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A SPECTROSCOPIC SURVEY FOR STRONG GALAXY–GALAXY LENSES

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We present a spectroscopic survey for strong galaxy–galaxy lenses. Exploiting optimal sight–lines to massive, bulge–dominated galaxies at redshifts $z \sim 0.4$ with wide–field, multifibre spectroscopy, we anticipate the detection of 10–20 lensed Lyman–α emitting galaxies at redshifts $z \gtrsim 3$ from a sample of 2000 deflectors. Initial spectroscopic observations are described and the prospects for constraining the emission–line luminosity function of the Lyman–α emitting population are outlined.

1 Introduction

Despite considerable advances over the past two decades in the study of individual gravitational lens systems, the assembly of large, uniformly–selected samples 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: *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 [1] 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[2,3]. 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[4]. The galaxy population has a surface density of $\sim 50\,\mathrm{deg}^{-2}$ and associated with each galaxy there is an area of sky, $\sim 1\,\mathrm{arcsec}^2$, in which any distant source will be multiply imaged, with an associated increase in brightness of a factor $\gtrsim$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 5589Å in a galaxy with redshift $z = 0.485$. Follow–up spectroscopy[5] and imaging[6] 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 Spectroscopic observations and candidate selection

With an efficient method for acquiring spectra along many optimal lines–of–sight there is the prospect of obtaining a large sample, $\sim$ 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 $3\,\mathrm{deg}^2$ field, is ideally suited to the initial spectroscopy. In September 1998 we obtained spectra of $\sim$ 500 early–type galaxies over two nights using the 2dF facility. Total exposure times of $\sim 8000\,\mathrm{s}$ 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 $\mathrm{s}^{-1}\mathrm{cm}^{-2}$ may be reliably detected i.e. fluxes comparable to those seen in high–redshift galaxy samples[3] can be reached. The unlensed fluxes are a factor $\sim$ 10 fainter. Example spectra of galaxies from 2dF are shown in Figure 1.

Candidate gravitational lenses are identified by applying an automated emission–line detection algorithm to the early–type galaxy spectra. The identification software matches a template early–type galaxy SED (derived from the mean of the sample) to each early–type galaxy spectrum via a wavelength–dependent transformation. The transformation is derived from the median smoothed ratio of the two spectra. Subtraction of the transformed template from the individual galaxy spectra removes large scale ($\lambda \gtrsim 100$Å) continuum variations while retaining small–scale differences such as narrow ($\lambda < 50$Å) emission lines. Such emission features may then be identified using standard matched filter techniques[7]. The effectiveness of the emission–line detection routine is demonstrated by the identification of [OII]3727 emission in 20% of the early–type galaxy sample (104/485 galaxies). Four anomalous emission lines, consistent with gravitationally–lensed Lyman–α emission, have also been identified utilising this technique. Candidate lenses must be confirmed via a second observation of the emission–line prior to follow–up observations to obtain the source redshift, via observation of a second emission feature[5], and the morphology of the lensed emission[6].

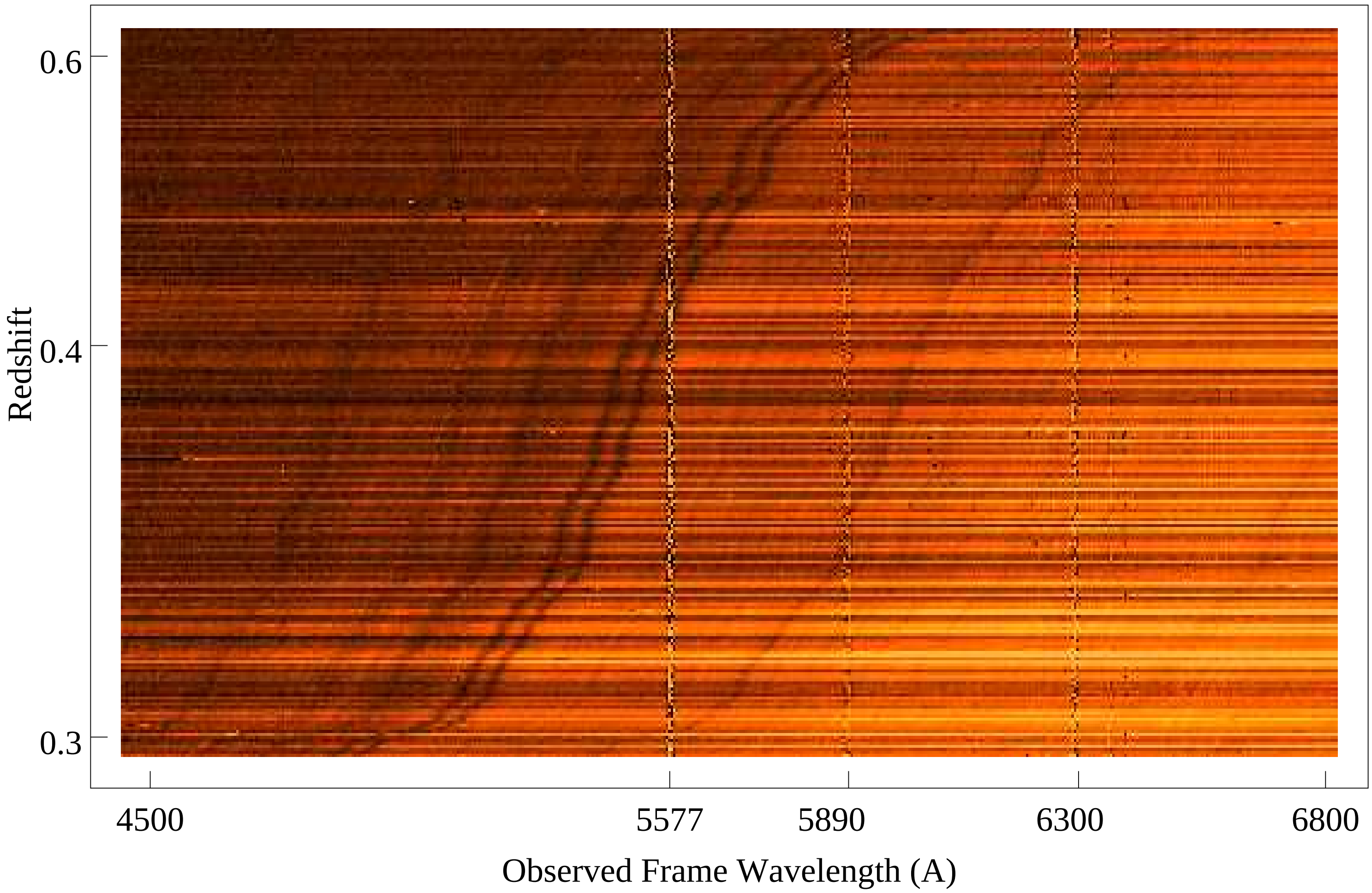

Figure 1: Observed–frame spectra of 485 distant early–type galaxies, redshifts $0.3 \leq z \leq 0.6$, arranged by increasing redshift. A number of prominent night–sky features are visible as vertical lines while features present in the galaxies, such as Calcium H+K and the G–band move to longer wavelength with increasing redshift.

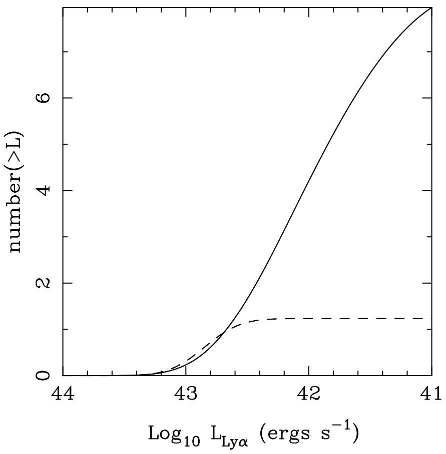

Figure 2: Cumulative number distribution of gravitational lenses versus intrinsic Lyman–α emission luminosity identified within a projected sample of 2000 early–type galaxy spectra. Two model luminosity functions are considered; a Schechter function described by the parameters $L^* = 1 \times 10^{43}$ h^2 ergs s^{-1}, $\alpha = -1.6$, $\phi^* = 1 \times 10^{-3}$ h^3 Mpc^{-3} $(\log L)^{-1}$ (solid line) and a Gaussian function of equal L^* and ϕ^* with a width parameter $\sigma = 0.25 \log L$ (dashed line). The model was realised using a cosmological model specified by the parameters $\Omega = 0.3$, $\Lambda = 0.7$.

3 Constraining the luminosity function of high-redshift Lyman–α emitting galaxies using gravitational lensing

A spectroscopic survey for gravitational lenses, employing a quantitative detection algorithm and a well–defined sample of deflectors, permits a unique experiment to probe the luminosity function of high-redshift Lyman–α emitting galaxies – to fainter flux limits than currently achievable.

The line–of–sight to each deflector may be considered as magnifying a region of the distant source plane. The total source plane magnification as a function of deflector–source impact parameter is calculated for the deflector sample using a ray–tracing algorithm, incorporating variations in deflector (e.g. central velocity dispersion and redshift) and source (e.g. surface brightness morphology and redshift) properties. To reproduce the effects of atmospheric seeing, lensed images are convolved with a Gaussian kernel of FWHM = $1''\!.5$, while to reproduce the 2dF observations, the lens model considers the total flux received from a $1''$ radius optical fibre centred on each deflector.

The sample of deflectors presents a magnified view of the distant source population, characterised by a Lyman–α emission–line luminosity function. The probability of detecting a lensed emission line of given observed frame properties (i.e. flux, wavelength and FWHM) drawn from this population is calculated via a 'monte–carlo' procedure whereby a grid of simulated emission lines of specified properties are superimposed onto observed early–type spectra, to be processed using the automated line detection algorithm.

Combining the magnification profiles generated by the deflector sample with an assumed Lyman–α emission–line luminosity function describing the source population, produces the number distribution of detected lenses as a function of Lyman–α luminosity (Figure 2). The number–luminosity diagram of identified lenses generated by a spectroscopic sample of 2000 early–type galaxies, considering two competing luminosity function models, clearly demonstrates the potential of the survey technique to probe the characteristics of the faint Lyman–α emitting galaxy population.

4 Conclusions

We have presented the strategy and initial observations for a spectroscopic survey for strong galaxy–galaxy lenses. The optimal line–of–sight strategy offers a powerful probe of the faint, Lyman–α emitting, galaxy population and of the dark matter profiles of massive early–type galaxies at cosmological distances. Application of the deflector–based survey strategy to other galaxy samples is underway [8] and we hope to compile a much larger sample of systems using additional 2dF observations.

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