Abstract. Most surveys for multiply-imaged gravitational lenses, outside of rich galaxy clusters, are based on sifting through large samples of distant sources to identify the rare examples of lensing. An alternative strategy, based on the selection of optimal lines-of-sight, offers a number of significant advantages. Utilising the multiplex capability of wide-area multifibre spectroscopy, together with tunable Fabry-Perot imaging, it is now possible to undertake such investigations. Progress in compiling a sample of high-redshift star-forming galaxies, gravitationally lensed by massive early-type galaxies at intermediate redshift, $z \sim 0.4$, is described.

1. Introduction

The potential of gravitational lenses to increase our knowledge concerning the amount and nature of dark matter, constrain key cosmological parameters and offer uniquely detailed views of faint distant objects is well known (Blandford and Narayan 1992). The development over the last decade of the field of “weak lensing” in which statistical studies of many sources, only slightly perturbed by the effects of lensing, are made has produced important new results concerning the distribution of mass in galaxy clusters and very large scale structures.
However, the assembly of examples of systems multiply imaged by individual galaxies has proved extremely hard.

Searches for individual examples of strong lensing have relied on the examination of a sample of objects, such as quasars or flat–spectrum radio–sources, where a large fraction of the sample lie at high redshift. Thus, towards each object there is a significant path–length over which an intervening deflector may interpose itself close to the line–of–sight. The lens search proceeds through the identification of sources whose morphology, multiple images or extended arcs for example, is consistent with the effects of lensing. Further imaging, at different wavelengths, and spectroscopy is then necessary to establish the source as a bona–fide lens and to obtain redshifts for the source and the deflecting galaxy. In practice, obtaining the redshifts is very difficult, particularly for radio–selected objects, and in the compilation of Kochanek et al (1999: \url{http://cfa-www.harvard.edu/castles}) only 19 of the 45 lensed systems possess both deflector and source redshifts.

An alternative search strategy is to examine optimal lines–of–sight by identifying a population of very effective deflectors, where it is known that any source lying behind the deflector will be significantly lensed, and then to examine the spectra of the deflectors for evidence of lensed background sources. Miralda–Escudé and Lehár (1992) pointed out that provided the surface density of faint, small, galaxies at high redshift is large, significant numbers of galaxy–galaxy lenses should exist. Subsequent observational developments have shown that the surface density of high–redshift, star–forming objects is indeed large (e.g., Steidel et al. 1996, Hu, Cowie and McMahon 1998). Provided a suitable sample of deflectors can be identified the optimal line–of–sight search strategy offers significant advantages, including i) high efficiency, the probability a lens will be seen along a line–of–sight is significant, ii) the deflector and source redshifts may be readily acquired, allowing the full lensing geometry to be defined, iii) the small, but extended, star–forming objects lead to resolved gravitational lenses, not unlike the radio–rings arising from morphologically extended radio emission, which provide much greater constraints on the deflector masses than the more familiar two– or four–image lenses of unresolved quasars.

Using APM measures of United Kingdom Schmidt Telescope \(B_JRI\) plates it is possible to identify the ideal population of deflectors – massive, bulge–dominated, galaxies at redshift \(z \sim 0.4\), essentially half–way between ourselves and any high redshift source. Specifically, locating the population of relatively bright, \(m_R \leq 20\), red, \(B_J – R \geq 2.2\), galaxies with redshifts \(0.25 \leq z \leq 0.6\) is straightforward (Warren et al. 1996). The galaxy population has a surface density of \(\sim 50\) deg\(^{-2}\) and associated with each galaxy there is an area of sky, \(\sim 1\) arcsec\(^2\), in which any distant source will be multiply imaged, with an associated increase in brightness of a factor \(\geq 10\). These early–type galaxies represent essentially optimal lines–of–sight to search for examples of strong lensing.

The presence of a lens is revealed by the detection of an anomalous emission line in the spectrum of one of the target distant early-type galaxies, so obtaining spectra of a large sample of the deflector galaxies represents the first stage in the lens survey. Examination of intermediate–resolution optical spectra of an initial sample of 160 colour–selected early–type galaxies revealed the presence of an emission line at 5589\(\AA\) in a galaxy with redshift \(z = 0.485\). Follow–up
spectroscopy (Warren et al. 1998) and imaging (Warren et al. 1999) have confirmed the B0047–2808 system as an optical Einstein ring with the source, a star–forming galaxy at $z = 3.595$, the first confirmed example of a normal galaxy lensing another normal galaxy and a demonstration of the viability of the optimal line–of–sight survey strategy.

2. The Spectroscopic Survey

With an efficient method for acquiring spectra along many optimal lines–of–sight there is the prospect of obtaining a large sample, 10–20 objects, of spatially resolved gravitationally lensed systems. The low–surface density of the galaxies on the sky means the Anglo–Australian Telescope’s 2dF multifibre instrument, with a 3 deg$^2$ field, is ideally suited to the initial spectroscopy. Total exposure times of $\sim 8000$ s produce galaxy spectra for which the completeness of redshift measurement is 95% and in which anomalous emission lines of fluxes $\sim 5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ may be reliably detected i.e. fluxes comparable to those seen in high–redshift galaxy samples (e.g., Hu et al. 1998) can be reached. The unlensed fluxes are a factor $\sim 10$ fainter. Example spectra of galaxies from 2dF are shown in Figure 1. Two fields, producing $\sim 250$ galaxy spectra, can be observed per night.

Figure 2 shows the number–redshift distribution for all 485 galaxies observed in a two–night 2dF run. The median redshift is $z_{med} = 0.391$ and the sample consists of luminous, relatively high–redshift objects that barely feature in wide–angle, bright surveys (e.g. Colless 1998) or narrow–angle, deep surveys (e.g. Cohen et al. 1999; Figure 1b).
Figure 2. Number-redshift histogram for the 485 galaxies observed over two-nights at the AAT in 1998 September using the 2dF instrument.

3. Tunable Filter Imaging

Follow-up of an emission line detection in the discovery spectra would, until recently, have involved the acquisition of a second slit-spectrum to confirm the line. Subsequent narrow-band (∼30Å) imaging, at an essentially random wavelength, to investigate the morphology of the emission, necessitates the fabrication of a custom filter, which is both time consuming and costly. However, the availability of tunable Fabry-Perot imaging, specifically the Taurus Tunable Filter (TTF) instruments at the AAT and William Herschel Telescope, enable monochromatic images to be obtained for emission lines at wavelengths covering virtually the whole optical spectrum. A resolving power of up to ∼1000 allows the signal-to-noise ratio to be maximised by using narrow bandpasses, ∼10Å, well matched to the narrow emission features. Observing efficiency has been further improved with the recently commissioned broad-narrow shuffle mode, that allows a comparison broadband image to be obtained during the observation with only a small increase in the total exposure time. The sensitivity of the TTF system is such that confirmation of emission at the target wavelength can be achieved as quickly as with a slit spectrum. Indeed, the imaging is superior in that even with a relatively wide slit it is possible to exclude prominent emission components, which may lie anywhere on a ring up to 3 arcsec in diameter. Thus, spectroscopic follow-up may be dispensed with entirely and confirmation and narrow-band imaging achieved using the TTF.

Figure 3 illustrates the effectiveness of the TTF. The image is a composite of a broad-band $J$ exposure, from UKIRT, and an 1800s TTF exposure from the AAT. The candidate lens system is the double image seen at top-centre. The lower of the two components is the core of a galaxy, redshift $z = 0.519$, magnitude $m_R = 18.8$, coordinates $00^h 42^m 49.5^s -27^\circ 52' 17''$ (Equinox B1950.0). The spectrum is that of a normal early-type galaxy with the addition of a weak emission line at 5800Å. The upper of the components visible in Figure 3, sep-
Figure 3. Greyscale image of a 37 × 37 arcsec region containing the gravitational lens candidate B0042–2752 – the double image visible towards the top. North is up and East to the left.

arated by ∼ 2 arcsec from the centre of the galaxy, is visible only in the TTF exposure, which covered a ∼ 10Å bandpass centred at 5800Å. The detection of the component in the narrow–band image is unambiguous. Combining the image with two additional TTF exposures produces an image where some evidence of extended emission may be present but much deeper TTF observations are required to confirm any lower surface brightness extended structure or the presence of fainter lensed images.

The most probable identification of the emission is with Lyα 1216Å from a star–forming galaxy at redshift z = 3.77. With this identification B0042–2752 is a very similar system to B0047–2808, the first lens discovered in the survey. The deflector and source in B0042–2752 are at slightly higher redshifts and the observed emission line flux is a factor ∼ 5 lower, $f_\lambda \sim 1 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$. However, without confirmation of the source redshift, via identification of a second emission line in the infrared ([O III] 5007 would appear at 2.388 µ), or evidence for a morphology unambiguously that of a lens, B0042–2752 remains only a lens candidate. Alternative explanations are certainly not particularly attractive. If the emission at 5800Å is [O II] 3727 the velocity of the line–producing region relative to the galaxy is ∼ +11,000 km s$^{-1}$, ruling out any plausible physical association, even within a rich cluster of galaxies. Chance projection of a faint HII galaxy is possible, with $z_{em} = 0.556$ if the line is [O II] 3727, or $z_{em} = 0.158$ if the line is [O III] 5007. There is no indication of any continuum emission from broad–band imaging data, or the TTF off–band images, and the putative HII galaxy must possess a large line equivalent–width, with an intrinsically faint continuum. The object would, for example, lie in the sparsely populated upper portion of Figure 2 of Hogg et al. (1998).
The survey spectroscopic observations are sensitive to the presence of an emission line object in an area of $\sim 5$ arcsec$^2$ per galaxy, giving a surveyed area of $\sim 800$ arcsec$^2$ for the sample of 160 galaxies. Assuming, rather optimistically, that [O II] or [O III] emission from a star–forming galaxy would be detected in our spectra over the redshift range $0.1 \leq z \leq 0.8$ gives a total volume of $\sim 22 h^{-3} \text{Mpc}^3$ ($H_0 = 100 h \text{ km s}^{-1}, q_0 = 0.5, \Lambda = 0$) in which an HII galaxy may be found. Therefore, the space density of HII galaxies, with properties consistent with the constraints outlined above, must be $\gtrsim 0.01 h^3 \text{Mpc}^{-3}$ for the a priori probability of finding such an object to be significant. Such a space density is substantially above that found in emission–line surveys to comparable line fluxes (e.g., Thompson, Djorgovski and Trauger 1995).

Further observations will determine whether B0042–2752 is the second lensed high–redshift galaxy to be identified in the survey. Irrespective of the outcome the combination of the AAT 2dF instrument and TTF imaging offers the prospect of compiling a well–defined sample of resolved gravitational lenses with a homogeneous deflector population. Investigation of the sample will provide unique information on the mass–to–light ratio in field elliptical galaxies and the morphology, emission line properties and masses of high–redshift star–forming objects currently too faint to be studied by any other means.

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