that the third radio source is not the lens galaxy, we no longer have a measurement of the lens galaxy position. These constraints are presented in Table 6.5, with 1 σ error bars (the observables are assumed to obey Gaussian statistics).

Now that all the observables have definite values, we find a band of allowed values in the $r_b, \gamma$ parameter space, shown in Figure 6-13. The allowed models have a central slope shallower than isothermal, and a corresponding break radius that gives the appropriate image C flux density. The isothermal model is no longer allowed, so we show the values of the other parameter values for the best fit model with inner index $\gamma = 0.5$ (Table 6.6). These other parameters vary by $< 20\%$ over the allowed region, and by $< 10\%$ over most of it. They are quite similar to the best fit isothermal values in the previous section, except that the lens galaxy and the source are displaced somewhat to the north. The central image lies south of the lens galaxy, and now this image rather than the lens galaxy itself must coincide with the third radio source.

The model fits the data well ($\chi^2 = 1.37$ for 2 degrees of freedom) within the allowed band, and as we move orthogonal to the band the fits become progressively worse and $\chi^2$ becomes large. Most of the disagreement is due to an insufficient $S_C$ in the lower right (a smaller break radius or steeper inner power law), and an excessive
Table 6.6: The best fit values of the lens model parameters for a fairly shallow core ($\gamma = 0.5$) in the B2319 lens galaxy, and taking the third radio source to be a central image. This model has $\chi^2 = 1.37$, the minimum value achieved.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$</td>
<td>0.782</td>
</tr>
<tr>
<td>$x_G$</td>
<td>0.063</td>
</tr>
<tr>
<td>$y_G$</td>
<td>-0.918</td>
</tr>
<tr>
<td>$x_{S1}$</td>
<td>0.082</td>
</tr>
<tr>
<td>$y_{S1}$</td>
<td>-0.686</td>
</tr>
<tr>
<td>$x_{S2}$</td>
<td>0.080</td>
</tr>
<tr>
<td>$y_{S2}$</td>
<td>-0.686</td>
</tr>
<tr>
<td>$S_{S1}$</td>
<td>3.63 mJy</td>
</tr>
<tr>
<td>$S_{S2}$</td>
<td>0.99 mJy</td>
</tr>
<tr>
<td>$s$</td>
<td>0.0753</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>-11.4</td>
</tr>
<tr>
<td>$r_b$</td>
<td>0.049</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

$S_C$ in the upper left. The 68% (95%) confidence region, defined by $\Delta \chi^2 < 2.30(5.99)$, lies within the solid (dashed) lines. A flat core ($\gamma = 0$) now has a definite break radius of 29 mas $<$ $r_b$ $<$ 48 mas, and a large core with break radius 200 mas $=$ 1350 pc has an inner index somewhat shallower than isothermal, $1.365 < \gamma < 1.522$ (both 68% confidence ranges).

As we would expect, the preferred band when we take the third source to be a central image (Figure 6-13 lies close to the boundary of the allowed region when we assume a central image non-detection (Figure 6-12). The region that gives a definite $S_C$ close to our detection limit lies close to the boundary of the region that results $S_C$ being fainter than that limit.

We also consider a super-massive black hole with the central mass assumed in Section 6.3.1, $2.5 \times 10^8 M_\odot$. We add a black hole with this fixed mass to the smooth galaxy models and determine the constraints on the parameters of the broken power law model. We again obtain a band of allowed models, shown in Figure 6-14 but these now produce a central image pair: the core image C and the super-massive black hole image D. Image D is fainter than image C by a factor of a few tens or hundreds for a smaller shallow core (inner index $\gamma < 1$), and by a factor of a few for steep central cusps (inner index $\gamma \sim 1.4$), for which the central images come close to merging. When the inner slope is a little steeper ($\gamma \gtrsim 1.5$), images C and D merge and are eliminated. Thus the requirement of a central image pair places a slight additional restriction: an SMBH lowers the maximum index of a steep central cusp by $\sim 0.1$.

We note that most of the allowed parameter space produces an SMBH image which is 10-100 times fainter than the core image. This SMBH image would likely have a flux density of $1 - 10 \mu$Jy, which could be detected with ultra-sensitive VLBI observations reaching rms noise of $\sim 2 \mu$Jy.
6.3.3 A Spurious or Unrelated Third Radio Source

A third possibility is that the third radio source is spurious, an artifact of the image processing, or comes from neither the lens galaxy nor the source quasar but from an unrelated object. We examine the the broken-power law model and its 13 free parameters, but find that the constraints on this model are very weak.

In this case there are 13 observables: two positions and one flux density for each of the bright sub-images A1, A2, B1 and B2; and an upper limit on the flux density of image C. These are the first thirteen constraints for the case where the third radio source is taken to be the lens galaxy (Table 6.2). The lens galaxy position from the absolute registration of the optical and VLBI images is uncertain by 0.45: it allows the lens galaxy to be almost anywhere between the bright images A and B, so we lose any significant constraints on the lens galaxy position.

In this case, the models can fit the data well for almost any values of the break radius $r_b$ and inner index $\gamma$. Even a model with a flat core $\gamma = 0$ and break radius $r_b = 0'4 = 2700$ pc has $\Delta \chi^2 = 0.2$ relative to the overall minimum of the isothermal model. The shallowest central profile plotted for the previous two cases is easily allowed. This is possible because the lens galaxy and the unlensed source position can both be located near the midpoint of the bright lensed images. This produces two bright images at a flux ratio of 5:1 and a very faint central image, even for a shallow profile. Such configurations are not possible if the lens galaxy is known to be located off-center. While the cross-section for these lens models is small (since the
Figure 6-14: Models for the lens galaxy of B2319, assuming the third radio source is a central image. The matter profile is isothermal ($\rho \propto r^{-2}$) at large radius, and goes as $\rho \propto r^{-\gamma}$ at small radius, with the break at radius $r_b$. A black hole of fixed mass $2.5 \times 10^8 M_\odot$ is added to the center of the lens galaxy. The inner power law index and break radius are allowed to vary. Within a band of allowed models a central image pair forms, with the core image flux density matching the measured flux density of the third radio source. The solid line encloses the allowed region at 95% confidence ($\Delta \chi^2 = 5.99$). The dashed lines show contours of the core image C to SMBH image D flux density ratio: from left to right the contours are $S_C/S_D = 100, 30, 10, 3$. For models near the lower right boundary images C and D come closer to merging. The two central images have similar flux densities and form at a separation $< 5$ mas, where they would appear as a single unresolved source. Along this boundary we treat the central image pair as a single image which must match the observed flux density of the third radio source.

lens galaxy and the source are very closely aligned), they cannot be excluded without some information on the lens galaxy position. Without a good position for the lens galaxy relative to the lens images, we have little power to constrain the central density profile.

Conversely, we investigate whether the bright image constraints constrain the lens galaxy position, taking the matter profile to be isothermal. In this case, the preferred lens galaxy position is $-0'16$ in right ascension and $-0'91$ in declination (relative to the bright sub-image A1). This is $0'22$ from the third radio source at $+0'06$ in right ascension and $-0'95$ in declination. However the constraints on the lens galaxy position are quite weak, and at the location of the third radio source $\Delta \chi^2 = 1.1$. The allowed region extends over much of the region between the bright images A and B.

---

3In the case that the third radio source is considered to be the central image, the lens galaxy position is not measured, but the lens galaxy is forced to be close to the central image. This moves the lens galaxy away from the midpoint of the bright images towards image B.
Figure 6-15: Constraints on the lens galaxy position of B2319, assuming an isothermal profile. The overlapping solid circles show the locations of the bright sub-images. The cross shows the position of the third radio source, the plus sign shows the lens galaxy position giving the best fit to the bright images ($\chi^2 = 0.05$). The line encloses the allowed region: outside this line the bright image constraints are not satisfied ($\Delta \chi^2 > 5.99$) or the external shear is unreasonably large ($> 0.2$). The best fit lens galaxy position is towards the edge of the allowed region, but there is a broad minimum: e.g. $\chi^2 = 1.19$ at the location of the third radio source.

(see Figure 6-15). Some positions can satisfy the bright image constraints, but only with a large external shear. Observations of galaxy groups near this lens suggest that they contribute a shear of $\lesssim 0.05$ (Auger et al. 2006), while a nearby galaxy can account for a shear up to $\sim 0.1$ (Rusin et al. 2001b), so we conservatively exclude regions where the required shear exceeds 0.2. The allowed region is defined partly by a 95% limit from the bright image constraints ($\Delta \chi^2 < 5.99$), and partly by the restriction on the shear.
Chapter 7

Conclusions

7.1 Combination of Galaxy Models

We find broadly similar results for the three lenses in which we have an upper limit on the central image flux density. The profiles are close to isothermal. The constraints are much stronger for J1838, the most asymmetric of the three lenses. The bright image flux density ratio $S_A/S_B$ is 13 for J1838, versus 6 for B0739 and B0445, and so the unlensed source position lies further from the lens galaxy center (further to the right in Figure 2-1). In order for the central image to remain undetectable, the matter profile must be much steeper in J1838 than in the other two systems.

For B2319+051, treating the third radio source as the foreground lens galaxy gives a similar allowed region to B0739 and B0445: models that are constrained to be fairly steep, but can be be further from isothermal than for the highly asymmetric lens J1838. Treating this third radio source as a central image selects a band of allowed models, similar to the boundary of the previously allowed region (Figure 6-13). A central image of definite flux density selects a band giving that value for $S_C$, while an upper limit on the central image flux density selects a half plane bounded by the band for the maximum allowed $S_C$.

7.2 Comparison with Other Central-Image Modelling

Keeton (2003) predicted the mean (de)magnification of the central core image, assuming that lens galaxies at $z \sim 0.5$ were early-type galaxies with the same profiles as a sample of 73 early-type galaxies at $z < 0.03$ for which photometric observations were available. In Figure 7-1 we reproduce the histogram of predicted mean central image magnifications, with a broad peak near $10^{-2.5}$. For comparison, we list the 99% upper limits on the core image magnification for the four galaxies in this thesis in Table 7.1 and mark these limits on Figure 7-1. We assume that the third radio source in B2319 is the lens galaxy and set an upper limit on the on the core image flux density for this system. We use the unlensed source flux density for the isothermal
Figure 7-1: Histogram of predicted mean central image magnifications when 73 nearby early-type galaxies with well-measured photometric profiles are placed at $z = 0.5$ and act as gravitational lenses, from Keeton (2003), reproduced by permission of the AAS. Galaxies with no core image are plotted at magnification $10^{-6}$. The histogram was calculated assuming no super-massive black hole was present. The solid vertical lines mark, from left to right, the 99% limits on the core image magnification for J1838, B0739, B2319 (taking the third radio source to be the lens galaxy) and B0445. The dashed vertical line marks the central image magnification for B2319, taking the third radio source to be the core image. These values are listed in Table 7.1.

Our sample is consistent with nearby early-type galaxies: three lenses have core image magnification upper limits which allow a large fraction of the predicted magnification distribution, and one lens has a tentative detection with a magnification which is at the high end of the distribution, but is not extreme. Future instruments could improve the core image magnification limits by a factor of 10-100 and sample the bulk of the distribution. If $z \sim 0.5$ early-type galaxies are indeed similar to their counterparts at $z < 0.03$, many core images should be detected. Conversely, if few core images are detected this would indicate that early-type galaxies have different profiles at $z \sim 0.5$ than they do at $z < 0.03$. Either result would have significant implications for galaxy evolution.

We now consider the constraints on matter profiles in observed lens galaxies.
Table 7.1: The core image magnification upper limits for the four lenses in our sample. For B2319 we set an upper limit on the magnification assuming that the third radio source is the lens galaxy (above the line) and measure a definite magnification assuming that this source is the core image (below the line). No black hole was considered, and the unlensed source flux density was taken for the isothermal model in the case of the upper limits, and for the best fitting shallow core model in the case of the B2319+051 measurement. We use $z_L = 0.558, 0.624$ for B0445 and B2319, respectively (the measured lens redshifts); $z_L = 0.36$ for J1838 (based on the lens galaxy photometric properties); and $z_L = 0.5$ for B0739 (a typical lens redshift).

<table>
<thead>
<tr>
<th>System</th>
<th>$S_S$</th>
<th>$S_C$</th>
<th>log$_{10}$ (Image C Magnification)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1838</td>
<td>80.3 mJy</td>
<td>&lt; 0.083 mJy</td>
<td>&lt; -2.99</td>
</tr>
<tr>
<td>B0739</td>
<td>6.54 mJy</td>
<td>&lt; 0.038 mJy</td>
<td>&lt; -2.24</td>
</tr>
<tr>
<td>B0445</td>
<td>3.54 mJy</td>
<td>&lt; 0.043 mJy</td>
<td>&lt; -1.92</td>
</tr>
<tr>
<td>B2319</td>
<td>6.45 mJy</td>
<td>&lt; 0.057 mJy</td>
<td>&lt; -2.05</td>
</tr>
<tr>
<td>B2319 (c)</td>
<td>4.64 mJy</td>
<td>0.096 mJy</td>
<td>-1.69</td>
</tr>
</tbody>
</table>

Other than PMN J1632–0033, previous studies have used one-parameter models, either setting a shallow inner slope for a core, or considering a single power law.

Winn et al. (2003) modelled PMN J1632–0033, the lens with a confirmed central image, using the same cuspy profile as this work. Given that the central image is detected with a definite flux, the allowed region in the break radius and inner index space becomes a narrow band (see Figure 6 of Winn et al. (2003)). A flat core has a fixed small size, and a larger core is forced to a particular value of the inner index. The allowed band for J1632 is similar to the allowed band for B2319, although lies at much steeper values.

Wallington & Narayan (1993); Evans & Hunter (2002) considered cored power law models for a typical lens galaxy, based on known radio-loud lenses. They determined the maximum radius of a constant density core which would demagnify the central image below the typical limit on the central image flux density. Their results were that the core radius should be less than 200–300 pc for the typical lens galaxy. MG1131+0456 was modelled with a cored power law model, and the best fit core radius was $\sim 0''2$ over a broad range of power law exponents (Figure 5 of Chen et al. (1995)). The redshift of the lens galaxy is not known, but for $0.3 < z < 1$ this corresponds to 900–1600 kpc.

When the inner index takes the value $\gamma = 0$, our broken power law model has a constant density core. While the forms of the lens galaxy profiles differ between the previous analyses and our work, all define a characteristic length scale scale at which the profile switches from a steep outer index to a flat inner index, and we can make rough comparisons of the constraints on these break or core radii. For our $\gamma = 0$ models, the limits on the break radii in our four galaxies are given in Table 7.2.
Table 7.2: The maximum break radii $r_b$ of broken power law density profiles with a flat inner core ($\gamma = 0$) at 95% confidence. The second and third columns give the constraints for just a power law profile, the fourth and fifth columns give the constraints when we add an SMBH with a mass predicted by the $M_{\text{BH}} - \sigma$ relation for the isothermal case. For B2319 we obtain a maximum break radius assuming that the third radio source is the lens galaxy (above the line), and a range of allowed break radii assuming that the third radio source is a central image (below the line). No SMBH is considered for B2319. All limits are at 95% confidence. We use $Z_L = 0.558, 0.624$ for B0445 and B2319, respectively (the measured lens redshifts); $Z_L = 0.36$ for J1838 (based on the lens galaxy photometric properties); and $Z_L = 0.5$ for B0739 (a typical lens redshift).

Note that many of the physical radii are uncertain by about 50% due to the lack of measured redshifts.

Compared to Wallington & Narayan (1993); Evans & Hunter (2002)'s general limits, the maximum allowed core sizes are considerably smaller for J1838 and B0739, and slightly smaller for B0445 and B2351 (when its third radio source is taken to be the lens galaxy). Adding a super-massive black hole at the level implied by the isothermal velocity dispersion and the $M - \sigma$ relation has only a small effect. J1838 has a large bright image magnification ratio and its constraints are better than the typical case, while the B0739 lens galaxy is less massive overall, so all the characteristic angular scales are small and the core size is more constrained. When B2351 is assumed to have a central image, modelling with a flat core gives a core size similar to the previous upper limits.

As noted in Section 1.1, hydrodynamical simulations of galaxy formation only reach scales of 300-1000 pc. Central images now probe galaxy cores on scales smaller than this, by up to an order of magnitude, and greater spatial resolution in the galaxy formation models is clearly desirable.

Other central image modelling has focused on single power law models. Winn et al. (2003) considered a single power law model $\rho \propto r^{-\gamma}$ for the density profile of J1632, finding $\gamma = 1.91 \pm 0.02$. This modelling did not include a central black hole. Rusin & Ma (2001) modelled the gravitational lenses CLASS B0739+366 and B1030+074 using a single power law model for the projected surface density $\Sigma(R) \propto R^{-\beta}$, both with and without a central black hole with a mass inferred from the $M - \sigma$ relation. Their only constraint was the limit on the bright image to central image magnification ratio, the
Table 7.3: The minimum power law indices $\gamma$ of pure power law density profiles $\rho \propto r^{-\gamma}$, at 95% confidence. The left column gives constraints for just the power law profile, the right column gives the minimum index when we add an SMBH with a mass predicted by the $M_{\text{BH}} - \sigma$ relation for the isothermal case. For B2319 we obtain a minimum inner index assuming that the third radio source is the lens galaxy (above the line), and a range of allowed break radii assuming that the third radio source is a central image (below the line). No SMBH is considered for B2319. We use $z_L = 0.558, 0.624$ for B0445 and B2319, respectively (the measured lens redshifts); $z_L = 0.36$ for J1838 (based on the lens galaxy photometric properties); and $z_L = 0.5$ for B0739 (a typical lens redshift).

<table>
<thead>
<tr>
<th>System</th>
<th>No SMBH</th>
<th>With SMBH</th>
<th>BH Mass $(10^8 M_\odot)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1838</td>
<td>&gt; 1.93</td>
<td>&gt; 1.86</td>
<td>0.5</td>
</tr>
<tr>
<td>B0739</td>
<td>&gt; 1.84</td>
<td>&gt; 1.79</td>
<td>0.23</td>
</tr>
<tr>
<td>B0445</td>
<td>&gt; 1.67</td>
<td>&gt; 1.59</td>
<td>2</td>
</tr>
<tr>
<td>B2319</td>
<td>&gt; 1.59</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B2319 (c)</td>
<td>1.50–1.67</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

observable which dominates $\chi^2$ in our modelling. Their limits on the smooth profile were $\beta > 0.85$ for B0739+366 and $\beta > 0.91$ for B1030+074, while the respective limits were $\beta > 0.84$ and $\beta > 0.83$ when a black hole was included.

We also model the three lenses J1838, B0739 and B0445 as single power laws, with and without a central black hole. Table 7.3 gives these limits. $\Sigma(R) \propto R^{-\beta}$ is equivalent to $\rho \propto r^{-\gamma}$ with $\gamma = \beta + 1$, so our limits for B0739 are slightly weaker than those of Rusin & Ma (2001) despite our improved limit on the bright image to central image magnification ratio. We attribute this to their slightly lower black hole mass and the difference in modelling approach. Allowing other observables besides the magnification ratio to vary gives more flexibility to fit marginally viable models.

Again, we note that a surface density index $\beta$ is equivalent to a density index $\gamma = \beta + 1$, so these 4 lenses are similar. The profile is slightly shallower than isothermal for J1632-0033 and B2319 (in the central image detection case), and the profiles are slightly shallower than or steeper than isothermal for B1030+074, J1838, B0739, B0445 and B2319 (in the lens galaxy detection case).

### 7.3 Implications for SMBH Images

As outlined in Section 1.3, the detectability of the image produced by a super-massive black hole (the SMBH image) depends crucially on the lens galaxy properties, in particular the steepness of the central slope. While we find that the galaxy profiles

---

1Rusin & Ma (2001) found a different value for the black hole mass by using a different choice of Hubble constant and an earlier version of the $M - \sigma$ relation.
<table>
<thead>
<tr>
<th>System</th>
<th>$\theta_E$ (kms$^{-1}$)</th>
<th>$\sigma$ (mas)</th>
<th>$\theta_b$ (mas)</th>
<th>$\theta_b/\theta_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1838</td>
<td>528</td>
<td>154</td>
<td>$&lt; 1.3$</td>
<td>$&lt; 0.002$</td>
</tr>
<tr>
<td>B0739</td>
<td>268</td>
<td>129</td>
<td>$&lt; 3.5$</td>
<td>$&lt; 0.013$</td>
</tr>
<tr>
<td>B0445</td>
<td>711</td>
<td>217</td>
<td>$&lt; 26.7$</td>
<td>$&lt; 0.038$</td>
</tr>
<tr>
<td>B2319</td>
<td>782</td>
<td>230</td>
<td>$&lt; 27.1$</td>
<td>$&lt; 0.035$</td>
</tr>
<tr>
<td>B2319 (c)</td>
<td>782</td>
<td>230</td>
<td>22.2–55.2</td>
<td>0.028–0.071</td>
</tr>
</tbody>
</table>

Table 7.4: The Einstein radii and velocity dispersions (in the isothermal model) and break radii limits (in the $\gamma = 0$ flat core models) for our four lenses. For B2319 we obtain a maximum break radius assuming that the third radio source is the lens galaxy (above the line), and a range of allowed break radii assuming that the third radio source is a central image (below the line). The mass parameter for the flat core cases, which is analogous to the Einstein radius, varies by a few percent between the isothermal and the allowed $\gamma = 0$ models.

are steep, the limits are not so steep as to greatly depress the prospects for detecting SMBH images.

Rusin et al. (2005) consider a single power law model for the density profile, $\rho \propto r^{-\gamma}$. Provided $\gamma < 1.8$, at least 10% of $10^8 M_\odot$ black holes produce a detectable SMBH image (where detectable is defined as the SMBH image having at least 0.01 times the flux density of the core image). Two of our four systems allow $\gamma < 1.8$ (Table 7.3), a sufficiently shallow profile that a central image pair may form, with the SMBH image $> 0.01$ times as bright as the core image. Even B0739 can have $\gamma = 1.85$, where the probability of a detectable SMBH image is $\sim 8\%$. If B2319 is assumed to have a central (core) image detected, then a simple power law profile has $\gamma \sim 1.6$, very favorable for SMBH image detection.

Considering cored isothermal sphere models for the lens galaxy profile, Bowman et al. (2004) calculated lensing cross-sections for formation of the SMBH image based on the ratio of the core radius to the overall Einstein radius, $\theta_c/\theta_E$. This is similar to the ratio of break radius to isothermal case Einstein radii, $\theta_b/\theta_E$ in our models when we set the inner index to be flat ($\gamma = 0$). The maximum allowed values for this ratio are shown in Table 7.4. For J1838 the ratio is less than 0.002, a value for which many black hole masses will lead to a negligible cross-section for formation of the SMBH image (e.g. Figure 6 of Bowman et al. (2004)). This potential is so steep that it is likely the SMBH has eliminated the central image pair. For the other three lenses the ratio of break radius to Einstein radius can still be of order $10^{-2}$. For these ratios the cross sections for SMBH images are still high, and central image pairs may well be present in these systems. Note that if the third source in B2319 is a central image then there is likely to be a SMBH image 10-100 times fainter than the core image (see Section 6.3.2 and Figure 6-14).

The Expanded Very Large Array (EVLA) is scheduled for completion in 2012, and its observations of gravitational lenses should provide a wealth of information
on galaxy cores. Bowman et al. (2004) predicted the types of gravitational lenses in a putative EVLA lensing survey with limiting sensitivity 1 μJy, for different cored isothermal sphere models of lens galaxies. Referring to their Figure 10 and Tables 6 and 7, we note a striking difference in the lenses observed for different values of the core radius to Einstein radius ratio $\theta_c/\theta_E$. For large cores, $\theta_c/\theta_E = 0.05$, the survey would detect 410 lenses, of which 320 would have a detected central core image and 12 would have both a core and an SMBH image. For small cores, $\theta_c/\theta_E = 10^{-4}$, the same survey would detect 790 lenses, of which none would have a core image and 180 would have an isolated SMBH image: a configuration in which one bright image forms away from the lens galaxy, one faint image forms near the SMBH and no other images form. The types of gravitational lenses found in future (but imminent) lens surveys, should measure typical core sizes in external galaxies very well.

Detection of an SMBH image, either as part of a central image pair or as an isolated SMBH image, would be an exciting result. A central image pair allows a measurement of the black hole mass, with the lens galaxy profile introducing an uncertainty of 0.5-1.0 dex (Rusin et al. 2005). The properties of an isolated SMBH image are determined almost entirely by the super-massive black hole (Bowman et al. 2004), allowing an accurate measurement of its mass. A set of such black hole mass measurements at $z \sim 0.5$ would test for evolution in the $M - \sigma$ relation, independent of assumptions about the structure of the AGN emission regions.

### 7.4 Future Work

B2319 requires follow-up observations, to confirm the existing tentative detection, and to determine whether the source is a central image. We have applied for 10 hour observations with the phased VLA, the Green Bank telescope and the VLBA, at each of 1.4 GHZ and 5 GHz. With the longer observations and a more uniform array we will have better uv plane coverage, and the beam will be better shaped. These data will be measure the spectral index and the surface brightness of the third source, determining whether it is a central image or emission from the lens galaxy.

As described in Section 2.3, two targets from ELVIS have still to be reduced and analysed, and one target may be reobserved to replace an observation for which the wrong co-ordinates were used in the correlation. Additional targets may be added to the survey, either existing systems with more symmetric bright images, or newly discovered systems. The CLASS survey did not follow up many candidates for which the flux density ratio in the original VLA snapshot exceeded 10:1 (Myers et al. 2003), and I will be involved in projects to make detailed observations of such candidates with the VLA and MERLIN, in collaboration with Steve Myers and Ian Browne. There is a good chance of turning up some additional candidate central images, and the certainty of improving the sample of upper limits.
Bibliography

Argo, M. K., Jackson, N. J., Browne, I. W. A., York, T., McKean, J. P., Biggs, A. D.,
Blandford, R. D., de Bruyn, A. G., Chae, K. H., Fassnacht, C. D., Koopmans,
L. V. E., Myers, S. T., Norbury, M., Pearson, T. J., Phillips, P. M., Readhead,


Bevington, P. R. & Robinson, D. K. 2003, Data Reduction and Error Analysis for

Biggs, A. D., Browne, I. W. A., Jackson, N. J., York, T., Norbury, M. A., McKean,

Biggs, A. D., Rusin, D., Browne, I. W. A., de Bruyn, A. G., Jackson, N. J., Koopmans,
L. V. E., McKean, J. P., Myers, S. T., Blandford, R. D., Chae, K.-H., Fassnacht,

Biggs, A. D., Wucknitz, O., Porcas, R. W., Browne, I. W. A., Jackson, N. J., Mao,


ph/0605178

Browne, I. W. A., Wilkinson, P. N., Jackson, N. J. F., Myers, S. T., Fassnacht, C. D.,
Koopmans, L. V. E., Marlow, D. R., Norbury, M., Rusin, D., Sykes, C. M., Biggs,
A. D., Blandford, R. D., de Bruyn, A. G., Chae, K.-H., Helbig, P., King, L. J.,
McKean, J. P., Pearson, T. J., Phillips, P. M., Readhead, A. C. S., Xanthopoulos,


Ellithorpe, J. D. 1995, Ph.D. Thesis
Gebhardt, K., Bender, R., Bower, G., Dressler, A., Faber, S. M., Filippenko, A. V.,
Green, R., Grillmair, C., Ho, L. C., Kormendy, J., Lauer, T. R., Magorrian, J.,
Hopkins, P. F., Hernquist, L., Cox, T. J., Di Matteo, T., Robertson, B., & Springel,
1922
Inada, N., Oguri, M., Keeton, C. R., Eisenstein, D. J., Castander, F. J., Chiu, K.,
Hall, P. B., Hennawi, J. F., Johnston, D. E., Pindor, B., Richards, G. T., Rix,
Kaspi, S., Maoz, D., Netzer, H., Peterson, B. M., Vestergaard, M., & Jannuzi, B. T.
JBO, http://www.jb.man.ac.uk/research/gravlens/workshop1/prcdngs.html
King, L. J., Browne, I. W. A., Muxlow, T. W. B., Narasimha, D., Patnaik, A. R.,


82


—. 2004b, Nature, 427, 613


