Strong lensing and LOFAR surveys
in association with the Surveys KSP Science proposal

Background

Strong-gravitational lenses are systems in which the gravitational field of a foreground galaxy multiply images a background source. They are important because studies of lens systems probe mass profiles, including the dark matter, of galaxies, and are beginning to give us major insights into galaxy structure and evolution.

Models and simulations predict that galaxies should have a mass distribution that is a combination of a baryonic cusp in the central few kiloparsecs, together with a “universal” dark matter profile (Navarro et al. 2006) in the outer regions. Current lensing analyses, with the restricted number of well-studied lenses, show that the profile on scales of 1–20 kpc is remarkably well fitted by a profile intermediate between the expected baryonic and dark matter slopes, namely an isothermal profile (e.g. Cohn et al. 2001, Wucknitz et al. 2004, Koopmans et al. 2008). This appears to hold quite accurately even when other complementary studies (weak lensing and stellar dynamics, e.g. Koopmans & Treu 2004, Gavazzi et al. 2008) are used, although there are now hints (Bolton et al. 2012) that the slope may evolve with redshift.

More than 200 lens systems are currently known. The largest number (∼80) have been discovered in the SLACS survey (Bolton et al. 2006) based on the identification of multiple-redshift systems in the SDSS, and similar studies using BOSS are now yielding lenses (Bolton et al. 2012). A further ∼40 have been discovered in radio surveys, the largest number (22) in the CLASS survey of flat-spectrum radio sources (Myers et al. 2003; Browne et al. 2003). SLACS survey lenses are well suited for mass profiles, since the background sources are extended; CLASS lenses have been used for mass determinations but also, via variability studies, for extraction of the Hubble constant (e.g. Biggs et al. 1999; Suyu et al. 2010; Wucknitz et al. 2004). Variable radio lenses are extremely valuable for mass profiles, since if $H_0$ is known, the time delay together with the image positions gives an accurate mass model for the lensing galaxy, free of the usual degeneracies which plague many mass models. Time delays, coupled with the flux ratios of quasar lensed images, can also be used to detect low-mass substructure in massive haloes, and test CDM galaxy formation scenarios (Fadely & Keeton 2012).

Scientific motivation

Radio lenses make up about one-sixth of known lenses, and have mostly been discovered by targeted surveys. These are expensive in telescope time for current narrow-field telescopes (for example, the CLASS survey required 16500 separate VLA pointings to discover 22 lenses) and, even with telescopes such as the EVLA and e-MERLIN, will be prohibitive if we wish to increase the known lens sample by an order of magnitude. What is essential for such a programme is a combination of high survey speed together with the high resolution needed to recognise lens systems, typically on the order of the 1" image separation. LOFAR, including the international baselines, is the one instrument available before the SKA which fits this primary criterion.

A major impact of lensing studies over the next decade will be the study of galaxy structure, as outlined above. Moreover, lensing allows this to be done in cases where lensing galaxies are beyond the reach of detailed stellar dynamics, thus allowing us to study the evolution of galaxy structure. As well as this basic application, which a much larger sample of LOFAR lenses will allow us to address, there are two further important applications of radio-loud lens systems:

(i) CDM simulations of galaxy formation are just beginning to have the resolution to probe
sub-galactic scales and make predictions about the internal structure of galaxies. For example, they overpredict the number of Galactic satellites (Moore et al. 1999; Klypin et al. 1999) and an immense amount of work has been devoted to understanding this. Recent work (e.g. Moore et al. 2006) has addressed the important role of baryons in the centres of galaxies and secure theoretical predictions will be available in the next decade, but the whole issue is still a severe problem (Boylan-Kolchin et al. 2011).

Gravitational lenses are vitally important for this work, as they are the only way of detecting lumpy dark-matter substructure in \( z \sim 0.5 \) galaxies. This is possible because lumps of dark matter close to the line of sight to a lensed image will perturb its position and, especially, its magnification in such a way that the lens can no longer be modelled by a simple, smooth model (Mao & Schneider 1998; Dalal & Kochanek 2002; Metcalf 2002). Radio lenses are important here because the fluxes of the components are much less affected by microlensing by stars in the lens galaxy, because radio sources are bigger than optical quasars. The big problem is the small number (8) of four-image radio lenses. A larger sample is urgently needed for progress in this area.

(ii) Images forming close to the centre of the lens galaxy allow probes of its gravitational potential within the central 100pc (Wallington & Narayan 1993; Rusin & Ma 2001; Winn et al. 2003). This is only possible in radio lenses, as the optical picture is contaminated by light from the lensing galaxy. The lensed image is stronger the less singular the central potential, and therefore probes the steepness of the central stellar cusp together with the mass of the central black hole. In addition, central black holes may produce additional images which if detectable measure black hole masses more directly. An e-Merlin Key Project is studying this, but the numbers of objects available for study is still very small.

The study of the central potential of galaxies is very important because there is a close relation (Gebhardt et al. 1998, Ferrarese & Merritt 2000) between the central BH mass and the mass of the bulge, implying that the two processes are very closely related during the process of galaxy formation. These quantities are difficult to measure over a wide range of redshift, leaving lensing as a promising method to do this. However, only one secure central image has been detected in a single galaxy lens (Winn, Rusin & Kochanek 2003), and only about ten suitable lenses for central image detection are known. These are being studied with e-MERLIN, but progress will require a much larger number of lenses.

In short, we need a factor-10 increase in the number of lenses for two reasons: (i) to provide statistics which will allow the study of lens galaxy structure as a function of redshift, thereby measuring galaxy evolution, and (ii) to provide reasonable quantities of rare lenses (those particularly suitable for central image detection, substructure detection or lenses of different Hubble types or high redshift).

**Practicalities**

About 1 in 700 radio sources at \( z \geq 1 \) are lensed. The major requirement for a radio survey is therefore a large number of sources, which LOFAR will provide: in \( 10^8 \) sources one expects 100000 lenses, a factor of 500 increase. In practice, an image of a lensed object is needed which clearly shows the lensed structure, typically at the 10-50\% level compared to the total flux density, which cuts these numbers by a factor of about 30. Nevertheless, a large number of potential discoveries are expected in the overall LOFAR survey.

How can the number of discoveries be maximised? The major factor is resolution, because the typical separation of lensed images is about 0.5"–1". Surveys at lower (2-3") resolution are still useful, and in conjunction with optical data can be used to vastly increase the efficiency
of targeted searches with the EVLA (Jackson & Browne 2007), but surveys with long-baseline
LOFAR with subarcsecond resolution could be expected to find lens systems directly. How many
could be found immediately depends critically on the stability of the PSF, but it is likely that
between 50 and 100 systems would be found straightforwardly (Jackson 2002; Wucknitz et al.
2006); the limiting factor is the requirement to maintain a small (<95%) false-positive rate which
will allow easy followup and confirmation with higher-resolution telescopes such as the EVLA.
However, the discoveries are unlikely to be limited to the immediately obvious LOFAR lenses.
Combination of the LOFAR-120 survey with the 100000-LRG sample from SDSS allows us im-
mediately to identify potential lensed radio sources with plausible lensing galaxies. Many studies
have shown that this type of “lens-selected” approach (e.g. Bolton et al. 2006, Faure et al. 2008)
reduces followup effort and maximises discovery. Detailed estimates (Wucknitz 2002) suggest
that several hundred lenses should be found this way. Second, the use of two complementary
but pre-existing catalogues, one slightly lower resolution but wider area, has been shown to be a
second potential way of discovering lenses as used by the MUSCLES survey (Jackson et al. 2008,
2009). In principle, a LOFAR radio survey together with an optical survey such as Pan-STARRS
would be an extraordinarily powerful lens engine (see Jackson & Browne 2007 for a list of tricks
that can be used for lens discovery with combined radio and optical catalogues).
There is one other extremely powerful synergy for lens discovery; new far-IR and sub-mm in-
struments (particularly Herschel/ATLAS) are now producing large numbers of lens candidates
(e.g. Negrello et al. 2010). This is because they operate in regions of the spectrum where the
K-correction together with the shape of the Planck curve allows easy viewing out to high red-
shift, and because the extremely steep log N-log S gives a high magnification bias. The resulting
extremely high lensing fraction (e.g. Negrello et al. 2007) gives large samples of highly probable
lenses, at a resolution too poor to confirm or rule them out. They are, however, expected to have
radio fluxes in the tens of \( \mu \)Jy (Negrello et al. 2007) making them accessible to LOFAR with
international baselines and visible in LOFAR surveys. These lenses are likely to contain a large
number of high-z systems, giving correspondingly powerful information on galaxy evolution.

**Observations**

In the Surveys KSP observations, large areas of sky will be observed in order to discover new
lenses, using the international baselines for the required resolution. In addition, we propose
separate observations of a small number of known lenses. This has two main purposes. First, the
high resolution at low frequencies will allow us to detect much more extended structure, which
tends to have a steep spectrum and therefore escape scrutiny at GHz frequencies. This in turn
will provide extra observational constraints, allowing us to get similar or better constraints on
the mass model on different scales to recent results in the optical. It will also be complementary
to the e-MERLIN lens Legacy Project that is being conducted at higher frequencies. The second
reason is that the main search will discover many lenses, but also throw up many false positives.
In order to distinguish these, many years of experience indicate that it is vital to have a well-
controlled training set of known lenses, in order to control the filtering process on the main
Survey candidates.

In this first cycle, we restrict the sample to the 8 objects (Tab. 1) which we believe are certain
to have enough correlated flux on the 0.3-arcsec scale to do this work. B0218+357 is particularly
important because it is at the centre of the Lenc field (Lenc et al. 2008) which has been studied
with low-frequency VLBI and will be a very important calibration and test field for the long
baselines.
We are developing methods to handle data using the long baselines in surveys. These include methods to handle differential Faraday rotation, both in terms of short-term workarounds and also more long-term solutions. Successful imaging has been demonstrated on bright sources by O. Wucknitz and A. Deller, e.g. on the imaging of the bright but complex source 3C123; the objects proposed here should be less challenging in terms of structure. For the larger-scale surveys, methods are again under development and we have a plan involving initial investigations of IBs in the MSSS data. The overall pipeline is yet to be decided, but is likely to feature the use of a restricted set of baselines including Dutch remote stations, and a phased-up superterp, instead of all the intra-Dutch baselines. The data can be rotated to individual positions within the field and averaged around individual sources. All these measures are used to reduce the data to a manageable size. Separate storage and processing facilities are available at Jülich and in Bonn which can be used for this work, as demonstrated in our early long-baseline imaging efforts. This can alleviate the processing bottle-neck at CEP.

One $\sim 12$ h track (depending on declination) is required per target. Details of the observing setup and analysis strategy will be provided in the regular proposals under this umbrella.

<table>
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<th>name</th>
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<th>$S_{50}$</th>
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<td>02:21:05.5 +35:56:14</td>
<td>2.1</td>
<td>4</td>
<td>0.3</td>
<td>double+ring, Lenc field</td>
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<td>2.4</td>
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<td>6</td>
<td>6.3</td>
<td>double, lobes</td>
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<td>1.0</td>
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<td>1.0</td>
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<td>quad+arc/ring</td>
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</table>

Table 1: Targets for the ‘known lenses’ project, fluxes in Jy. Total observing time $\sim 96$ h in HBA, total raw data $\sim 350$ TB, LTA storage after appropriate averaging $\sim 8$ TB.

References

- Negrello M., et al., 2010, Sci, 330, 800