Gravitational lensing and galaxy evolution with e-MERLIN

e-MERLIN Legacy Proposal. Request: 696 hours (58 imaging tracks, 52 with Lovell).

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Abstract

The UK gravitational lensing community have agreed a co-ordinated strategy for the next generation radio facility, e-MERLIN, which will make ground-breaking progress in strong (multiple-image) lensing research. Our proposed Legacy Survey is two-pronged: a high-z lens discovery programme, using the approved Herschel ATLAS Key Programme and SCUBA-2 SASSy surveys, and a deep mapping programme of known lenses. The heavily magnification-biased submm surveys will have $\sim 50-100\%$ lens selection efficiency out to $z \simeq 5$, generating the largest and most distant sample of lenses to date. The $z_{\rm lens} > 1$ objects can be efficiently selected using K-band cross-identifications (e.g. with UKIDSS LAS). The project will play the role for e-MERLIN that the pioneering CLASS survey had for MERLIN. We will map the brightest radio sources in the $z_{\rm lens} > 1$ catalogue, identified in FIRST. The lens sample will allow evolution of galaxy mass profiles to be studied out to unprecedented redshifts. Using well-proven techniques, we will separate the dark halo and baryonic component of each lens galaxy to directly observe the build-up of stellar mass and its interplay with dark matter over this period.

Deep mapping of existing radio lenses, together with selected sources from the Herschel and SASSy surveys, will allow discovery of many central images. These are crucial for investigating mass distributions in the central regions of galaxies over a wide range of redshift, and hence probing changes in the central mass as a result of changing black hole mass and baryon distribution over a significant fraction of cosmic time. e-MERLIN gives the required factor of 10 extra sensitivity needed to do this. Mapping the extended radio emission in the images will also provide us with the ability to make detailed investigations of CDM substructure in lenses at a frequency where microlensing is not a serious problem.

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Scientific justification

This proposal will generate the most distant sample of gravitational lenses to date, and study existing and new lens systems in greater detail than ever before. The main purpose is to investigate the baryonic and dark matter distribution of galaxies from 0.01-10 kpc scales and how it evolves with redshift, confronting predictions of CDM and galaxy evolution. It will also allow us to investigate faint AGN in sub-mm galaxies and dark matter substructures in galaxies.

1. Background: gravitational lensing

Gravitational lensing is a unique way to probe mass distributions throughout the universe and investigate structures from sub-galaxy to cluster scales. Lensing is produced by the effect of foreground objects on the radiation from background objects, resulting in distorted and magnified images. In cases where the foreground lens has a surface mass density greater than a critical density, as is often the case with galaxies, multiple images are produced; such systems are known as strong gravitational lenses and are the subject of this proposal. Approximately 200 galaxy-mass lens systems are known. Of these, about half are cases in which quasars are lensed by foreground galaxies, producing multiple images. The other half are systems with extended background galaxies lensed by foreground galaxies, typically producing arcs and rings (Einstein rings) with a characteristic size depending on the mass of the lens. For typical lens systems, in which the lens is a large elliptical galaxy at a redshift of a few tenths, the images are separated by about an arcsecond. The separation depends on the square root of the mass; the smallest-separation (335-mas) lens system, CLASS B0218+357, contains a spiral galaxy lens, and the largest multiple-image systems have separations of about $20''$ due to the influence of a cluster in addition to the lensing galaxy.

Lens systems are important for a number of reasons. The most significant is that they allow us to learn about masses and mass distributions of the lensing object independent of the light that it emits. The zeroth-order observation, the radius of the Einstein ring, provides the most accurate measurement of mass available in galaxies at cosmological redshifts, namely the mass contained within the Einstein radius. Learning more about mass distributions can, however, be more difficult, depending on the lens system. In particular, the radial mass slope is difficult to measure with the number of constraints normally available, unless one is lucky with the system (e.g. there is a complex Einstein ring, or more than one source) or unless additional information is available. This additional information can, for example, be measurements of velocity dispersion which give the mass within the effective radius r_e in addition to the mass within the Einstein radius from gravitational lensing. The most notable series of systems in which this has been done is the SLACS survey (Bolton et al. 2006). The results indicate that large elliptical galaxies at low redshift ($z < 0.35$) have mass distributions close to singular isothermal ellipsoidal form ($\rho \propto r^{-2}$) in the range 5 kpc<r<30 kpc, and also indicates that this slope varies little with redshift (Koopmans et al. 2006) and that the modelling techniques are highly robust (Barnabè et al. 2008). Detailed mass modelling has been done on individual objects, which is beginning to allow the separation of distributions of light and dark matter (Dye & Warren 2005, Dye et al. 2008). The measurement of time delay between images, combined with a known value of H_0, also gives powerful extra constraints on the mass distribution[1].

The statistics of gravitational lensing give direct measurements of galaxy evolution, given a global cosmological model. The increasing size of well-defined samples, such as the CLASS and SDSS quasar surveys, allow measurement of the number and mass evolution of galaxies over an increasing range of redshift (Chae & Mao 2003; Mitchell et al. 2005; Matsumoto & Futamase 2008). The fact that lenses magnify background objects, usually by factors of up to 10, also allows us to study intrinsically fainter objects without building a hundred times bigger telescope. This fact is likely to become increasingly important in pushing studies of many different types of object to faint levels with new telescopes such as e-MERLIN.

2. The need for this proposal

Studies of mass distributions of lensing galaxies have hitherto given rather general results about mass distributions and galaxy evolution. We are now reaching the point where lensing is about to come of age in terms of serious confrontation between observables and predictions of large-scale simulations of structure

[1] This cannot be done with SLACS lenses, as the sources are extended and non-variable objects.

formation in the Universe. For this we need an expanded lens sample, preferably of objects at higher redshifts than SLACS and that can be studied at the high resolution that radio observations provide. *Identification of a significant number of such lens systems is one aim of this project.* e-MERLIN provides a step-change in the available observational inputs to this process. *Collection of the necessary detailed observations is the other aim of this project.*

a) CDM predictions at sub-galaxy scales.

Cold Dark Matter (CDM) simulations have become increasingly sophisticated in recent years, and are now beginning to predict structure on galaxy and sub-galaxy scales, despite the difficulties in achieving high resolution in the simulations and the necessity to handle baryon physics (baryon cooling into the centres of CDM potential wells means that the central ∼10 kpc of galaxy haloes is baryon dominated). The baryonic matter distribution modifies the underlying NFW-type dark matter profile into a steeper profile, which lensing and kinematic observations show to be universally (and surprisingly) close to isothermal. Few such observations exist at significant ($z > 0.3$) redshifts, however.

In principle, CDM simulations also predict much more sub-galactic structure on smaller scales down to $10^7 M_\odot$ (Moore et al. 1999) than is seen around our own Galaxy, although the gap has been closing in recent years with the discovery of Galactic satellites (e.g. Zucker et al. 2006). If such substructures are dark, they are very difficult to detect in galaxies at large distances; but in lens galaxies, the effect of a substructure close to an image's line of sight may affect the position, and to a greater degree, the flux, of the observed image. The result can be that it is impossible to fit a smooth model to the lens observables without invoking smaller-scale structure. The first such claim was made by Mao & Schneider 1998; further work suggests flux anomalies and, consequently, substructure, in about half the objects for which good measurements are available. Indeed, it seems that at the range of radius which is probed by lensing studies, there may be *too much* inferred substructure when compared to CDM simulations.

Both the overall mass distribution and the presence of substructure are observationally and theoretically controversial, because of the high resolution and complicated physics required for the simulations, and due to dearth of good constraints and the presence of microlensing in optical images. Optical microlensing occurs because the sources are typically small, and the fluxes are therefore affected by movement of stars in the lens galaxy. Most substructure determinations have therefore been based on radio-loud lens systems. e-MERLIN gives the improvement in sensitivity and resolution that will allow a major advance, both in the provision of constraints on the overall mass distribution and also in the measurement of the statistics of substructure.

b) Central mass distributions and galaxy evolution.

It is important to study the central regions (within about 100pc) of galaxies[2] because *understanding the central regions appears to be important in understanding many other questions about the formation and evolution of galaxies.* This is because in nearby elliptical galaxies, where the central black hole mass can be well measured by dynamics of gas disks, the BH mass correlates extraordinarily well with the large-scale velocity dispersion of the bulge on size scales a factor 10^6 larger (Gebhardt et al. 2000, Ferrarese & Merritt 2000). Either the BH controls the formation of the rest of the galaxy, or there is a tight link between the formation of the galaxy and the amount of material fed to the BH. Kinematics of circum-BH gas disks cannot be studied directly in distant galaxies, although some progress can be made by reverberation mapping studies of active galaxies in estimating BH masses. There is other evidence that global and central properties of galaxies correlate well. Nearby galaxies with a flat central light distribution are brighter, rapid rotators, whereas those with cuspy distributions tend to be fainter and rotate slower (Faber et al. 1997). On theoretical grounds, one expects central potential wells to show evidence of nuclei of previously-merged galaxies, and of the interaction of baryons and dark matter (potentially erasing cusps).

Accurate estimates of the mass in the central 100 pc of distant galaxies is beyond current capabilities. However, gravitational lenses provide an important diagnostic because non-singular lens systems always produce a central image whose line of sight passes very close to the lens centre and therefore probes the gravitational potential at this point. Specifically, the flux is sensitive to the steepness of the potential; more nearly singular potentials (e.g. if a very massive central BH is present), produce fainter central images. Only one convincing central image has been detected (Winn, Rusin & Kochanek 2004) due to sensitivity limitations, but we expect many more with the increase in sensitivity provided by e-MERLIN ("[we] may require observational sensitiv-

[2]The first paper to do this systematically (Faber et al. 1997) has collected 441 citations.

ity to improve by an order of magnitude before detections of core images become common" – Keeton 2003). Radio lenses are essential for this work, since the central lensed image in an optical picture will be hopelessly contaminated by the lensing galaxy.

c) Source populations

Gravitational lensing offers the rare opportunity of probing populations much fainter than can be reached by blank-field surveys. In the submm for example, the limiting factor is not detector sensitivity, but rather the point source confusion limit with the wide ($\sim 5 - 20''$) submm beams. Traditionally, the only ways to probe fainter populations than the confusion limit have been through stacking analyses, or through strong-field lensing from foreground galaxy clusters. The former method has the obvious disadvantage that it only probes the first moment of the submm fluxes in a population, but gives no information on the variation in the population, let alone the properties of individual objects. The latter method again has the obvious disadvantage of cosmic variance in the small high-z cosmological volumes sampled, though individual objects can be studied in detail, albeit in small numbers. In this proposal we will make an important new approach: the detection of strongly lensed populations in a very wide-field Herschel submm survey, probing ~ 10 times fainter than the blank-field confusion limit, and selected from a much larger cosmological volume and thus representing a fairer sample of the Universe.

Within this context, we propose two studies of lens systems at *higher redshifts than existing samples (Fig. 1).* In section 3 we describe a study which will reveal the mass distributions of the highest-redshift lenses, and in section 4 we describe detailed studies of existing $z \sim 0.5$ lenses.

3. A high-z lens discovery survey

Submm surveys are arguably the ideal way to find large numbers of lenses, and thanks to the radio-far-IR correlation, bright submm survey sources are also accessible targets for e-MERLIN. The negative submm K-correction means that submm sources are generally at redshifts $z \geq 1$ with flux density depending on luminosity but largely independent of redshift. The selection function is therefore both very well-constrained and simple. The steep submm source counts observed at $850 - 1300\,\mu$m ($dN/dS_\nu \propto \nu^{-\alpha}$ with $\alpha \simeq 3 - 4$), and widely predicted at $250 - 500\,\mu$m, together with the strong evolution of submm galaxies, give bright submm surveys a high optical depth (up to 50–100%) to gravitational lensing and a strong magnification bias.

We will select lenses from two major submm legacy surveys: the SCUBA-2 All-Sky Survey (SASSy), and the Herschel Astrophysical Terahertz Large Area Survey (ATLAS). SASSy is the joint second-largest Legacy Survey on the JCMT. Its two-year plan (awarded time starting 2009) is to map $2000\,\mathrm{deg}^2$ in a strip from the North Ecliptic Pole, through the North Galactic Pole to the Galactic Plane, to a 5σ depth of 150 mJy at $850\,\mu$m, as well as a similar area along the Galactic Plane. SASSy's proposed five-year plan will map all the JCMT-accessible sky. The Herschel Astrophysical Terahertz Large Area Survey (ATLAS) is the largest Open Time Key Project awarded on Herschel, mapping around $500\,\mathrm{deg}^2$ to the brightest limit permitted by scanning speed and the need for cross-scan data for map reconstruction. The $5\,\sigma$ point source sensitivity limits of the Herschel ATLAS key project are typically 50-70mJy (5σ) at wavelengths of $110 - 500\,\mu$m. Herschel launches in Spring 2009, and we expect the first ATLAS data to arrive within the first year.

ATLAS and SASSy will be exceptional sources of new gravitational lens candidates. Negrello et al. (2007), following the formalism of Perotta et al. (2003), made quantitative predictions for the numbers of strong lenses (magnification > 2). They interpreted the number of dusty galaxies detected at mJy levels by submm and mm-wave surveys following the model of Granato et al. (2004; updated to take into account the most recent $850\,\mu$m counts). In this model, submm galaxies are protospheroidal systems in the process of forming most of their stars in a violent starburst. The model accounts for a large body of multifrequency data at different redshifts (see Negrello et al. 2007 and references therein) but in particular fits the $850\,\mu$m counts and the redshift distributions of the $850\,\mu$m sources (Aretxaga et al. 2007), which are crucial ingredients for determining the amplitude of the magnification bias. The lenses have been modelled as a mix of Singular Isothermal Sphere (SIS) and Navarro Frenk & White (NFW) profiles according to the recipe of Porciani & Madau (2000). However, as shown in Perrotta et al. (2002), the choice of either a purely SIS model or a purely NFW model would introduce an uncertainty lower than a factor of 2 in the magnification bias.

The most conservative predicted counts of strongly lensed sources at the wavelengths of Herschel/SPIRE and at $850\,\mu$m (the wavelength at which the mJy-counts are constrained by the SHADES data) are displayed in Fig. 1. The fraction of strongly lensed protospheroids (dashed-line) is found to be very high at bright

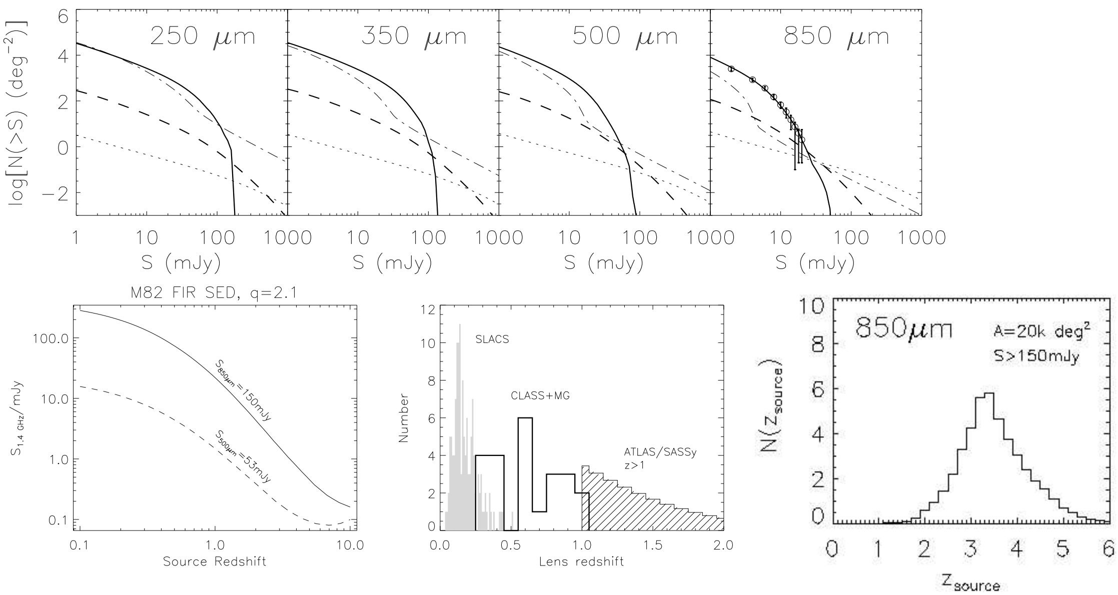

Figure 1: **Above**: Predicted counts of high-z protospheroidal galaxies at different wavelengths: unlensed (solid line) and strongly lensed (dashed line). The contribution to the counts from other galaxy populations is also shown: late-type (starburst plus normal spiral) galaxies (dot-dashed line, from Silva et al. 2005) and flat-spectrum radio sources (dotted line: from de Zotti et al. 2005). The 850 μm data are from Coppin et al. 2006. **Below**: Left panel - Predicted radio flux density limits of the lenses to be found by the SASSy (solid line) and ATLAS (dashed line) surveys, as a function of redshift, derived using the well-studied radio-far-infrared correlation and assuming an M82 far-infrared SED and $q = 2.1$. Central panel - redshift histogram of our known CLASS lenses and the SLACS lenses, combined with the predicted lens histogram of the submm-selected lenses. Right panel - predicted source redshifts for SASSy (the corresponding ATLAS histogram peaks at slightly lower redshifts, $z_{\rm peak} \simeq 2.5$, with a significant tail extending to $z = 5$).

submm fluxes where the surface density of unlensed protospheroids (solid line) sinks rapidly. As an example, *all* the high-z protospheroids with flux above $S_{500\mu\rm m} \gtrsim 100$ mJy are predicted to be strongly lensed. Fig. 3 also shows a typical reconstruction of the sources of one of these lensed galaxies, which will allow a good lens model to be derived, and indicates some of the cosmological constraints derivable from the lens sample.

The other source populations contributing to the counts are easily distinguished from (lensed and unlensed) protospheroidal galaxies. Essentially all conventional radio sources that will be detected in the submm will be the flat-spectrum blazars, already known from low-frequency surveys like NVSS, FIRST, SUMSS and PMN. The starburst and normal late-type galaxies should be easily identified in the optical; those with $\gtrsim 100\,\mu$Jy at 500 μm are at $z \ll 1$ and therefore already in IRAS and the forthcoming AKARI all-sky catalogues. However, high-z dusty galaxies are expected to be very faint in the optical. After removing these other populations, we are left with a sample almost exclusively made of strongly lensed sources, that is, we expect a selection efficiency for such sources close to 100 per cent. For comparison, the Cosmic Lens All Sky Survey (CLASS) found 22 gravitational lens systems amongst over 16000 radio sources.

We therefore expect several hundred strong lenses in the ATLAS 500 μm survey, and several tens in SASSy. These predictions are conservative since the adopted lens model does not account for substructures and/or satellite galaxies which would further enhance the flux amplification and increase the magnification bias (Dunlop et al. 2004). More lenses are expected if the assumed upper limit to the magnification μ is relaxed (e.g. Pacagia & Scott 2008). For $2 \leq \mu \leq 30$ we predict 20 strong lenses in SASSy's first two years.

We predict that these lenses will be accessible targets for e-MERLIN, on the basis of the radio-far-infrared correlation. Assuming $q = 2.1$ and an M82 far-infrared SED, Fig. 1 (lower left) shows the predicted L-band flux of a gravitational lens at the $> 5\sigma$ 500 μm ATLAS flux limit, and the $> 5\sigma$ 850 μm SASSy flux limit.

This will be the primary lens discovery project for e-MERLIN, generating the most distant sample of lenses to date. The project will play the role for e-MERLIN that the pioneering CLASS survey had for MERLIN, but with much greater efficiency. The e-MERLIN array is of central importance to the lens exploitation of the Herschel ATLAS survey and SASSy, providing essential confirmation of multiple imaging in fields at declinations too high for ALMA, and in equatorial fields well in advance of ALMA.

Our large unbiased sample of strongly lensed galaxies enables several key cosmological science goals.

- We will reconstruct the properties of submm galaxies up to 10× fainter than the blank-field confusion limit, effectively sparse-sampling a sufficient comoving volume to be immune to cosmic variance.
- The extended radio morphologies in submm-selected galaxies lead us to expect several examples of extended radio rings. Using our in-house methodologies to reconstruct the unlensed source (Wucknitz 2004, Dye & Warren 2005), we will study the radio morphology of these high-z starbursts with much higher angular resolution than would be possible in the absence of lensing.
- We will study in more detail the central Active Galactic Nucleus (if any) in sub-mm galaxies. A substantial fraction of submm bright galaxies is known to harbour an AGN (Alexander et al. 2005). This will allow us to study fainter AGN than otherwise possible and thus permit a better understanding of the growth of super-massive black holes in forming spheroids and their relationships with their host galaxy.
- We will derive independent constraints on cosmological parameters through the lens-redshift test and on the evolution of dark energy from the splitting angle statistic (see e.g. Zhang et al. 2007a).

4. Deep mapping of radio lenses

4.1 Description of the observations

We propose the collection of a legacy dataset consisting of images with μJy-level rms of *all* $\delta > -20$, $S_{5\mathrm{GHz}} > 10$mJy, radio-loud gravitational lenses with compact structure, together with the best bright, high-redshift lenses from the Herschel survey. Radio surveys, principally the CLASS survey (Myers et al. 2003, Browne et al. 2003) have conducted complete surveys of the northern sky for lens systems, and this is therefore the definitive list of objects in which the scientific aims of section 1 can be addressed. The CLASS sample has already generated over a hundred papers extracting science to the limits of current observations.

Currently there are 33 known radio lenses, of which 22 were discovered by the CLASS survey (21 original discoveries plus a large-flux-ratio lens system by Boyce et al. 2008) and the remainder by the MG and PANELS surveys. Of these, 32 are accessible to e-MERLIN, and four lie south of the equator. Full tracks of all of these objects will provide a complete, self-contained reference sample for future work. The images produced by this legacy programme will be an obvious starting point for the community in future proposals for deeper observations in standard e-MERLIN time and for multi-wavelength followup.

The sample is divided approximately equally into double (two-image) systems and quad (four-image) systems. For reasons which we explain in subsequent sections, double-image systems are more suitable for central image studies and 4-image systems for substructure/mass model studies. This imposes different requirements in terms of frequency; central images are subject to scattering in the lens galaxy, requiring higher frequency observations, whereas detection of steep-spectrum extended structure for substructure studies requires lower frequency in the larger objects. We therefore propose to use L-band observations for the more extended quads and C-band for the small quads and doubles. In cases where extensive structure, or bright central images, are seen, further open-time observations may be sought for followup at different frequencies. In a few cases there are both doubles and quads/rings in the system, and for these sources we therefore request observations at both frequencies.

4.2 The route to the science: central images

Keeton (2003) presents simulations of central image flux densities, using a best-guess model for the lens mass distribution. This best guess is based on light distributions (Faber 1997) of nearby galaxies studied with the HST, and consists of a cuspy model where inner and outer power laws are free parameters, together with a central BH predicted by the scaling relations of Gebhardt (2000) and Merritt & Ferrarese (2001). To establish a ballpark number, if the well-studied nearby galaxy M87 is taken as typical, and moved to a redshift of 0.5, the median magnification for the central image, integrating over the possible source positions, is 0.002. In a typical gravitational lens system, this corresponds to a central image flux of 50–100μJy. *This, and the fact*

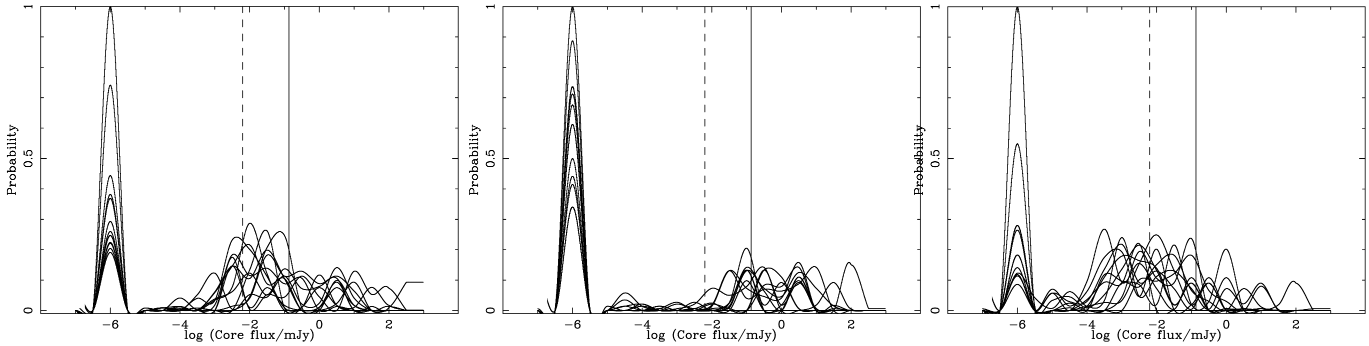

Figure 2: Probability distribution of core flux density; one line is plotted for each lens system. The probability distribution for each lens system arises by choice of different galaxies from the Faber et al. (1997) observations (Keeton 2003). Models in which the central image is wiped out by a black hole are placed arbitrarily at 1 nJy. The 3σ sensitivity of MERLIN (solid line) and e-MERLIN (dashed line) lie clearly on opposite sides of the peak of the probability distribution. The diagram on the left is the model in which galaxies at $z = 0.5$ are exactly similar to local ellipticals. In the middle is shown the effect of a factor 2 decrease in the break radius of the inner cusp; all of the images in the $\sim 20\mu$Jy range disappear. On the right, the effect is shown of an increase by a factor 2 of the convergence at the break radius (i.e. the galaxy's overall mass-to-light ratio). Note that all 15 known radio double lenses are needed to observe shifts in these distributions.

that one central image has already been seen, suggests that with current MERLIN we are just above the level at which large number of central images will be detectable. In most cases we require MERLIN resolution, rather than that of the VLA, because the central image typically forms ~200 mas from one of the other lensed images. Two-image lens systems are used for this work, since in four-image systems the central image forms close to the centre of the lens galaxy and is even more heavily demagnified. Occasionally the lens galaxy may have a weak nuclear radio component (e.g. CLASS B2108+213), but multi-frequency observations can be used to distinguish lensed images from nuclear images on spectral grounds.

We note that e-MERLIN is the ideal instrument for detection experiments, because its resolution is well-matched to the problem. Attempts using VLBI (e.g. Boyce et al. 2006, Zhang et al. 2007) suffer from severe problems due to non-homogeneity of the array, calibration problems, and statistical effects which cause the effective detection threshold to be up to 10 times the RMS noise (Zhang et al. 2007)[3]. The upshot is that e-MERLIN should be able to beat not only existing MERLIN, but also the High Sensitivity Array (VLBA plus Green Bank, Arecibo and the phase VLA) by a factor of 10 in detection limit.

What would we see? We can simulate this by using HST observations of local galaxies from Faber et al. (1997) to construct a mass model involving a Nuker law and a black hole mass consistent with the studies of Gebhardt et al. (2000). We then move the Faber et al. galaxies to $z \sim 0.5$ and for each of the 15 known doubly-imaged radio lenses, we use the lens's known image positions to calculate a model, and hence a core flux density, for each galaxy, weighting the probability of each galaxy by its lensing cross-section[4]. Note that we can use the HST observations here as a proxy for the central mass distribution, as the central image probes the region of the galaxy where the dark matter contribution is negligible.

Fig. 2 shows the results. *Note that the sensitivity increase of e-MERLIN is precisely matched to that which covers the peak of the probability distribution.* The most "boring" result is that central regions in galaxies at redshift 0.5 are exactly the same as at the current epoch. In this case, we *expect* the increased sensitivity of e-MERLIN to detect most of the central images. If we adjust the shape of the central cusp (Fig. 2) of $z = 0.5$ galaxies compared to local ones, for example, by adjusting the break radius, we see that the expected distribution moves. It is obvious from Fig. 2 that *we need to observe all known 2-image lenses* to get the statistics needed, and moreover observing them all in a homogeneous manner is important. Only a legacy-type programme will provide us with this information. By studying the overall distribution as well as detailed modelling of each individual lens system, we can therefore measure the evolution of the central profile shape.

4.3 The route to the science: mass profiles, substructure and polarization

The use of gravitational lenses to reconstruct mass distributions in lensing galaxies is now well established (Wucknitz, Biggs & Browne 2004, Koopmans et al. 2006, Dye & Warren 2005, Dye et al. 2008) in mostly

[3]This is because the central image position is known from the range of models which fit the bright image constraints to within one e-MERLIN beam, but only to within many hundreds of VLBI beams, any of which could contain the central image.

[4]The full process is described by Keeton (2003).

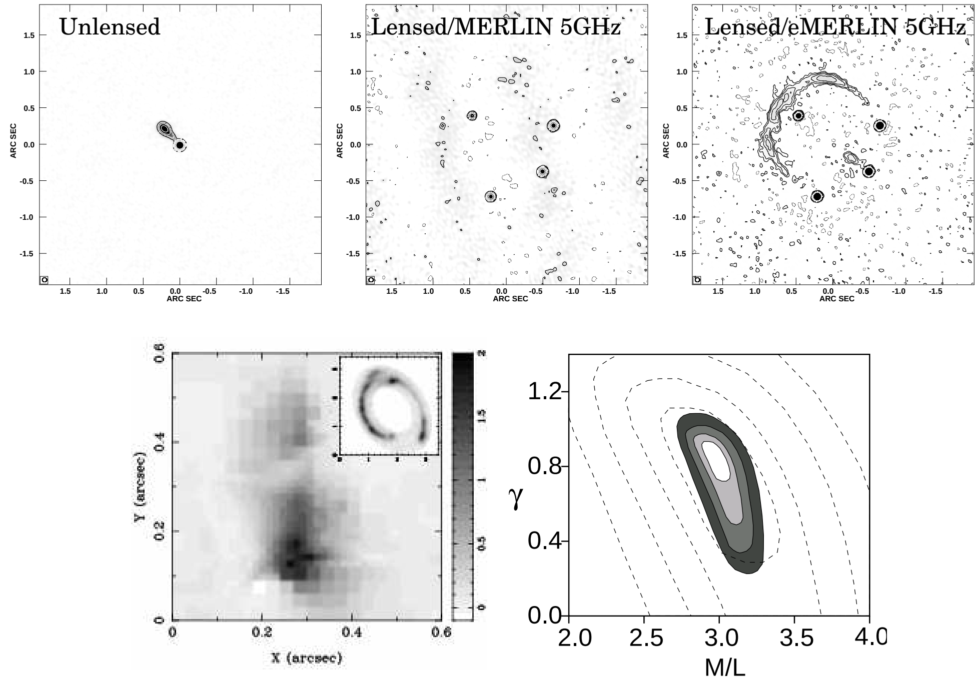

Figure 3: Top: Jet source (left) with a 200-mas jet of 10% of the core brightness, lensed by a galaxy with similar properties to that of CLASS B0712+472 into a 50-mJy lens system and observed with current 5-GHz MERLIN (middle panel) and e-MERLIN (right panel). Below: reconstruction of a typical source (left). (Right) Lens model confidence limits (68, 95, 99, 99.9%) on the dark matter inner halo slope, gamma, and baryonic M/L derived assuming a 2mJy simulated source. (Solid contours: full track, dashed contours: 3-hour exposure divided into a number of chunks at different hour angles).

relatively low-redshift galaxies ($z \sim 0.1 - 0.2$). The results – galaxy mass distributions in the kiloparsec range are roughly isothermal and vary little with redshift – are interesting and unexpected, because we would expect a more concentrated distribution in the baryonic centres and a different slope further out, where the dark matter dominates. This apparent "isothermal conspiracy", together with the substructure problem, was identified as the most important unsolved question during the 2006 KITP workshop on the subject. We are now just beginning to be able to investigate light and dark matter distributions separately (Dye et al. 2008) and it appears that despite considerable variation between slopes of light and dark matter individually, the overall slope is isothermal. What is going on: is this an artefact of the inversion, an effect of evolution, or a not-yet-obvious correlation with a third variable? More and better data is required at high resolution and high redshift.

The proposed observations (Fig. 3) will provide a dataset at high resolution and signal-to-noise. Importantly, the sample will be predominantly at higher redshift than existing surveys such as SLACS, and thus allow conclusions about evolution as well as simple derivation of mass profiles. Also importantly, radio sources contain jets and structure on many different scales which give more detailed constraints than a smooth background galaxy with a more or less constant structure between systems. Use of e-MERLIN together with followup VLBI observations will provide many more constraints than the lensing of a single smooth elliptical galaxy in an optical image. The power of this approach is illustrated, for example, by existing work on the CLASS lens B0128+437 (Biggs et al. 2004, Zhang et al. 2008). Here, the macromodel from the lensed images is inconsistent with the detailed structural information provided by VLBI, leading to the conclusion that mass substructures on scales smaller than the lensing galaxy are present. In CLASS B0218+357, work on combining VLBI images with constraints on the macromodel from lower-resolution observations of the Einstein ring has been crucial in determining detailed mass distributions in this spiral lens galaxy, leading among other things to some of the best estimates of the Hubble constant from lensing (Wucknitz, Biggs & Browne 2004). Again, such studies are not possible when the only source structure available is a smooth galaxy on the 1″ scale.

Combining the lensing information with the measured distribution of baryons obtained from deep optical/NIR imaging, we will be able to reconstruct the dark matter halo profile (Dye et al. 2008, fig. 3) and investigate the interplay between baryons and dark matter in the inner core of galaxies. High resolution imaging of large samples of high-z lenses are ideal to test whether the "isothermal conspiracy" is linked with evolution or whether it represents modelling degeneracy. The observations will use the 4-image/arc systems within the known radio lenses for two reasons; the sources are closer to the galaxy centres and are likely to produce more extended arc structure, and the four point images give additional information about the mass distribution via the radio fluxes which are not subject to modification by microlensing. Use of the quad radio fluxes together with the deconvolution of extended structure should therefore provide simultaneous information about overall mass profile and smaller-scale substructure. Combination of e-MERLIN images with high-bandwidth VLBI observations will allow us to perform this inversion to recover mass distributions on scales from 1 arcsecond down to a few milliarcseconds, corresponding to the influence of matter on scales from $10^{11} M_{\odot}$ down to $< 10^{7} M_{\odot}$. This provides a unique opportunity to recover both the overall light and dark matter mass profile, *and* probe the substructure components in a single galaxy, an extremely interesting study which has not been done yet.

The large 2 GHz bandwidth of the proposed C-band (and in some cases also L-band) long-track observations will allow additional science projects to be carried out with the Legacy dataset. For example, the multiple lines of sight that are traced by the lensed images can be used to probe the lensing galaxy. This technique has been very successful at optical wavelengths where the level of dust extinction, and extinction laws have been tested for galaxies out to redshift 1. At radio wavelengths we can uniquely probe the magnetic field of these distant galaxies by searching for Faraday Rotation by a magnetic plasma. Such a study of all the known radio-loud lensed AGN has never been done before. The 2 GHz continuous bandwidth (at C-band) is needed because the Faraday Rotation measure is $\propto 1/\lambda^2$. However, to increase the signal-to-noise, the individual channels will be averaged into several sub-bands.

We can also look for absorption in the lensed images over the full bandwidth. This could be in the form of free-free absorption, but also as molecular absorption by a cloud in the lensing galaxies seen in the spectrum of the lensed images. Hydroxide (OH) and Methanol (CH_3OH) are two of the most common molecules in our own galaxy and are used as tracers for dust and gas. We would search for excited OH (6.0 GHz rest-frame) and CH_3OH (6.7 GHz rest-frame) at C-band. We would probe galaxy redshifts out to 0.68, which currently includes most of the sample with radio-loud AGN. Also, we can search for molecular emission and absorption from the distant lensed source. Here, we use the lensing magnification of up to several tens to probe the high redshift Universe. Our main goal is to search for high redshift water masers (22.2 GHz rest-frame). Luminous water masers are found within a few parsec of the supermassive black hole at the centres of AGN, providing information on the mass of the black hole, the size of the accretion disk and the speed of radio-jet outflows. However, AGN with water masers are almost exclusively known at $z < 0.06$. The discovery of a water maser in the lensed quasar MG 0414+0534 at $z = 2.64$ shows that finding maser emission at high redshift is feasible (Impellizzeri et al. 2008, Nature, submitted). With e-MERLIN, we hope to find additional examples in the redshift range 2.7-4.5.

References

Alexander D.M., et al., 2005, ApJ 632, 736
Aretxaga I., et al. 2007, MNRAS 379, 1571.
Barnabè M., et al., 2008, astro-ph/0808.3916
Biggs A.D., et al. 2004, MNRAS 350, 949.
Bolton A.S., et al. 2006, ApJ, 638, 703.
Bolton A.S., 2008, ApJ, 682, 964.
Boyce E.R., et al. 2006, ApJ 648, 73
Boyce E.R., et al. 2007, MNRAS 381, L551.
Browne I.W.A., et al. 2003, MNRAS 341, 13.
Chae K.H., Mao S. 2003, ApJ, 599, L612.
Coppin K., et al. 2006, MNRAS 372, 1621.
Davis R., Muxlow T., Conway R. 1985, Nat 318, 343
Dunlop J.S., et al. 2004, MNRAS 350, 769.
Dye S., Warren S.J. 2005, ApJ, 623, 31.
Dye S., et al. 2008, MNRAS 388, 384.
Faber S.M., et al. 1997, AJ, 114, 1771.
Ferrarese L., Merritt D. 2000, ApJ, 539, L971.
Gebhardt K., et al. 2000, ApJ, 539, L139.
Granato G.L., et al. 2004, ApJ, 600, 580.
Keeton C.R. 2003, ApJ, 582, 17.
Koopmans L.V.E., et al. 2006, ApJ, 649, 599.
Mao S., Schneider P. 1998, MNRAS 295, 587.
Matsumoto A., Futamase T. 2008, MNRAS 384, 843.
Merritt D., Ferrarese L. 2001, ApJ, 547, 140.
Mitchell J.L., et al., 2005, ApJ, 622, 81.
Moore B., et al. 1999, ApJ, 524, L19.
Murphy D., Browne I., Perley R., 1993, MNRAS 264, 298
Myers S.T., et al. 2003, MNRAS 341, 1.
Negrello M., et al. 2007, MNRAS 377, 1557.
Pacagia G. & Scott D., 2008, astro-ph/0801.0274
Perrotta F., et al. 2002, MNRAS 329, 445.
Porciani C., Madau P. 2000, ApJ, 532, 679.
Rusin D., Ma C.P. 2001, ApJ, 549, L33.
Silva L., et al. 2005, MNRAS 357, 1295.
Wucknitz O. 2004, MNRAS 349, 1.
Wucknitz O., Biggs A.D. & Browne I.W.A. 2004, MNRAS 349, 14.
Winn J., Rusin D., Kochanek S., 2004, Nat 427, 613
Zhang M., et al. 2007, MNRAS 377, 1623.
Zhang Q., et al. 2007a, astro-ph/0708.2164
Zucker B., et al., 2006, ApJ,

Links to related datasets

Herschel is scheduled to launch in Spring 2009, and we expect the first data from the Herschel ATLAS survey to arrive within the first year. The Herschel ATLAS survey covers several fields:

- NGP block: a rectangular block 15 degs by 10 degs centred on $\alpha = 199.5°$, $\delta = 29°$. This field crosses the North Galactic Pole and was surveyed in the SDSS. It will be surveyed in four near-IR bands with UKIRT as part of the UKIDSS legacy survey. It is the obvious target for a survey with the new low-frequency array telescope (LOFAR). It is also accessible to SCUBA-2, Pan-STARRS, and the southern half is accessible to ALMA.

- At declinations difficult for e-MERLIN without Chilbolton (and therefore not considered in this proposal), ATLAS covers three GAMA fields at 9hrs, 12hrs and 14hrs. Each field covers about $12\,°$ in RA and $3\,°$ in dec, centred on 9hr, 12hrs and 14.5hrs respectively. This field has been surveyed by the SDSS and 2dFGRS. It will soon be surveyed in four optical bands by the KIDS legacy survey (VST) and in five near-IR bands by the VIKING legacy survey (VISTA). Within the field there are three 50 deg^2 subfields that will be surveyed in the GAMA redshift survey about to be started on the AAT (P.I. Driver), which will yield $\simeq 10^5$ redshifts, including $\simeq 7000$ for H1K sources. There is also access to ALMA, SCUBA-2, Pan-STARRS, and the SKA-precursor telescopes.

- Also at declinations inaccessible to e-MERLIN, there is an SGP 23hrs block centred on $\alpha = 348.9°$, $\delta = -32.9°$, and an SGP 2hrs block centred on $\alpha = 36.7°$, $\delta = -33°$.

The most natural multi-wavelength counterpart to SASSy is the AKARI All-Sky Survey, which has mapped the whole sky at $10\,\mu$m, $20\,\mu$m, and four bands from $60 - 150\,\mu$m, to a position-dependent depth of $\sim 200 - 400$ mJy at $100\,\mu$m. SASSy sources which are $100\,\mu$m AKARI drop-outs are likely to lie at $z_{\mathrm{source}} > 1$.

We intend to propose a VLBI programme for obtaining long-spacing data on all e-MERLIN L-band deep-mapping targets. This will allow constraints on the lens model in these objects on multiple scales, giving a secure macromodel from e-MERLIN combined with imaging of smaller-scale structure in the lens galaxies by VLBI lensing constraints. If the programme is approved, we will also propose C-band VLA observations to fill in short spacings on C-band e-MERLIN targets and again provide additional constraints on the lens profile deconvolution.

Technical justification

There are two parts to the programme, and we address the issues separately for each part.

1. Deep mapping of existing radio lenses

Table 1 shows the list of existing lenses which are part of this programme. The table includes the number of images forming each system, the 5-GHz flux density in mJy, the size of the lens system (i.e. separation of the images), and the proposed observing band. As explained in the science case, we predominantly need 5-GHz observations for the double lens systems, to achieve maximum point source sensitivity in flat-spectrum sources. For 4-image lenses the choice is normally C-band for small-separation lenses (see Fig. 3 for a simulation), as here we expect structure on ∼200-mas scales (and existing experience with MERLIN suggests that for these objects C-band is normally more successful in revealing interesting structure). In a few cases, where evidence exists in the literature or unpublished maps for larger-scale structure, we use L-band observations to give maximum sensitivity to steep-spectrum emission of relatively low surface brightness. L-band is also used for the widest-separation lenses, again to match the resolution to the structure available. In some lenses, both scientific aims (detection of central images and detection of extended structure) are realizable; for example CLASS B1933+503 has both doubly and quadruply imaged sources. Such objects will be observed in both bands. The success of the observations will depend on the strength of the extended radio structure which is being lensed (Fig. 3 assumes 10% of the core brightness in extended radio structure). We know already from MERLIN observations (and in some cases VLA observations with much lower raw sensitivity) that nearly half of the systems (Table 1) have extended structures, albeit not yet always at the levels to give well-constrained mass reconstruction. It would be very unfortunate not to achieve a substantially higher success rate with twenty times the sensitivity. We aim to obtain VLA C-band data to fill in the short spacings and increase the range of imaged structures in cases where e-MERLIN observations are approved, although the simulations (e.g. Fig. 3) have been done without such addition.

The aim of the C-band observations is to obtain maximum point source sensitivity. In one full track including the Lovell telescope we should be able to obtain an r.m.s. noise level of 2μJy, sufficient to detect a large majority of central images (5σ at 10μJy; see Fig. 2 of the science case). The main issue is dynamic range; in order to do this the typical dynamic range required is about 3000:1 at points about 0.5–1$''$ from the primary and, in a limited number of cases, where the primary point image has 200-300mJy flux density, about 20000:1. We note that the existing MERLIN system has routinely achieved dynamic ranges of several thousand to 1; for instance, observations of 3C273 taken 25 years ago achieved 10000:1 (Davis, Muxlow & Conway 1985) over a map a similar number of beamwidths across as those we are proposing. Achieving such a dynamic range over a much larger bandwidth will be challenging, but discussions with Dr T. Muxlow suggest that this should be possible. We note in this context that the ability to make maps of order 10^4 dynamic range will be *required* for much e-MERLIN science, and in particular for studies of the active galaxy population. Our approach will be to begin with the weaker sources and work with the MERLIN instrument team to identify any calibration requirements before attempting the more demanding objects. For most of this part of the programme the use of the Lovell is highly desirable, the only exceptions being the brightest six sources at C-band where we may be limited by dynamic range. It becomes essential for the weaker half of the 2-image sample, in order to reach the depths which give a reasonable chance of detecting third images, and for the L-band observations where surface brightness sensitivity is very important.

The Chilbolton telescope would be very useful in the case of the equatorial and southern sources highlighted in Table 2. While use of this telescope is not essential, if it were available within a reasonably short timescale we would request that these observations be deferred accordingly.

For the subsidiary aims of the project, namely serendipitous detection of spectral line absorption, the default spectral resolution of eMERLIN 5 GHz in continuum mode is ∼15 km s^{-1} and the sensitivity is ∼0.2 mJy channel^{-1}. This is sufficient to detect OH absorption, which can have a FWHM up to 800 km −1, and water maser emission that can have a FWHM up to 100 km s^{-1}.

2. ATLAS/SASSy lenses

Our aim in this part of the programme is to make full-track observations of lens candidates from the SASSy legacy survey and the Herschel ATLAS Open Time Key Project. The former will be distributed uniformly in declination, while the latter will be taken from a rectangular $15^\circ \times 10^\circ$ block centred on the North Galactic Pole at $\alpha = 199.5^\circ$, $\delta = 29^\circ$. The lenses themselves are expected to be giant ellipticals. Since the radiogalaxy

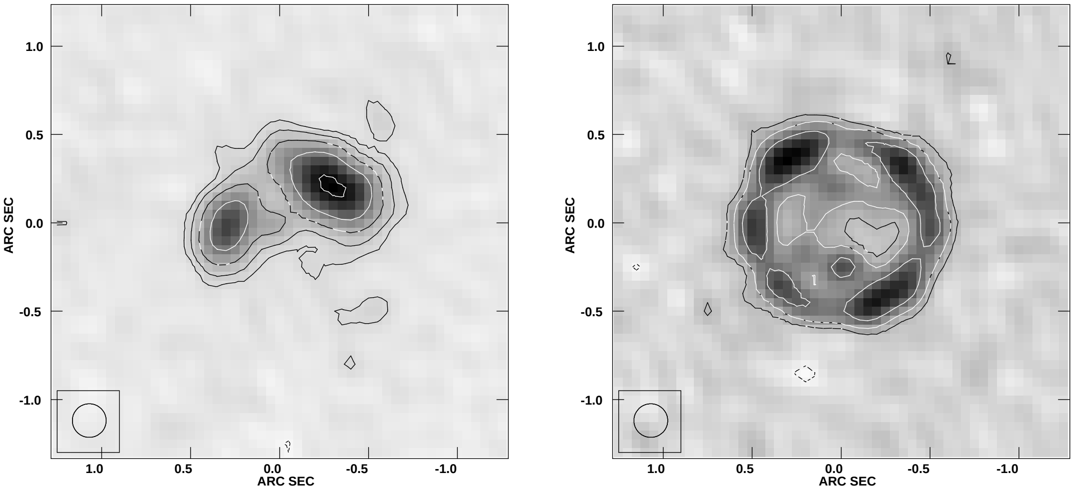

Figure 4: Simulation of the *median* flux density of source to be selected for the $z_{\rm lens} > 1$ ATLAS/SASSy mapping programme (2mJy). The source consists of a point together with two extended Gaussian components each extended on a scale of ∼300-400 mas, roughly what is expected for the known population of star-forming galaxies, and is observed for a track with e-MERLIN+Lovell. On the right is the optimistic case of a thin Einstein ring, also of total flux density 2mJy.

K-z relation follows roughly 1 mag brighter than L_*, we can use this to estimate the apparent K magnitudes of the lenses, finding $K > 18$ sufficient to filter $z_{\rm lens} < 1$ systems. This is well within the capabilities of UKIDSS LAS (for ATLAS) or rapid K-band 4m-class snapshots for the few tens of SASSy lens candidates. At these K-magnitudes and for our anticipated submm positional uncertainties, we predict foreground mis-identifications in $< 0.3\%$ of cases. We expect the median 1.4 GHz flux of SASSy lenses to be about 1 mJy, but the median flux of ATLAS to be about 0.1 mJy (see Fig. 1). We will therefore pre-select the radio-bright lens candidates using FIRST to identify the $S_{\rm 1.4GHz} > 1$ mJy systems.

The collaboration contains a major resource of expertise in scheduling and analysis of imaging with existing MERLIN. Members of the collaboration have been involved in the CLASS gravitational lens survey (Browne et al. 2003) in which over 300 MERLIN images of lens candidates have been made in order to separate lenses from objects with intrinsic structure. It has been clearly demonstrated in this work that, provided the question asked of the data is reasonably simple (is the source one point, two points, or one point with some resolved structure?) the answer is unambiguous, even with a relatively poor coverage of the $u - v$ plane. We should be able to get much more reliable information with e-MERLIN and therefore image the more complicated structure of the Herschel/SASSy lens systems which have extended sources. A simulation of a source within a factor of 2 of the faintest end of the survey (1mJy at L-band) is given in fig. 4.

We rely on our previous experience to guide the e-MERLIN observing schedule. We will make full tracks on each of the submm-selected lens candidates, resulting in a total observing time of 20×12 hours. Each observation will reach an rms noise level of about 5μJy/beam including the Lovell telescope, sufficient to detect secondaries with flux ratios of 10:1 of the primary flux density (again, experience with the CLASS survey shows that only very rarely are true lens flux ratios greater than this, e.g. Boyce et al. 2008). The resolution requirement absolutely requires the use of e-MERLIN, as the Einstein ring radius of any lenses will be similar to those in the first part of the programme. Again we emphasise that, because of the unique properties of the object SEDs in the Herschel band, this will allow e-MERLIN to be a highly efficient lens discovery engine as well as providing structural information for those objects that are lenses.

List of targets

Object	#images	$S_{5\mathrm{GHz}}$ (mJy)	Sepn/$''$	Band	Ex str	Comments
20 SCUBA-2 and Herschel sources detected in FIRST ($S_{1.4\mathrm{GHz}} > 1$ mJy) and with $K > 18$ from UKIDSS LAS (ATLAS), or in follow-up K-band snapshots of 5σ SASSy sources (SASSy).						
CLASS 0128+437	4	48	0.55	C	V	
PMN J0134−0931	4+ring	530	0.7	C	*	Chilbolton
CLASS 0218+357	2+ring	1200	0.34	C	*	
CLASS J0316+4328	2	65	0.4	C	*	
MG 0414+0534	4	980	2.4	C	V	
CLASS B0445+123	2	30	1.4	C	*	
CLASS B0631+519	2+ring	45	1.2	LC	*	
CLASS B0712+472	4	38	1.5	C		
CLASS B0739+366	2	25	0.53	C	V	
MG 0751+2716	ring	200	0.7	C	*	
CLASS B0850+054	2	68	0.7	C	V	
Q0957+561	2	66	6.3	L	*	
CLASS 1030+074	2	220	1.6	C	V	
MG 1131+0456	2+ring	200	2.1	LC	*	
CLASS B1127+385	2	40	0.7	C	V	
CLASS B1152+199	2	70	1.6	C	V	
CLASS B1359+154	6	66	1.7	C		
CLASS B1422+231	4	560	1.7	C		
CLASS B1555+375	4	36	0.5	C		
CLASS B1600+434	2	130	1.4	C		
CLASS B1608+656	4	73	2.3	L		
PMN J1632−0033	2+C	230	1.5	C		Chilbolton
MG 1654+1346	ring	130	2.1	L	*	
PKS 1830−211	2+ring	10000	1.0	LC	*	Chilbolton
CLASS B1933+503	4+4+2	60	1.0	LC	*	
CLASS B1938+666	4+2+ring	320	1.0	LC	*	
PMNJ 2004−1349	2+ring	34	1.2	C	*	Chilbolton
MG 2016+112	2/4	85	3.5	LC	*	
CLASS B2045+265	4	30	2.7	C		
CLASS B2108+213	2	20	4.6	L		
CLASS B2114+022	2+2	140	1.3	C	*	
CLASS B2319+051	2	30	1.4	C	V	

Table 1: List of objects. The observing band for the known lenses is C-band for all double lenses, in which central images will be sought. For most of the quad lenses, C-band is better matched to the structure we expect to detect, and the increased sensitivity over L-band compensates for the spectral index. In addition, imaging tracks at L-band are sought for large rings, or for sources in which we already know that interesting structure is present at this spatial scale. Additional VLA C-band observations will be sought where necessary to provide short-spacing data on the larger objects, although the primary science goals should be achievable with e-MERLIN alone. Lens systems with known arcsecond-scale structure (MERLIN or VLA) are indicated with a star in the "extended structure" column, and those with reasonable amounts of VLBI structure on the ∼5–20mas scale are indicated 'V'. In the event that the Chilbolton antenna becomes available, the objects marked would benefit from the observations being deferred until this happens. The total number of tracks is 58 (20 for the Herschel/SASSy lensed and 38 for the existing radio lenses).

Pipeline requirements

We will produce the following legacy data products:

- Deep L-band calibrated and cleaned maps
- Deep C-band calibrated and cleaned maps
- Beam maps
- Lens models
- Multi-wavelength follow-up images and catalogues, where generated in-house
- Serendipitous background source catalogues: positions, S/N, peak and total fluxes, generated on a best-efforts basis only

The L-band and C-band maps for each object will be released to the UK community six months after the data is taken, and the releases will be reviewed on an six-monthly rolling basis. The submm survey sources are the products of external consortia (though overlapping with this consortium), so the e-MERLIN maps will be provided in relative coordinates only until the positions are released by the submm survey teams.

Although we list lens models, calibration and map-making separately, and assign separate working groups to some of these activities below, they are closely related. Our goal is to have final lens modelling products optimized directly on the visibilities, avoiding regularization bias, and avoiding the possibility of deconvolution artefacts being input into the lens modelling process. To this end, Wucknitz is leading the effort to adapt the visibility-based modelling method LensClean to the specific eMERLIN needs, including bandwidth synthesis.

Management

Our programme falls naturally into two components: a lens discovery programme and an existing lens mapping programme. As the former is essentially a follow-up of submm surveys, we feel that the sub-project on lens discovery should most properly be led by a management team representative from both the parent submm surveys, rather than someone external to these consortia. The deep mapping of known lenses is quite properly separately led, and this dual-pronged science approach is reflected in the PI and co-PI roles. In addition, we have defined the following scientific and technical working groups:

- **Scheduling and Observations (leader: Jackson)**: Birkinshaw, Clements, Dye, McKean, Negrello, Rawlings, Serjeant. Many of the team have experience in radio surveys; Jackson has extensive experience in lens discovery, both as part of the CLASS survey and in subsequent work.
- **Calibration and image production (leader: Rawlings)**: Biggs, Birkinshaw, Browne, Heywood, Jackson, McKean, White, Wucknitz. Biggs, Birkinshaw, Browne, Heywood, Jackson, McKean and Rawlings all have considerable experience in interferometry. Birkinshaw is a leading researcher in SZ and AGN radio astronomy; Browne was the PI of the CLASS gravitational lens survey; Rawlings is vice-chair of the European SKA Consortium.
- **Interface with ATLAS (leaders: Dye and Negrello)**: Clements, Coppin, De Zotti, Eales, Hopwood, Hughes, Mortier, Nieves, Perez-Fournon, Scott, Serjeant, Thompson, Vaccari. Dye and Negrello are the working group heads within ATLAS, and Serjeant co-leads the ATLAS AGN group. Dye led the UKIDSS science verification and is responsible for the design and implementation of UKIDSS LAS.
- **Interface with SASSy (leader: Clements):** membership as with ATLAS interface group. The team have extensive experience and expertise in submm survey astronomy. Serjeant led the SASSy extragalactic case; Serjeant, Thompson and Scott sit on the SASSy management committee. Serjeant also sits on the executive committees of SHADES and the JCMT Local Galaxies Legacy Survey.
- **Source Modelling (leader: Serjeant):** Birkinshaw, Blain, Chapman, Clements, Coppin, De Zotti, Nieves, Scott, Vaccari.
- **Lens Modelling (leader: Dye):** Bacon, Birkinshaw, Negrello, Scott, Waerbeke, Warren, Wucknitz. Dye, Warren and Wucknitz are internationally leading researchers in lens modelling and reconstruction.
- **Application of LensCLEAN (leader: Wucknitz)**
- **Central images (leader: Jackson):** Bacon, Dye, Warren, Zhang.
- **Polarization (leader: McKean):** Biggs, Browne, Wucknitz

The working group heads, the PI and co-PI will comprise the Executive Committee, who will manage the survey. Decisions will be devolved from the Executive Committee to the working groups where possible, for efficient working procedures and following lessons learned in managing other consortia.

Following Herschel ATLAS and SASSy models, we have agreed the following publication policies:

- There should be at least one "umbrella" paper for each of the survey components (lens discovery and deep mapping), in which all consortium members will be invited to join. All consortium members will be free to join any other papers resulting from this legacy survey. However, co-authorship of these non-umbrella papers will be purely on merit.
- Survey effort should be acknowledged and rewarded by paper leadership, as far as possible. The Executive Committee will arbitrate if there are competing bids for science analysis papers that the relevant working group head(s) cannot resolve.
- Publications of submm-selected sources are also subject to the regulations of their respective submm surveys. None of the e-MERLIN papers is to be deemed an "umbrella" paper of the *submm* surveys, ATLAS and SASSy.

Finally, we have agreed to hold 3-monthly video/telecons, to produce six-monthly management reports, and to hold a face-to-face "jamboree" once a year of all consortium members.

Legacy value

This programme will be a lasting cosmological reference survey, which will spawn many community-wide follow-up studies. This lasting legacy value is due to several key factors.

1. **Large, homogeneous sample selection**, both in the submm-selected and radio-selected lens samples.

   - The radio-selected targets are taken from the CLASS (and MG) surveys, which investigated all flat-spectrum objects in the northern sky for evidence of lensing which had $S_{5\mathrm{GHz}} > 30$ mJy. This is ideal for statistical studies and has frequently been used in this way, e.g. for galaxy evolution and derivation of cosmological parameters. This is also the only large sample which has been used in this way.

   - The new submm-selected targets are taken from large, homogeneously-reduced legacy submm data sets. The largely featureless (broad-band) Rayleigh-Jeans spectra of submm galaxies leads to a well-understood and well-characterized selection function. This clean statistical selection will give this new sample the same advantages of CLASS.

2. **Robustness to microlensing.** The physical sizes of the sources also means that the fluxes, used for mass models and studies of CDM substructure, are not affected by microlensing. It is therefore a standard reference sample, widely known and used, which is not going to change in the future.

3. **The first large $z_{\mathrm{lens}} > 1$ sample**. There are currently very few known gravitational lenses above a redshift of 1. This is currently the best opportunity for increasing by a factor of 2 the redshifts at which we can probe spheroid matter distributions. It is a key niche for e-MERLIN and the main pillar of our lens discovery programme, and will create a sufficiently large sample for statistical comparisons with the existing known $z_{\mathrm{lens}} \simeq 0.5$ samples.

4. **Uniform data quality.** Experience with the CLASS survey has shown that it is vital, when selecting lenses, to have observations conducted in a uniform manner across the whole list of lens candidates. This legacy programme will provide such a dataset.

5. **Probe of the submm-faint population.** Gravitational lensing is the only route to studying individual objects below the submm confusion limit, and our survey sparse samples objects from a much larger and more representative sample of the Universe than galaxy cluster lenses. Gravitational magnification also makes these objects much more accessible targets for multi-wavelength follow-ups than blank-field populations, and this advantage has been abundantly exploited in lensed SCUBA-selected galaxies. We fully expect a similar level of activity in our new submm-selected lenses, and our e-MERLIN imaging will be key to interpreting the lensed submm-bright population.