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on the pathway to the SKA
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Strong gravitational lensing and the SKA

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Abstract. I examine the current state of knowledge about galaxy-scale gravitational lenses and their uses to determine mass distributions in galaxies. I discuss the use of the Square Kilometre Array as a lens-finding machine and its possible areas of scientific impact.

1. Current progress in strong gravitational lensing

"Strong" gravitational lensing refers to multiple imaging of a background object by a foreground mass. The cases in which this multiple imaging is observable are dominated by systems in which the foreground mass is a lensing galaxy, in some cases aided by a cluster.

The first lens system was discovered by Walsh et al. in 1979, and the tally is now somewhat over 100 lenses. The largest contributor is now the SLACS survey (Bolton et al. 2006; Treu et al. 2006; Koopmans et al. 2006) which is an optical survey based on the Sloan Digital Sky Survey (York et al. 2000) and which targets systems where the SDSS automated analysis finds two redshift systems at almost the same point on the sky. The OLS survey (Willis et al. 2006) uses the same principle, and the two together should eventually produce about 50–100 more lenses to add to the ∼30 already found. Searches in the radio waveband have also been undertaken, the largest being the CLASS survey (Myers et al. 2003; Browne et al. 2003) which found 22 lenses by a blind search of over 16000 compact radio sources. Smaller optical and radio surveys and serendipitous discoveries make up the rest of the tally.

As every grant application on the subject points out, gravitational lensing is an excellent way to study mass distributions in galaxies independent of the distribution of light. In practise, the major problem is the lack of constraints resulting from the fact that only a small part of the lens plane is covered by light rays deflected into the observer's line of sight. This problem can be partially alleviated if the source is extended or multiple sources are situated behind a given lens. There is still a great deal of debate, however, on the extent to which such sources give us really secure knowledge of galaxy mass distributions (Kochanek et al. 2001; Saha & Williams 2001; Warren & Dye 2003; Dye & Warren 2005; Koopmans 2005). Some of the resulting degeneracy can be broken in cases where lensing information can be combined with stellar dynamics (e.g. Treu & Koopmans 2004) and in favourable cases the mass profile of galaxies can be derived. This is already beginning to yield interesting results not only on the basic mass distributions (essentially, they are isothermal with a fairly small dispersion), but also on galaxy evolution (Koopmans et al. 2006) – the inner mass slope evolves remarkably little with redshift, suggesting strong coupling of gas and dark matter during galaxy formation.

We can also learn something from the way in which models of lensed systems break down. As the astrometric accuracy increases to the milliarcsecond level, the ability of smooth galaxy models to fit lens systems usually breaks down, and attempts to fix it by making galaxies slightly less smooth (Evans & Witt 2003) do not work in all cases (e.g. Biggs et al. 2004; Congdon & Keeton 2005). The obvious conclusion is that small-scale mass structures are being seen, as predicted by CDM simulations (Mao & Schneider 1998; Dalal & Kochanek 2002; Kochanek & Dalal 2004; Metcalf 2002; Metcalf et al. 2004; Bradac et al. 2004) and current research involves attempts to investigate exactly how these substructures affect the observables and even whether they are consistent with the amount predicted by CDM (Mao et al. 2004).

The final area in which lensing has played an – arguably undervalued – part is the determination of the Hubble constant. The use of time delay between brightness variations of lensed images (Refsdal 1964) is in principle a very clean way to determine absolute distances and H_0, provided that the mass model is well known. Again, the possibility of doing this to a good enough accuracy to be competitive with the HST Key Project's 10% error (Freedman et al. 2001) is under dispute. Models allowing complete freedom, subject to elementary arguments of physical plausibility, allow scatter of 30-50% in H_0 for typical systems (e.g. Williams & Saha 2000). The major degeneracy involves the details of the mass distribution in the annulus between the images (e.g. Kochanek 2004) which is often difficult to determine for an individual lens system due to lack of constraints. Determinations to date have mostly been in the range 60-75 $\mathrm{kms^{-1}Mpc^{-1}}$, consistent with the Key Project, although there is a worrying subset of well-constrained lenses which imply a lower H_0 (Kochanek 2002). The observation that well-constrained lenses – even if they are not suitable for time delay measurement due to non-variable sources – have a relatively small range of mass distributions (Koopmans et al. 2006) allow one to turn a systematic error in a single system into a random one if many systems are measured. Crudely, since 13 time delays have been measured, this reduces the overall error by $\sqrt{13}$ to a value better than that from the

Key Project. Alternatively, we can try and beat down the errors in systems which have a measured time delay and which have good model constraints (e.g. Wucknitz et al. 2004, York et al. 2005 find values of 70-75 kms^{-1}Mpc^{-1} for B0218+357, Fig. 1).

For further reading on strong gravitational lensing, a complete and up-to-date review of the subject is given by Kochanek (2004). Longer articles specifically directed at the use of future telescopes to find lenses can be found in Jackson (2003), Kochanek (2003) and Koopmans, Browne & Jackson (2005).

2. What the SKA can discover

The outlines of a possible SKA survey were given by Jackson (2003) and Koopmans et al. (2004). Essentially, the SKA is capable of an all-sky survey down to an rms of 1μJy in a few months, and this is sufficient to find lenses with a total flux density of 20-30μJy (less than 10μJy in the favourable case of an equal double system). It should in principle be possible to conduct surveys over a wide bandwidth, which gives increased sensitivity and also allows detection of the HI line at moderate redshift with sufficient spectral channels. Below the level of about 1mJy at 1.4GHz it is likely that starburst galaxies dominate the source counts although some AGN-like systems do remain even below this level (Richards et al. 1999; Muxlow et al. 1999; Snellen & Best 2001), and that the total number of such objects will be about 10^4 per square degree at the 20-μJy level, together with about one-tenth of this number of active galaxies. Typical lensing optical depths in blind surveys such as CLASS, in which the sources have median redshifts of about 1, are about 1:600, implying detection of about 15 lenses per square degree. Whether this is achieved depends on the redshift distribution of the starburst population (lensing cross-sections go approximately as $(1+z)^4$ in this region – Turner et al. 1984), which is currently unclear although some incomplete redshift samples have been achieved (e.g. Afonso et al. 2006) suggesting that the median redshift declines slowly with decreasing redshift. A full sky survey would therefore be likely to detect about 10^5 lenses. The SKA has a notable advantage over earlier instruments such as LOFAR in resolution, which will allow it to resolve systems with Einstein radii between $0.5''$ and $2''$ typical of galaxy lensing. It also has advantages in high-frequency field of view made possible by a greater data-rate, and in sensitivity, which gives an increase of a factor of a few hundred in lens detection rate. The resolution advantage also applies compared to the earlier optical Large Synoptic Survey Telescope (LSST) which will find somewhere in the region of 10^3 lenses. The SKA also has the advantage of potentially giving redshifts for free, assuming that the HI line can be measured in the lens systems; and direct astrophysical modelling of galaxy mass distributions can be done with the discovery images, although deeper images would be useful for the fainter lens systems.

3. Uses of lens systems

Assuming that so many lens systems can be found, one can attempt to guess the topics of controversy ten years hence and ask what contribution SKA will make. I suppose one should assume that the cosmological parameters including H_0 will be determined by then, although the ability of the SKA to perform wide-field coverage and devote large amounts of observing time to sources via multibeaming capability will mean that time delays will be easy to determine in the minority of lens systems which contain variable, non-starburst, sources. If the Hubble constant is known, measurement of the time delay can in any case give an important extra constraint on the mass model. However, the topics of galaxy formation, structure and evolution will certainly not be fully worked out by then; indeed, space missions with roughly the same or slightly shorter timescale (e.g. GAIA) have such topics among their science drivers.

The guaranteed science return therefore includes measurements of mass distributions in galaxies over a wide range of luminosity, redshift and Hubble type. Since only a fraction of lenses give good mass model constraints, it is important to have a large starting samples of 10^5 rather than 10^3. This is also important if one wishes to study rarer types of lens systems such as those with a disk lens (Fig. 1); these form about 10–20% of the total lensing population. Moreover, the rare examples with high-redshift lenses will also be represented in such a large sample and will be very important for studies of galaxy evolution beyond the $z \sim 0.8$ which we have been able to probe so far.

A further guaranteed return involves the study of central images in lens systems. Images formed at a Fermat maximum in the lens potential close to the line of sight to the lensing galaxy are important, as they allow us to study the gravitational potential very close to the centre of the galaxy (typically within the central 10 pc). Roughly speaking, steep central mass gradients resulting from a steep inner cusp or from a large central black hole, reduce the magnification of the central image. So far only one clear detection of a central image has been made (Winn et al. 2004) yielding constraints on the mass distribution. With the new generation of radio telescopes such as e-MERLIN and the EVLA such detections will become possible in many more systems, and the sensitivity of the SKA should make this a routine operation.

Finally, it is almost certain that the faintest radio sources detectable with the SKA will be those with a magnification due to lensing. Lensing magnification has already been exploited by many other surveys, such as the SCUBA blind surveys in the regions of clusters which exploited lensing magnification to decrease the effective survey flux limit (Smail et al. 2002). Lensing magnification of factors between 5 and 10 should allow detection of lensed objects of intrinsic radio flux of less than 10 nJy in 24 hours with a SKA-type array. This corresponds to

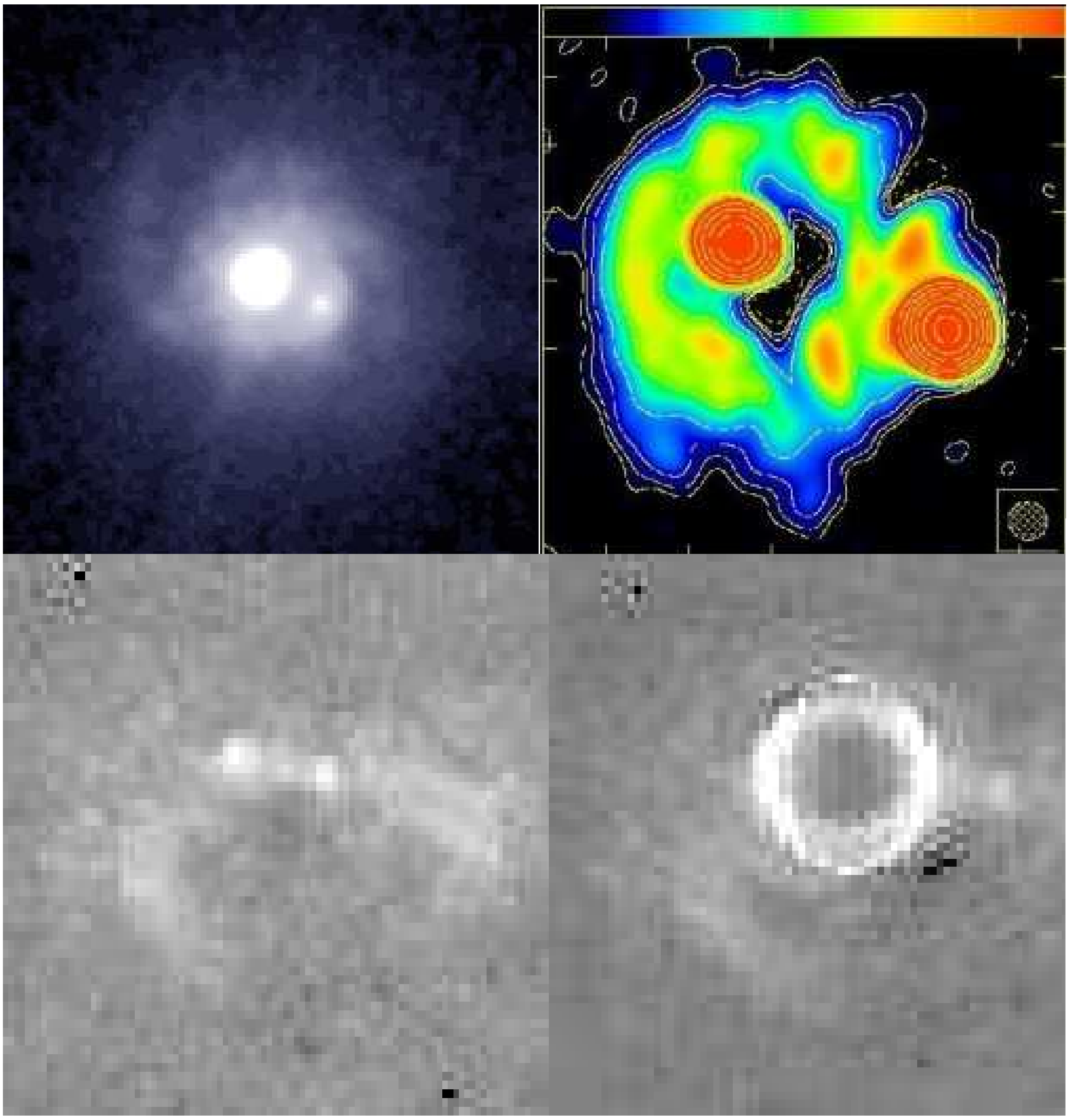

Fig. 1. Top panels: The lens CLASS B0218+357, the smallest-separation known galaxy lens. On the left is an HST/ACS image (York et al. 2005) showing two images separated by 335 mas and the spiral lensing galaxy, and on the right is a Merlin/VLA image (Biggs et al. 2001) showing the two images together with an Einstein ring. The source is a strong radio AGN. Below is a faint radio source from the Hubble Deep Field imaged by Muxlow et al. (2005) and its appearance if seen with a gravitational lens galaxy in the foreground.

relatively modest star-forming galaxies such as M82 at redshifts of z>1.

4. Conclusions

The SKA will have a major impact on gravitational lens studies by providing a basic set of 10^5 gravitational lenses. Most will have extended background sources and give good constraints on mass models; the redshift information will come for free via the HI information; the resolution will be high enough that the discovery image will have immediate astrophysical application without major followup; and the sample will be large enough that rare classes of lenses can be isolated and studied in non-negligible samples. Although the scientific payoff is virtually guaranteed, serendipitous discoveries are possible and even likely with such a powerful instrument.

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References

Afonso, J., et al., 2006, AJ, 131, 1216
Biggs, A.D., Browne, I.W.A., Muxlow, T.W.B., Wilkinson, P.N. 2001, MNRAS, 322, 821
Biggs, A.D., et al., 2004, MNRAS, 350, 949

Bolton, A.S., et al., 2006, ApJ, 638, 703
Bradac, M., et al., 2004, A&A, 423, 797
Browne, I. W. A., et al., 2003, MNRAS, 341, 13
Congdon, A. B. & Keeton, C.R. 2005, MNRAS, 364, 1459
Dalal, N., Kochanek, C.S. 2002, ApJ, 572, 25
Dye, S., Warren, S.J. 2005, ApJ, 623, 31
Evans, N., & Witt, H. J. 2003, MNRAS, 345, 1351
Freedman, W. L., et al., 2001, ApJ, 553, 47
Jackson, N., 2003, Proc Oxford Meeting on the Square Kilometre Array
Kochanek, C.S. & Dalal, N., 2004, ApJ, 610, 69
Kochanek, C.S., 2002, ApJ, 578, 25
Kochanek, C.S., in Kochanek C.S., Schneider, P.,& Wambsganss, J., 2004, Gravitational Lensing: Strong, Weak and Micro, 33rd Saas-Fee Course, eds. G Meylan et al., Springer, Berlin
Kochanek, C.S., 2003, in Hubble's Science Legacy: Future Optical/Ultraviolet Astronomy from Space, ASP Conf. Proc. 291, held 2-5 April 2002 at University of Chicago, Chicago, Illinois, USA. Ed Sembach, K., et al.
Kochanek, C.S., Keeton, C.R., & McLeod, B.A., 2001, ApJ, 547, 50
Kochanek, C.S. & Dalal, N., 2004, ApJ, 610, 69
Koopmans, L. V. E., Browne, I.W.A., & Jackson, N. J., 2004, NewAR, 48, 1085
Koopmans, L. V. E. & Blandford, R.D., 2004, PhT, 57f, 45
Koopmans, L. V. E., 2005, MNRAS, 363, 1136
Koopmans, L. V. E., et al., 2006, 649, 599
Mao, S. & Schneider, P., 1998, MNRAS, 295, 587
Mao, S., Jing, Y., Ostriker, J.P., & Weller, J., 2004, ApJ, 604, L5
Metcalf, R. B., 2002, ApJ, 580, 696
Metcalf, R. B., Moustakas, L.A., Bunker, A.J., & Parry, I.R., 2004, ApJ, 607, 43
Muxlow, T. W. B., et al., 1999, NewAR, 43, 623
Muxlow, T. W. B., et al., 2005, MNRAS, 358, 1159
Myers, S. T., et al., 2003, MNRAS, 341, 1
Refsdal, S., 1964, MNRAS, 128, 295
Richards, E. A., 1999, ApJ, 526, L73
Williams, S. P., 2001, AJ, 122, 585
Smail, I., Ivison, R. J., Blain, A. W., & Kneib, J.-P., 2002, MNRAS, 331, 495
Snellen, I. & Best, P. N., 2001, MNRAS, 328, 897
Szokoly, G. P., et al., 2004, ApJS, 155, 271
Treu, T. & Koopmans, L. V. E., 2004, ApJ, 611, 739
Treu, T., et al., 2006, ApJ, 640, 662
Turner, E. L., Ostriker, J. P., & Gott, J. R., 1984, ApJ, 284, 1
Walsh, D., Carswell, R., & Weymann, R., 1979, Nature, 279, 381
Warren, S. J. & Dye, S., 2003, ApJ, 590, 673
Williams, L. L. R. & Saha, P., 2000, AJ, 119, 439
Willis, J. P., et al., 2006, MNRAS, 369, 1521
Winn, J. N., Rusin, D., & Kochanek, C. S., 2004, Nature, 427, 613
Wucknitz, O., Biggs, A. D., & Browne, I. W. A., 2004, MNRAS, 349, 14
York, T., et al., 2005, MNRAS, 357, 124
York, D., et al., 2000, AJ, 120, 1579