Gravitational lens surveys with LOFAR

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Introduction

Gravitational lensing is the best method to determine the mass distribution of distant galaxies with high accuracy. With a large sample of lens systems at a range of redshifts, we can study not only the structure but also the evolution of galaxies. We identify three main topics, in which lensing can help to resolve controversial problems.

- Most galaxies at moderate redshifts seem to have very close cores. How do we catch up with them and take the lead again?

- How does the central density profile of galaxies look like? Do they have cores or cusps, how do masses of central black holes evolve?

- Are small sub-halos as abundant as predicted by the CDM structure formation simulations (image from Springel, et al., 2005). The statistics of substructure provides information about the properties of dark matter.

We can help answering these questions by modelling the mass distributions to fit the structure of gravitationally lensed sources. In order to obtain information about the complete mass distribution, lensed extended sources like the ones shown in Fig. 2 should be used and modeled with lensClean (Wucknitz, 2004). There are several advantages in using radio observations. Most important is the wide range of resolutions that can be achieved with radio arrays. Another important advantage is that microlensing and propagation effects can usually be neglected at radio wavelengths. So far we know less than 50 radio lenses, whilst the number of optical lenses has grown well above that and is increasing further. We should catch up with them and take the lead again!

Fig. 1: Radio lenses with extended sources can be used to detect substructure in galaxies, which is expected from structure formation simulations (image from Springel, et al., 2005). The statistics of substructure provides information about the properties of dark matter.

New lens surveys

Source-targeted search

As shown in Tab. 1, LOFAR (see Fig. 3) not only probes a new frequency range but also new parameter space. In terms of resolution and sensitivity of wide-area radio surveys. With these surveys, it is for the first time possible to identify lens systems directly from the source surveys using morphological criteria. In previous surveys, follow-up observations of complete source samples were necessary (Myers et al., 2003; Browne et al., 2003). This previous approach would be prohibitive for the extreme number of sources expected in LOFAR surveys.

Abstract

Deep surveys planned as a Key Science Project of LOFAR provide completely new opportunities for gravitational lens searches. For the first time do large-scale surveys reach the resolution required for a direct selection of lens candidates using morphological criteria. We briefly describe the strategies that will be used to exploit this potential. The long baselines of an international E-LOFAR are essential for this project.

Fig. 2: Two examples from the bright end of typical lens systems expected to be found in LOFAR surveys. The fraction of star-burst galaxies (and other extended sources) will be higher than in the previous survey CLASS. Left: PKS J1311-3211 (HST image from Claeskens et al., 2006), a lensed star-forming galaxy at z = 0.658 with a quadraply imaged Seyfert core. Right: The “9 o’clock arc”. At z = 2.73 this is the brightest known Lyman break galaxy (Almaini et al., 2007). WSRT (4h at 5 GHz) superimposed upon SDSS colour image. Deeper VLA-B observations are scheduled for November 2007.

Lens-targeted search

There are more efficient ways of finding lens systems than to scan through a whole LOFAR catalog of hundreds of millions of sources. Luckily our colleagues from the optical community are providing large catalogues of medium-redshift galaxies which are potential lenses. By cross-correlating these galaxy catalogues with the LOFAR source catalogues, we can establish a large sample of lens systems with well-defined selection criteria for the lens galaxies. Combining the Luminous Red Galaxies (LRG) from the SDSS with the 120 MHz LOFAR survey, we expect to find about 500 lenses in 5000 candidates. With upcoming larger galaxy surveys, this number can be significantly increased.

Tab. 1: Comparison of two planned LOFAR surveys (pre-descope planning, 450m baseline) with the most relevant existing radio surveys.

<table>
<thead>
<tr>
<th>survey area</th>
<th>frequency (MHz)</th>
<th>field size</th>
<th>number of sources</th>
<th>resolution (400 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOFAR 200</td>
<td>120 MHz</td>
<td>14.5×2.5′′</td>
<td>40′′&lt; δ &lt;30′′</td>
<td>∼1.8</td>
</tr>
<tr>
<td>LOFAR 400</td>
<td>360 MHz</td>
<td>55×20′′</td>
<td>120×500′′&lt; δ &lt;1.2</td>
<td>∼10</td>
</tr>
<tr>
<td>FIRST</td>
<td>1.4 GHz</td>
<td>1.0×0.5′′</td>
<td>62&lt; δ &lt;42</td>
<td>0.08</td>
</tr>
<tr>
<td>VLA A</td>
<td>1.4 GHz</td>
<td>∼60′</td>
<td>45&lt; δ &lt;20</td>
<td>0.6</td>
</tr>
<tr>
<td>VLA B</td>
<td>1.4 GHz</td>
<td>∼60′</td>
<td>120&lt; δ &lt;30</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Limitations

Even with additional stations in neighbouring countries, the resolution of LOFAR will be sufficient to securely identify only lenses with relatively large separations. Fig. 5 shows the dirty beams expected for a LOFAR survey at 120 MHz. We see that a good number of international stations is not only required for the resolution but also for good mapping properties, which is confirmed by simulations of an unresolved radio source and a lensed star-burst galaxy shown in Fig. 6.

Fig. 3: A small part of the low-band antenna fields in the LOFAR core near Exco (Netherlands). Photo taken in April 2007.

The expected lensing rates for this source population is 1:2000, leading to potential numbers of 400 000 and 15 000 lenses in the LOFAR surveys at 120 and 200 MHz respectively. Because of morphological and resolution limitations, we will be able to identify only a small fraction of these lenses. At 200 MHz, 900 lenses are a more realistic number, for which we probably have to follow-up around 10 000 candidates with the EVLA and/or MERLIN. At 120 MHz, longer baselines will be needed to detect more than just the systems with the largest image separations (see Fig. 4).

A good fraction of the LOFAR sources will be star-bursts galaxies, and the majority will have extensions and structures exactly on the scale that is needed for accurate lens models. We can thus build the perfect sample for the study of the structure and evolution of galaxies.

Acknowledgments

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References


Fig. 4: Histogram of image-separations in CLASS (Browne et al., 2003). The majority of lenses would be only marginally resolved by a 400 km LOFAR. This means that we are in a regime where even small improvements of the resolution result in a significant gain for lens surveys.

Fig. 5: Simulated dirty beams (long track, natural uniform weighting) for a LOFAR consisting of (a) only Dutch stations, (b) NL plus 3 in Germany, (c) NL plus 7 in Germany, in 4 in the UK, 2 in France and one each in Italy, Sweden, and Poland.

The recently announced de-scoping of LOFAR will modify the expectations for the lens surveys. Very roughly, a drop in sensitivity by a factor of 2 will lead to a reduction in the number of lenses by the same factor. Realistic expectations will depend on the adapted survey strategy and the number of international stations. We mostly need the sensitivity on long baselines, so that the reduction of the Dutch LOFAR can be compensated by more international stations. This would at the same time make calibration easier and improve the mapping quality.

More international stations are thus highly welcome!

Fig. 6: Simulated Clean maps of an unresolved FRI radio source (top) and (with different scale) a lensed star-burst galaxy (bottom). The full international array is needed to properly resolve and map the lensed source.

Fig. 7: A part of the flat-band antenna fields in the LOFAR core near Exco (Netherlands). Photo taken in April 2007.