Possible arcmin-separation gravitational lensed quasi-stellar objects in the 2dF QSO survey

L. Miller,[1]*† A. M. Lopes,[1] R. J. Smith,[2] S. M. Croom,[3] B. J. Boyle,[3] T. Shanks[4] and P. Outram[4]

[1]*Department of Physics, Oxford University, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH*
[2]*Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead CH41 1LD*
[3]*Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia*
[4]*Department of Physics, Durham University, Science Laboratories, South Road, Durham DH1 3LE*

ABSTRACT

We report the possible discovery of multiple gravitationally lensed images of quasi-stellar objects (QSOs) with angular separations on arcmin scales. The QSOs were selected from the completed 2dF QSO Survey as having redshifts and optical colours which are statistically consistent. In this paper we present higher-quality optical spectra of the candidates and discuss the likelihood that they genuinely are systems lensed by massive clusters of galaxies. From a comparison of the spectra it appears that up to six pairs of QSOs may be lensed multiple images, although the true number may be less than that and further observations should be undertaken to amass more evidence and to detect the lensing clusters. Two of the candidates may be associated with low-redshift clusters of galaxies.

Key words: gravitational lensing – quasars: general.

1 INTRODUCTION

Strong gravitational lensing of background objects by massive clusters of galaxies is expected to produce multiple images with wide separations, >30 arcsec, and multiple images of background lensed galaxies have long been known with radii of giant arc systems up to 70 arcsec (e.g. Kneib et al. 1996; Sahu et al. 1998; Smail et al. 1995). However, despite a number of searches, primarily in large-area radio surveys (e.g. Maoz & Rix 1993; Maoz et al. 1997; Ofek et al. 2001; Ofek et al. 2002; Phillips, Browne & Wilkinson 2001a; Phillips et al. 2001b), widely separated multiple images of quasi-stellar objects (QSOs) have not yet been found. This is attributable to the low probability of strong lensing along any given line of sight coupled with the relatively low numbers of known QSOs. The widest separation QSO lensed systems have separations ∼7 arcsec (Kochanek et al. 2002). Other wide-separation multiple QSO systems found to date are more likely to be 'binary QSOs' (that is, a pair of active black holes cohabiting the same parent host galaxy) rather than multiple images of the same QSO (Kochanek, Falco & Muñoz 1999).

We have searched a catalogue of 22 163 QSOs that comprises the recently completed 2dF QSO survey ('the 2QZ survey') for candidate wide-separation lensed QSO systems and have obtained higher signal-to-noise ratio spectra in an attempt to eliminate obvious non-lensed systems and to identify systems that are likely to be genuine lensed systems. After an incomplete survey of the most likely candidates, there remain six systems which, with varying degrees of confidence, are likely to be lensed.

2 THE SELECTION OF CANDIDATE LENSED SYSTEMS FROM THE 2QZ SURVEY

The 2QZ survey covers 740 deg^2 in two strips of sky, one centred on the South Galactic Pole (SGP) region and the other on the celestial equator in the region of the North Galactic Pole (NGP). The survey photometry is described by Smith et al. (2002) and the initial release of the first 10,000 QSOs is described by Croom et al. (2001a). In constructing the 2QZ survey, candidate QSOs were first selected from u, b_J and r photographic photometry of morphologically stellar objects, and objects whose colours lay bluewards of the main stellar locus were selected for low resolution spectroscopy at the two-degree field (2dF) facility at the Anglo-Australian Telescope.

The initial spectra obtained were of sufficient quality that reliable identifications of QSOs and measurements of their redshifts could be made, with an rms error in redshift measurement of typically 0.0035 (Croom et al. 2001a), although it should be noted that the redshift error for an individual object depends on its brightness and emission-line equivalent widths as well as observing conditions. The absolute accuracy of the photometry in each band is estimated as ∼0.17 mag at the faint survey limit (Smith et al. 2002). The relative photometric accuracy for objects measured close together

*E-mail: lam@astro.ox.ac.uk
†http://www-astro.physics.ox.ac.uk/~lam

on the same photographic plate is better than this, however: Mitchell (1989) found that, for objects more than 2 mag brighter than the completeness limit of the photographic plate, relative photometry accurate to ~0.05 mag was typical, with that value rising rapidly to values > 0.1 mag as the plate limit is approached.

The resulting catalogue of photographic photometry and spectroscopically confirmed QSOs was then searched for pairs or multiple systems whose colours were consistent given the large photometric uncertainties and whose redshifts were consistent given the typical redshift uncertainty. To determine the colour consistency, it was assumed that two QSOs, if lensed, should have the same u, b_J and r magnitudes apart from a magnitude offset arising from differential magnification of the images in a lensed system, and thus assuming negligible effects due to variations in QSO colours with time (see Section 4). The statistic used as the measure of colour consistency was

$$\sigma_{UBR}^2 = \sum_{i=1}^{3} (\Delta m_i - \overline{\Delta m_i})^2,$$

where Δm_i is the difference in apparent magnitude of the two QSOs measured in waveband i and $\overline{\Delta m_i}$ is the average magnitude difference for that QSO pair. Redshift consistency was measured by the difference, $|\Delta z|_{2QZ}$, in 2QZ catalogue redshift of two QSOs. Candidate multiple systems were initially selected if they satisfied the criteria $\sigma_{UBR} < 0.2$, $|\Delta z|_{2QZ} < 0.01$ and angular separation $\Delta\theta < 6$ arcmin. The colour criterion is close to the expected scatter in this statistic, given the photometric errors at the survey limit, and hence we expect the initial colour selection to select only ~50 per cent of the lensed systems. The redshift criterion is a factor of 2 larger than the expected scatter in $|\Delta z|_{2QZ}$ and this criteria should allow the majority of lensed systems to be selected. The stringent colour criterion was chosen in this initial study in order to maximize the probability of finding lensed systems, and hence further observations should be carried out to establish the true completeness of the selected sample.

A further check was made on the consistency of their radio properties by searching for detections in the NVSS (Condon et al. 1998). One candidate pair with clearly discrepant radio detections was removed from the sample of candidates. The NVSS properties of two remaining pairs are discussed further in Section 3.

Candidates with $18.25 < b_J < 20.85$ were selected from 12 307 QSOs in the SGP region and from 9856 QSOs in the NGP region of the 2QZ survey, and 38 pairs of QSOs in total met these criteria. Of the QSOs with confirmed redshifts, there were no candidate systems selected with more than two members, although some of the pairs do have additional *ubr*-selected companions for which 2QZ spectroscopic observations either were not carried out or did not lead to a positive identification.

Our expectation is that the majority of the selected pairs will not prove to be lensed systems. Test samples were also constructed in an attempt to assess the possible contamination. First, QSOs pairs that are more widely separated, but still within one degree of each other and measured on the same photographic plates, were selected with $|\Delta z|_{2QZ} < 0.02$ and the distribution of σ_{UBR} was compared with the σ_{UBR} distribution of the candidate pairs. No statistically significant difference was found, although this is probably a reflection of the large errors in σ_{UBR} arising from the large photographic photometry errors. A second test sample comprising QSO pairs with $\sigma_{UBR} > 0.5$ and $|\Delta z|_{2QZ} < 0.01$ was selected and the distribution of angular separations, normalized by the total number of pairs selected with $\Delta\theta < 10$ arcmin, was compared with the candidate lens sample selected to have $\sigma_{UBR} < 0.2$. This time there was an excess of

pairs on arcmin scales in the sample of candidate lensed systems consistent with a minority of the pairs being lensed systems, but because of the small numbers of pairs selected the test was not statistically significant. Hence at this stage there is no evidence either for or against the hypothesis that the selected sample contains a subset of lensed systems. Further evidence needs to be collected on all members of the sample in order to establish its completeness and contamination.

A key part of that evidence is the follow-up spectroscopy described in the next section. Because of limitations of observing time and observing conditions, only a subset of the candidates have had such observations, and only that subset is described in the remainder of this paper. For prioritizing the observations, the pairs were ranked in $|\Delta z|$ and also in σ_{UBR}: a composite rank was produced by multiplying these ranks and the top candidates in each region were observed. In the SGP region, 10 pairs were observed, but the spectroscopic follow-up is particularly sparse in the NGP region, where only for one pair have spectra been obtained of sufficient quality to allow some assessment of whether or not it may be lensed. At this stage the sample reported here cannot be regarded as either being complete or free from contamination by non-lensed pairs of QSOs. We postpone any discussion of the completeness of the sample to later work. We anticipate that in future the candidate QSO pairs in the NGP region will also have the benefit of more accurate, five-band, colours from the Sloan Digital Sky Survey (Stoughton et al. 2002), which should lead both to samples of candidates with lower contamination and with better quantified photometric uncertainties.

In the following sections each pair is designated by the IAU naming convention applied to the mean position of the pair, in the FK5 (equinox J2000) coordinate system. Table 1 summarizes the observed sample.

3 FURTHER OPTICAL SPECTROSCOPY

Spectra were obtained of the candidate pairs at the William Herschel 4.2-m telescope (WHT) on 2002 February 5–6 and at the Anglo-Australian 3.9-m telescope (AAT) on 2002 September 6–10. At the WHT, the ISIS long-slit spectrograph with 300B grating and EEV detector was used with on-chip binning to provide spectra from the blue arm with 1.7 Å pixel^{-1} dispersion. Observing conditions were poor, with seeing of about *2* arcsec for the spectra reported here, resulting in spectra with resolution about 8 Å. Data were also obtained with the ISIS red arm but were of insufficient quality to be useful. Observations at the AAT were carried out in generally good conditions with seeing in the range 0.7–1.6 arcsec. The 300B grating on the RGO long-slit spectrograph with EEV detector provided a dispersion of 1.6 Å pixel^{-1} and resolution of typically 6 Å (depending on the choice of slit width, which was varied according to the seeing at the time).

The typical integration time on each QSO varied between one and four hours depending on observing conditions and brightness of the QSO. In most cases the QSOs in each pair were sufficiently far apart that they could not be observed simultaneously. Instead, integrations on each QSO were split into intervals of 30 min duration, and no more than three integrations were carried out sequentially on one QSO without then observing the other member of the pair. By this process we could be sure that the spectra were taken under sufficiently similar conditions that any differences between them are likely to be genuine. For those QSOs observed in this way the slit position angle was arranged to be at the parallactic angle. In two cases, J1435+0008 and J0135−3021, the pair members were close together and were observed simultaneously with the slit oriented at

the appropriate angle. In the case of J1435+0008 the pair could be observed at hour angles such that the slit position angle was within 20° of the parallactic angle. In the case of J0135−3021 this was not possible, but the pair could be observed within 30° of the zenith where the effects of differential refraction should be small.

Spectra of all the pairs observed are presented in Fig. 1. In order to improve the signal-to-noise ratio per pixel the spectra have been smoothed with a top-hat function to a resolution specified in the figure caption for each pair. Each panel shows spectra of the two members of each pair superimposed. The spectra have been scaled by the total value of the observed (uncalibrated) count rate so that they may be compared. Each panel also shows the difference between the scaled spectra, for comparison. The spectra have been bias-frame subtracted and flat-fielded in order to remove instrumental features from the spectra, but have not had any flux calibration applied, in order to facilitate evaluation of any differences. The noise in the spectra is dominated by photon noise from the sky background, and the noise in each wavelength pixel is more uniform with wavelength in uncalibrated spectra. Absorption features arising from the terrestrial atmosphere remain in the spectra, most prominently at λ 7600 Å, and should be ignored when comparing spectra. The ratios of the total count rate between the spectra are given in Table 2.

One expectation of the 'lensed QSO' hypothesis is that the two images should have the same redshift. As the pairs were selected to have 2QZ survey redshift differences $|\Delta z|_{2QZ} < 0.01$ we would, in the absence of QSO clustering, expect the distribution of WHT or AAT redshift differences to be uniformly distributed within that range. QSO clustering has a scalelength in redshift of about 0.003 at $z \sim 1.5$ (Croom et al. 2001b), and if the QSOs in each pair are individual objects we would expect them also to have redshift differences arising from their peculiar velocities, so the 'separate QSOs' hypothesis predicts that even in the presence of QSO clustering there should still be a broad distribution of redshift differences when measured from the WHT or AAT spectra.

To test this, the redshift differences between each pair of WHT or AAT spectra have been measured by cross-correlation, after subtracting the continuum from the uncalibrated spectra and avoiding the atmospheric absorption feature at $\lambda 7600$ Å. Uncertainties in the redshift differences have been estimated assuming the noise in the spectra is dominated by uncorrelated photon shot noise in each pixel. A Monte Carlo method was adopted in which Gaussian noise of the same amplitude as the noise in each spectrum was added to smoothed versions of each spectrum to create a number of synthetic spectra with the same spectral features and noise properties as the actual data. The synthetic spectra were then cross-correlated with each other and the quoted uncertainty in the redshift difference is the rms of the values derived from the synthetic spectra. These uncertainties are lower limits to the true uncertainty as they contain no allowance for systematic differences and noise that may be correlated between pixels. However, the spread in values of the measured redshift differences is consistent with these uncertainty estimates, indicating that photon shot noise is the dominant source of uncertainty. Remarkably, we find six of the pairs to have velocity differences less than 200 km s^{-1} (Table 2 and Fig. 2). This is a strong indication that a number of these pairs are lensed systems. All separations for these pairs are sufficiently large that, if they were two different QSOs, the linear separations would be greater than 1 Mpc and they must occupy separate host galaxies. QSO clustering would cause a peak in the redshift distribution at $|\Delta z| = 0$, broadened not only by the measurement error but also by the relative peculiar velocities of the QSO host galaxies. Peculiar velocities at high redshift are expected to be lower than in low-redshift galaxy

surveys, but simulations still predict pairwise velocity dispersions σ ~ 350 km s^{-1} (Zhao, Jing & Börner 2002), significantly larger than would be inferred from Fig. 2.

Although the redshift difference is a quantitative measure of similarity between the spectra, we should also look for other differences in the spectra. We now give a brief evaluation of the comparison of the spectra of each pair. The discussion is ordered by an approximate degree of confidence in the likelihood that the pair is a lensed QSO. This evaluation is based not only on redshift difference but also on similarity of continuum shapes, emission line equivalent widths, line ratios, velocity widths and profiles. This comparison is necessarily somewhat subjective. It is never possible to prove that a pair of spectra are multiple images of the same lensed QSO, and in this case we have to rely on building up a body of evidence which can then be interpreted as either supporting the lensed hypothesis or providing evidence against it. The spectra we have obtained only cover the range of accessible optical wavelengths and vary widely in their signal-to-noise ratio. The spectra of a QSO pair viewed with high signal-to-noise ratio may appear to be discrepant, such as J2250−3105, whereas such a discrepancy may not have been apparent in lower signal-to-noise ratio spectra. The only reliable solution to this effect is to obtain higher quality spectra and other evidence for those pairs with poor signal-to-noise ratios. With these factors in mind, any evaluation at this stage cannot be regarded as conclusive, but none the less should help us to identify those QSOs that are most likely to be lensed, which can then be the subject of further observations to amass more evidence. The candidates we have observed were selected a priori to have similar optical colours (albeit with a large uncertainty) and redshifts, so we should not be too surprised to find that almost all of the observed pairs do indeed have very similar overall continuum shapes in the observations presented here. Instead, we must appeal to the wide range of detail in QSO spectra which we would not expect to match when comparing the spectra of independent QSOs.

3.1 J1435+0008

This pair was the only one presented here that was observed at the WHT. Other pairs were attempted but only inadequate spectra were obtained. Observing conditions were poor, with poor atmospheric transparency and poor seeing. The ISIS red-arm spectra contain too little signal, and we show here a comparison of the blue-arm spectra only. The dichroic between the red and blue arms of ISIS causes a sharp fall in response at $\lambda > 5000$ Å, with some oscillations in that response in this wavelength range. This is a good lensed QSO candidate, with a small redshift difference and an unusual ratio of Lyα and N v which is common to both spectra.

This QSO pair also appears in the Sloan Digital Sky Survey (SDSS) Early Data Release (Stoughton et al. 2002). Table 3 gives the SDSS photometry for this pair, together with the differences in apparent magnitudes and the associated error. It can be seen that the colours of the two QSOs are consistent with being the same to substantially higher accuracy than was possible with the 2QZ photographic photometry, although there does seem to be some some evidence for a systematic difference in colour with waveband. This may be taken as evidence against the system being lensed, or it may be accounted for either by spectral variability or by differential extinction between the light paths.

We also note the possibility of an elegant test of the lensed-QSO hypothesis: if these are images of the same QSO then, at redshifts near the QSO, the Lyα forest absorption lines should be identical
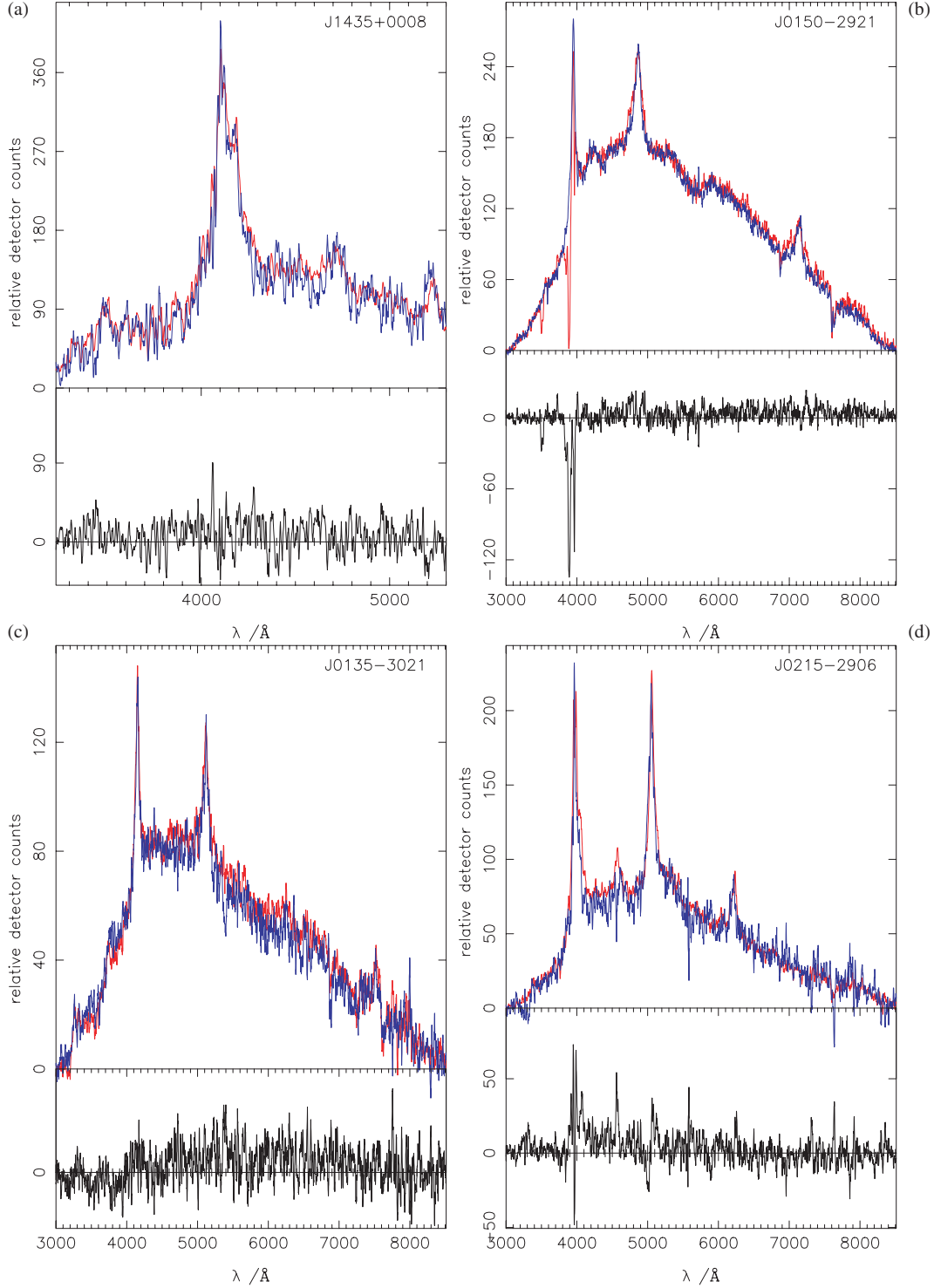
Figure 1. Scaled and superimposed spectra of the candidate lensed systems. The differences between the scaled spectra are also shown. To help distinguish genuine features from noise, all spectra are shown without any relative flux calibration applied. Atmospheric absorption features are still present in the uncalibrated spectra. The flux scale is the number of detector counts observed per pixel in individual exposures (typically of duration 1800 s) of one of the QSOs, with the count values of the second QSO scaled to match. (a) WHT ISIS blue-arm spectra of J1435+0008 smoothed to a resolution of 12 Å. (b) AAT RGO spectrograph spectra of J0150−2921 smoothed to a resolution of 12 Å. (c) AAT RGO spectrograph spectra of J0135−3021 smoothed to a resolution of 15 Å. (d) AAT RGO spectrograph spectra of J0215−2906 smoothed to a resolution of 15 Å. (e) AAT RGO spectrograph spectra of J0223−2949 smoothed to a resolution of 15 Å. (f) AAT RGO spectrograph spectra of J2228−2857 smoothed to a resolution of 15 Å. (g) AAT RGO spectrograph spectra of J2235−2717 smoothed to a resolution of 15 Å. (h) AAT RGO spectrograph spectra of J2210−3204 smoothed to a resolution of 12 Å. (i) AAT RGO spectrograph spectra of J2203−3133 smoothed to a resolution of 12 Å. (j) AAT RGO spectrograph spectra of J2250−3105 smoothed to a resolution of 12 Å. (k) AAT RGO spectrograph spectra of J2329−2957 smoothed to a resolution of 12 Å.
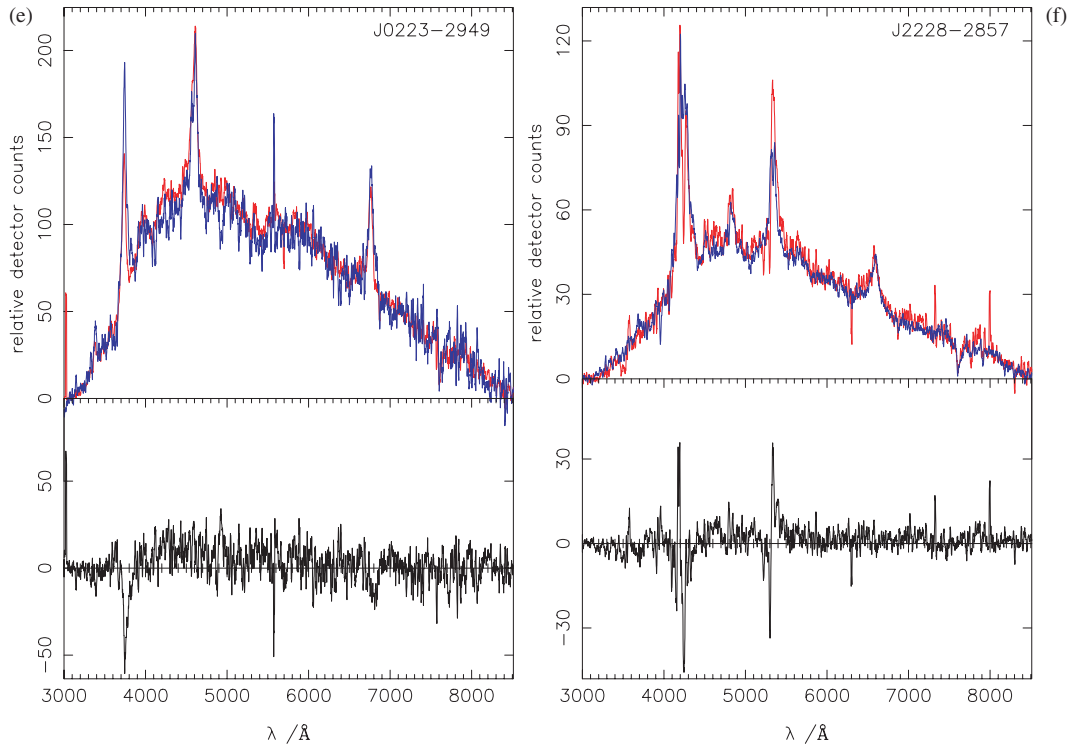
Figure 1 – *continued*

in both spectra. If the pair were not a single lensed QSO, then the QSO separation would be ∼1 Mpc and the Lyα lines would not be expected to be common between the QSOs: sight lines that are separated on such scales when comparing unrelated QSOs show significant differences in their Lyα forest absorption (D'Odorico et al. 1998). Forest lines at redshifts significantly different from the QSO may none the less differ between the images in either hypothesis because the light rays for each image would have diverged to a significant extent. In the case of J1435+0008 the ultraviolet (UV) part of the spectrum is noisy, but none the less it does appear to have possible absorption features in common between the spectra.

3.2 J0150−2921

This is possibly one of the most enigmatic pairs of spectra obtained. The spectra have good signal-to-noise ratio and appear identical in every respect apart from one gross feature: the presence of a broad absorption line system in one of the spectra. For reasons described in Section 4 we do not believe that this should be taken as evidence against the system being a lensed QSO, and because of the otherwise striking similarity between the spectra in these observations with good signal-to-noise ratios we regard this as being one of the systems most likely to be a single-lensed QSO.

This system also has a number of bright galaxies in the vicinity, of which three have had redshifts measured by the 2dF Galaxy Redshift Survey (Colless et al. 2003). The positions and redshifts of the two QSOs and of the three galaxies are shown in Fig. 3. This system is discussed further in Section 5.

We also note here that although neither of the QSOs is detected in the NVSS survey there are four detected sources of radio emission extending over some arcmin approximately symmetrically placed

with respect to the centre of the system, and approximately perpendicular to it. It may be that the radio emission is the substructure of a single extended double radio source associated with one of the galaxies in the field.

3.3 J0135−3021

There are some small differences visible in the UV parts of the spectra of this pair which lead to the somewhat high value of redshift difference given in Table 2. However, these spectra were taken simultaneously, with the slit rotated to the position angle defined by the coordinates of the two QSOs, and the observations presented here were made with the pair within about 30° of the zenith. Slight errors in aligning the slit with the pair could result in a small differential loss of light owing to atmospheric refraction which may contribute to the small differences at λ < 4500 Å. At this stage we still regard this pair as possibly being a lensed QSO, although further observations are needed.

3.4 J0215−2906

This pair has very similar spectra with a redshift difference of zero to high accuracy. There are some residual features present in the difference of the scaled spectra which may argue against the lensed QSO hypothesis but which may simply be observational noise or may reflect low-level emission variations (see also Section 4).

3.5 J0223−2949

This pair has spectra identical within the noise except in the C IV line, where there is a residual difference whose maximum is about
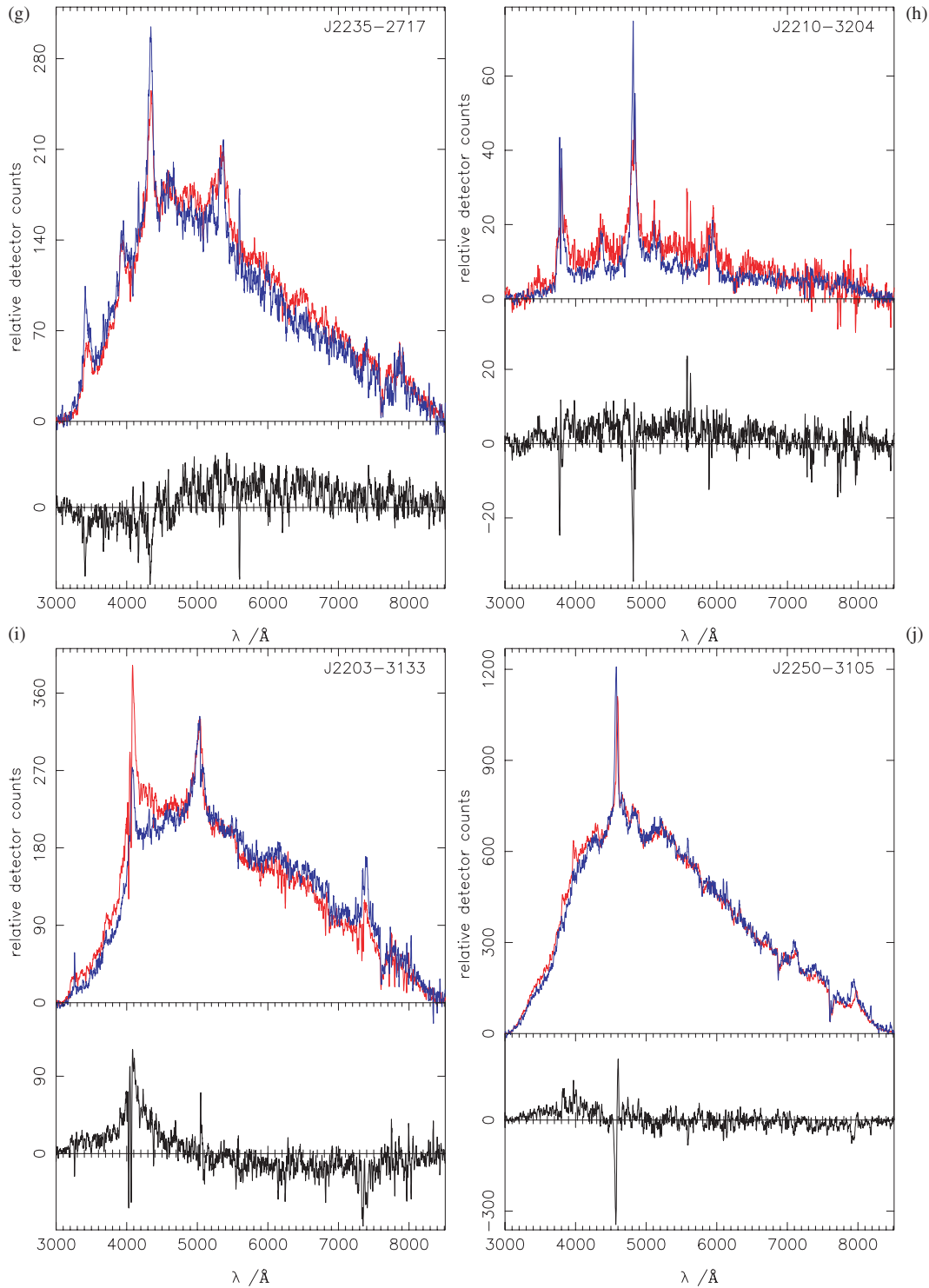
Figure 1 – *continued*

one-third the maximum of the emission-line. The other emission lines and the detailed continuum shape are extremely similar, however, and the redshift difference is consistent with zero at the 2σ level. We regard this as being a possible lensed system that requires further observations.

This system also has a number of bright galaxies in the vicinity (Fig. 3), of which 10 have had redshifts measured by the 2dF Galaxy Redshift Survey (Colless et al. 2003). This system is discussed further in Section 5.

There is a 8.6-mJy NVSS (Condon et al. 1998) radio source 54 arcsec to the north of the northern QSO which is not reproduced near the southern QSO. However, that radio source is coincident with the bright peculiar-shaped galaxy at $z = 0.1147$ and it is unlikely that the radio source is related to the QSO.
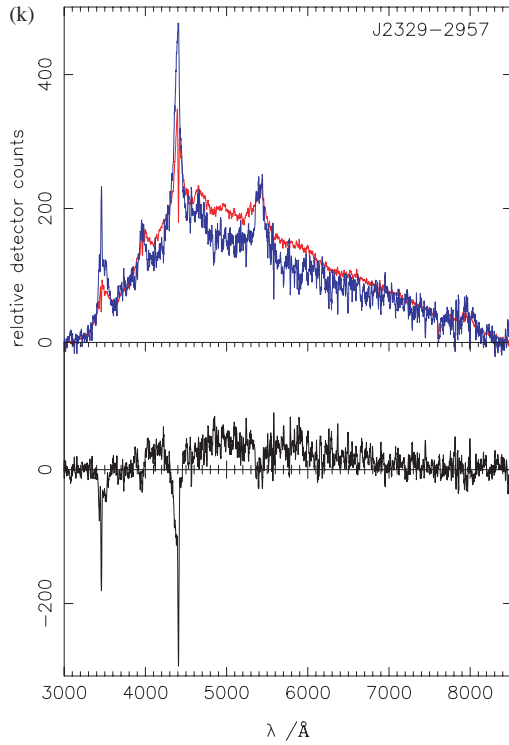
Figure 1 – *continued*

Table 2. Observed redshift differences and flux ratios between the WHT/AAT spectra. The flux ratio is defined as the ratio of the flux from the second listed QSO in Table 1 to the flux from the first listed QSO of each pair.

Pair	Redshift difference	Spectrum flux ratio
J1435+0008	$+0.0004 \pm 0.0016$	0.40
J0150−2921	-0.0010 ± 0.0007	0.72
J0135−3021	$+0.0051 \pm 0.0014$	0.71
J0215−2906	-0.0001 ± 0.0011	0.27
J0223−2949	$+0.0015 \pm 0.0010$	0.32
J2228−2857	$+0.0037 \pm 0.0016$	2.13
J2235−2717	$+0.0000 \pm 0.0019$	0.28
J2210−3204	$+0.0017 \pm 0.0016$	2.00
J2203−3133	-0.0100 ± 0.0015	0.67
J2250−3105	-0.0063 ± 0.0005	0.27
J2329−2957	-0.0089 ± 0.0022	0.19

in emission-line strength and/or QSO intrinsic absorption features (see Section 4).

3.7 J2235−2717

Although the redshift difference for this pair is consistent with being zero, the QSOs do have significantly different emission-line ratios, and we believe this pair is rather unlikely to be a lensed system.

3.8 J2210−3204

This pair exhibits significant differences in line strength between the two spectra and is also unlikely to be a lensed QSO.

3.9 J2203−3133

This pair has quite different continuum shapes and a large redshift difference and is unlikely to be a lensed QSO.

3.10 J2250−3105

This pair has very similar spectra, but there does appear to be a continuum difference between the UV parts of the spectra and a

There are also weaker NVSS detections at the NVSS detection limit, one a 2.8-mJy source 45 arcsec from the southern QSO, the other a 3.5-mJy source 24 arcsec from the northern QSO. Both the reality of these weak radio detections and the possibility of their being associated with the QSOs needs investigation with a higher resolution, higher sensitivity radio map.

3.6 J2228−2857

This pair has very similar spectra but does display some significant differences in the Lyα/Nv and C IV lines. This could be a lensed system if we are prepared to accept the possibility of time variations

Table 1. Observed QSO pairs. The columns are: mean right ascension of the pair (equinox 2000), mean declination, mean 2QZ survey redshift, colour difference statistic, 2QZ redshift difference and angular separation, followed by the right ascension, declination and 2QZ catalogue apparent *b* magnitude for each member of the pair.

$\overline{RA}$ (J2000) (h m s)	$\overline{Dec}$ (J2000) (° ′ ″)	$\overline{z}$	σ_{UBR}	$\|\Delta z\|_{2QZ}$	$\Delta\theta$ (/arcsec)	RA (J2000) (h m s)	Dec. (J2000) (° ′ ″)	b	RA (J2000) (h m s)	Dec. (J2000) (° ′ ″)	b
14 35 07.4	+00 08 53	2.378	0.03	.0086	33	14 35 08.32	+00 08 44.4	20.13	14 35 06.42	+00 09 01.5	20.03
01 50 55.6	−29 21 57	1.556	0.09	.0011	200	01 50 50.10	−29 23 06.3	19.77	01 51 01.10	−29 20 47.5	20.34
01 35 31.2	−30 21 54	1.683	0.14	.0009	46	01 35 31.01	−30 22 17.1	20.69	01 35 31.49	−30 21 31.9	20.45
02 15 55.8	−29 06 21	2.264	0.07	.0063	347	02 15 48.09	−29 08 42.0	20.08	02 16 03.54	−29 03 59.8	20.79
02 23 00.7	−29 49 05	1.416	0.02	.0018	236	02 22 59.28	−29 51 01.5	19.64	02 23 02.03	−29 47 08.0	20.50
22 28 23.4	−28 57 35	2.453	0.17	.0011	270	22 28 13.72	−28 58 22.1	20.64	22 28 33.07	−28 56 48.9	19.94
22 35 20.5	−27 17 18	1.810	0.07	.0049	316	22 35 16.20	−27 19 45.4	18.50	22 35 24.82	−27 14 50.5	20.16
22 10 05.1	−32 04 00	2.119	0.11	.0061	330	22 09 56.21	−32 06 00.3	20.81	22 10 14.03	−32 02 00.0	20.71
22 03 09.4	−31 33 49	1.643	0.19	.0015	89	22 03 11.80	−31 34 21.6	19.75	22 03 07.09	−31 33 16.5	19.43
22 50 32.1	−31 05 00	0.637	0.19	.0059	242	22 50 22.71	−31 04 45.4	18.40	22 50 41.45	−31 05 14.4	20.17
23 29 07.8	−29 57 00	1.841	0.12	.0002	67	23 29 06.87	−29 57 31.9	20.28	23 29 08.69	−29 56 28.7	19.70
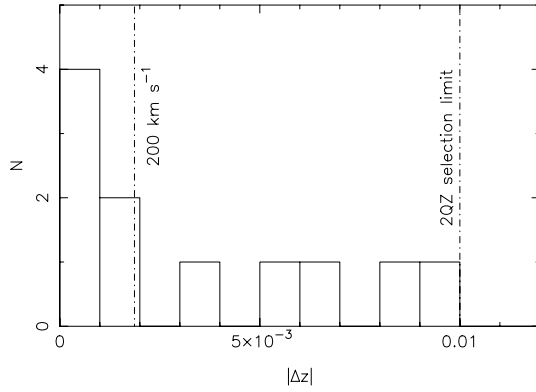
Figure 2. The histogram of WHT/AAT redshift differences, $|\Delta z|$, listed in Table 2. The original selection limit based on 2QZ redshifts is shown, as is the redshift difference expected for a pair at the mean sample redshift of $z = 1.8$ with a relative peculiar velocity difference of 200 km s^{-1}

Table 3. SDSS Early Data Release photometry for the QSO pair J1435+0008, showing the apparent magnitudes in the SDSS wavebands, their associated photometric errors, and the magnitude differences between the QSOs and the errors in those quantities.

QSO	u	g	r	i	z
J143508+000844	21.37	20.72	20.57	20.64	20.37
±	0.09	0.03	0.03	0.05	0.13
J143506+000901	20.49	19.92	19.87	19.98	19.74
±	0.05	0.02	0.02	0.03	0.08
Δm	0.88	0.80	0.70	0.66	0.63
±	0.10	0.04	0.04	0.06	0.15

significant redshift difference. We consider this unlikely to be a lensed pair.

3.11 J2329−2957

This pair exhibits significant differences in emission line equivalent widths and ratios and a significant redshift difference, making it also unlikely to be a lensed QSO.

4 TIME-DELAY AND THE FORMATION OF BROAD ABSORPTION FEATURES

At least two of the pairs have spectra which match very well their redshifts, continuum slopes, emission-line equivalent widths and profiles but which do none the less show some significant differences between the two QSOs. One, J0150−2921, has spectra which appear identical apart from the existence of C IV broad absorption in one QSO and not the other. Such an observation has previously been used to argue against QSO pairs being lensed versions of the same object (Green et al. 2002) but the recent discovery that broad absorption lines can form on time-scales of 10 yr (Ma 2002) changes that conclusion.

In fact, large separation lenses could have a significant time-delay between the lensed images. The actual time-delay is strongly dependent on the lens mass distribution and on the symmetry of the light paths through the lens potential. As we have so far detected a possible lens in no more than one of these systems, and as the mass distributions in any lenses are unknown, we cannot yet calculate a predicted time-delay. But in principle we should expect a delay which could be as large as the time-delay calculated from the maximum possible path length difference in a simple geometry (and ignoring the time dilation term)

$$\Delta t < \frac{\theta^2}{2c}\frac{D\,D_{\mathrm{LENS}}}{(D - D_{\mathrm{LENS}})}$$

where θ is the angular separation of the images, D is the observer–QSO angular diameter distance and D_{LENS} is the observer–lens angular diameter distance, assuming a flat universe. For an angular separation of 200 arcsec this corresponds to approximately 5000 yr. The closeness of the match of the spectra of J0150−2921 indicates that in fact the broad absorption features have indeed formed in one QSO within this time-scale. The available time is certainly much greater than the 10-yr formation time observed by Ma (2002). One explanation for such rapid formation of absorption features is the ejection of remnant material from solar-mass objects being destroyed in the vicinity of the black hole. As the crossing time of the broad-line region of such material is of the order of 10 yr, this seems a feasible explanation. An alternative explanation for both the difference in our spectra and also the variability seen by Ma (2002)
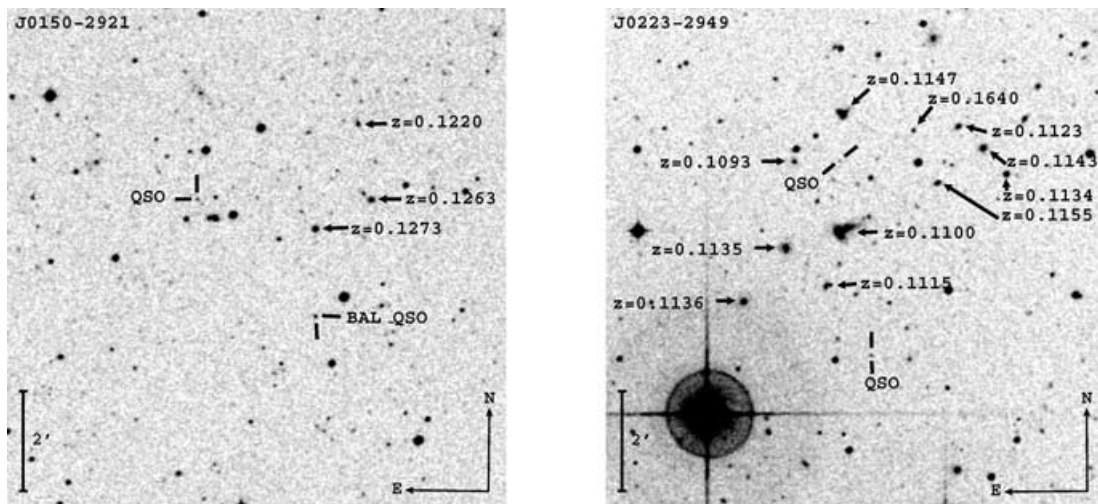
Figure 3. ESO sky survey images of 10 arcmin regions around J0150−2921 and J0223−2949 showing the locations of both QSOs and the redshifts of the galaxies in the vicinity measured by the 2dF Galaxy Redshift Survey. The orientation and image scale are also shown.
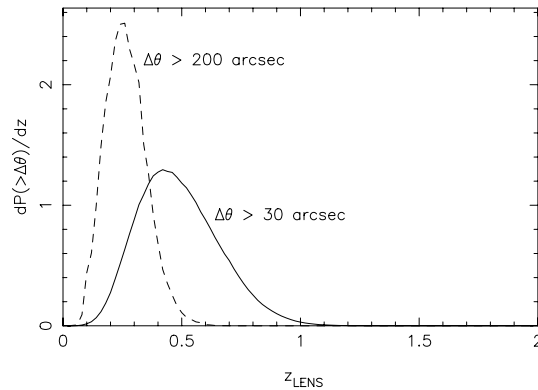
Figure 4. The *a posteriori* probability distribution of redshift, z_{LENS}, for a lensing cluster producing multiple images of a QSO at $z = 2$ with separations either >200 or >30 arcsec, assuming the ΛCDM cosmology and cluster lens model described in the text.

might be that the size of a broad-absorption line gas cloud is only of order 10^{-3} of the distance of the cloud from the central source of UV radiation.

If this conclusion is correct, it also reopens the possibility that the 7.3-arcsec pair, Q2345+007, is a lensed QSO and not a binary QSO. Green et al. (2002) have noted that the X-ray properties differ, but also note that one QSO shows a broad absorption line system. If the difference in X-ray properties is caused by X-ray absorption associated with the optical broad absorption line feature, as suggested by Green et al. (2002), then formation of an absorption system on a time-scale of the order of 5 yr could explain the observed results.

Two other QSO pairs exhibit some differences in their broad emission lines, and again it is possible that these also arise from long time-scale spectral variability. Small, Sargent & Steidel (1997) have studied spectral variability specifically with this question in mind, and find that emission-line variations of this magnitude are common on time-scales of a few years.

Time variation may have the unwanted effect of causing the sample to be incomplete, if colours or spectral features vary significantly so that either candidates are not initially selected, or if they are subsequently rejected in a spectral comparison. Given the potentially long time-delays between light paths in systems of such wide separation, it is difficult to allow for this effect as no measurements of variability in unlensed systems can be made on those time-scales. In the long term the best approach would be to select candidates on the basis of observables that should be time-independent, such as redshift difference between multiple images, and to apply independent tests of the lensing hypothesis such as the Lyα forest comparison discussed above or looking for characteristic features of lensing such as giant arcs associated with the host galaxy of a QSO. In this paper we do not address this question further, preferring instead to view this paper as providing evidence for the existence of extreme systems which may then be used as evidence to justify more complete surveys.

5 IDENTIFICATION OF THE LENSES

If these systems of paired QSOs are indeed lensed QSOs, then the lenses should be identifiable as clusters of galaxies. As described in Section 2, one of the possible lensed systems, J0223−2906, appears associated with a galaxy cluster at $z = 0.11$. 10 galaxies in the vicinity have redshifts, measured by the 2dF Galaxy Redshift Sur-

vey, that are close to this value, with a velocity dispersion of about 600 km s^{-1} (Fig. 3). Such a velocity dispersion would however produce an image splitting of only about 20 arcsec for an isothermal sphere lens, so if this cluster is the lens then either an anisotropic or a more centrally concentrated mass distribution is needed. The total mass required to produce the observed image splitting is $\sim 6 \times 10^{14}$ M$_\odot$. There is also a weak *ROSAT*-detected X-ray source close to the position of the two bright galaxies which lie along the line joining the two QSOs, although the origin of the emission is not known. At present it is not clear if sufficient mass is present in this cluster to produce the observed image splitting. One other system, J0150−2921, may also have a low-redshift cluster associated with it, again based on redshift measurements from the 2dF Galaxy Redshift Survey, although in this case only three redshifts are currently known (Fig. 3).

In order to estimate the expected distribution of lens redshifts we consider the calculations presented by Lopes & Miller (2004) in which the lensing clusters are assumed to have spherically-symmetric Navarro, Frenk & White (1997) mass profiles, and to have an abundance predicted by the Sheth & Tormen (1999) evolving mass function. Here we assume a cold dark matter (CDM) power spectrum (Bardeen et al. 1986) modified to include an approximate correction for baryons (Sugiyama 1995) in a ΛCDM cosmology with $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ and a power-spectrum normalization given by $\sigma_8 = 0.9$. In this model, it is found that the distribution of lens redshifts is not sensitive to the choice of cosmological parameters, although the abundance of lensing systems is. Magnification bias is calculated as discussed by Lopes & Miller (2004).

Within this model, it is clear that a lensing cluster is expected to have $z_{\mathrm{LENS}} < 1$, and for the widest separations the model predicts that any lens should have $z_{\mathrm{LENS}} < 0.5$. However, the total probability predicted for 200 arcsec lensed systems is so low that such systems are expected only if there are significant departures from the assumptions of the model, in which case the lens redshift distribution would need to be recalculated.

6 COMPARISON WITH MODELS

At this stage it cannot be regarded as conclusive that these candidate systems are indeed lensed, and we also do not yet have an accurate assessment of the completeness of the lensing search. None the less it is interesting to compare the results presented here with the expectations of lensing models. Li & Ostriker (2002) and Lopes & Miller (2004) have calculated the expected distribution of angular separations arising from strong lensing by massive clusters of galaxies in the standard cosmological framework that assumes structure grows hierarchically from initial Gaussian perturbations in a universe dominated by CDM and dark energy. With cosmological parameters as determined from the *WMAP* observations (Spergel et al. 2003) the expected number of systems with $\Delta\theta > 10$ arcsec in the 2QZ survey of 2×10^4 QSOs is about 0.5 (Lopes & Miller 2004), so it is possible, although not highly likely, that the 2QZ survey contains wide-separation lensed systems. However, the distribution is expected to be dominated by angular separations towards the lower end of the range, and in this standard model the expected number of systems with $\Delta\theta > 30$ arcsec is only ~ 0.1 (Lopes & Miller 2004). One possible explanation is that the widest-separation systems presented here are not in fact lensed, despite the similarity of the redshifts and spectra. A second is that the values of cosmological and cluster model parameters are not as assumed in calculating the above numbers: key parameters are σ_8, w, Ω_M and also parameters

of the model such as the dependence of cluster halo concentration on mass, redshift and cosmology and the cosmic scatter in halo concentration (for details see Lopes & Miller 2004). Alternatively it may be that the models do not yet comprise the full complexity required to model accurately the statistics: possible deficiencies include the assumption of the Navarro et al. (1997) mass profile (see also Oguri, Lee & Suto 2003) and the assumption of a smooth distribution of mass. Other departures from the standard cosmological model, such as the existence of non-Gaussian fluctuations, could also modify the lensing probabilities.

For these reasons we believe it is imperative to carry out observational tests of the candidate lensed systems presented here in order to test these models, rather than using the predictions of the models to argue against the interpretation of these systems as being lensed.

7 COMPARISON WITH PREVIOUS OBSERVATIONS

Previous searches have been undertaken for lensed QSOs with comparable separations, and it is interesting to investigate whether the detection of any systems in 2QZ would be inconsistent with those searches.

Ofek et al. (2001, 2002) searched a sample of size $\sim$8000 radio-loud QSOs without finding any evidence for multiple images in the separation range $5 < \Delta\theta < 30$ arcsec. Phillips et al. (2001b) examined a complete sample of 11 670 flat-spectrum radio sources for possible multiple images separated in angle by $6 < \Delta\theta < 15$ arcsec and found no lensed systems. An incomplete sample of $\sim$15 000 radio sources yielded one possible lensed system. The first step in comparing these results with those from the 2QZ survey is to compare sample selection.

The range of angular separations probed by the radio surveys is generally smaller than considered here, although had any 2QZ pairs with $\Delta\theta > 10$ arcsec been lens candidates they should have been identified as such. For comparison purposes we shall use the cluster-lensing model to compare surveys covering different ranges in separation, although we have argued above that the overall lensing probabilities predicted by such models may be too low to explain the existence of more than one lensed system in the 2QZ survey. The model of Lopes & Miller (2004) with parameters $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 0.9$ and $z_{QSO} = 1.5$ predicts relative lensing probabilities of 1, 1.7 and 1.3 for the separation ranges 6–15, 5–30 and >10 arcsec, respectively, assuming the same magnification bias in each case. If the models are indeed deficient in some way, or if the values of parameters are different from that assumed, these relative probabilities will be different, but they suffice for the discussion in this section.

In fact, because of the double radio and optical selection of the FIRST survey (Ofek et al. 2001) the magnification bias could be a factor 5 smaller for that survey compared with the JVAS/CLASS or 2QZ surveys (Ofek et al. 2002; Phillips et al. 2001b; Lopes & Miller 2004), so the overall expected relative lensing probabilities in the three surveys are 0.2, 1.7 and 1.3 for FIRST, JVAS/CLASS and 2QZ respectively.

We also need to make some assumption about sample completeness and to multiply the probabilities by the sample sizes. Here we shall adopt a conservative view of the JVAS/CLASS result and say that out of 15 000 QSOs no lensed systems were found, and we adopt an assumed completeness of 50 per cent for the 2QZ survey. At this stage this figure is illustrative only. With these assumptions, the predicted relative numbers of systems in each survey are 0.1, 1.6 and 1.0 for the FIRST, JVAS/CLASS and 2QZ surveys, respectively.

Now suppose the entire data set contains one lensed system: the *a posteriori* probability of that system being found in the 2QZ survey is 37 per cent. However, if there are more systems in the 2QZ survey, the probability of there being none in the other surveys falls to 13, 5, 2 per cent for 2, 3 or 4 2QZ systems. Thus, if the surveys are indeed comparable in this way, the existence of two lensed systems within the 2QZ survey would not be inconsistent with the other surveys, but a larger number could be.

Finally, however, we note that another possibly significant factor in calculating the expected lensing probabilities is the redshift distribution of the source population. Wambsganss, Bode & Ostriker (2004), Oguri et al. (2004) and Lopes & Miller (2004) have demonstrated that cluster lensing probability strongly increases with the mean redshift of the source population, and also depends to some extent on the distribution of source redshifts about the mean. The redshift distribution is not well-known for the CLASS and FIRST surveys, but appears likely to have a median value in the range $1.0 < z < 1.4$ (Ofek et al. 2002; Phillips et al. 2001a,b). The 2QZ median redshift is 1.5. Lensing probability increases by a factor of about 3 as the source redshift is increased from $z = 1$ to $z = 1.5$ (Lopes & Miller 2004), so if the typical redshift of sources in the radio surveys is even slightly lower than that of QSOs in the 2QZ survey this would also lower the relative probability of discovering lensed systems in the radio surveys.

Our overall conclusion from this comparison is that, observationally, the results from the 2QZ and radio surveys may not be incompatible, but clearly further work needs to be done both to establish more accurately the redshift distribution of the JVAS/CLASS sources and to establish the reality of the 2QZ candidate systems.

8 CONCLUSIONS

Evidence has been presented for the discovery of the first lensed QSOs with multiple images separated on arcmin scales. If these are genuine lensed systems then we should expect the associated lenses to be observable as massive clusters of galaxies. Further evidence needs to be collected to establish that these are indeed lensed, however. One such piece of evidence that is independent of assumptions of the nature of the lens would be the existence of common Lyα forest absorption in candidate lensed QSO spectra. The existence of giant arcs associated with a system would also provide strong evidence for cluster lensing, especially if the host galaxies of the QSOs could be detected and shown to be distorted by lensing. Detection of the lens itself, either by direct imaging or weak-lensing, would also provide convincing evidence.

Consideration of the expected distribution of angular separations indicates that, although a number of the identified systems may be lensed, a number of those with the greatest separations may not be. Confirmation or discounting of the widest separated systems is particularly important as any such systems would challenge our current understanding of lensing by galaxy clusters.

Among the examples found, one candidate lensed system has been found to display broad C IV absorption in one image and not the other, which could be due to the formation of such absorption systems on time-scales of tens of years. Further searches for wide-separation lenses may be partially incomplete because such absorption systems would affect optical colours, spectra and the flux in other wavebands, including possibly the X-ray band. Broad-line region variability may also render search methods based on colour and/or spectroscopic comparison partially incomplete unless generous selection criteria are allowed. Finally, it may be that optical searches are biased against lenses with separations less than a few tens of

arcsec because of obscuration in galaxies associated with the cluster lens.

ACKNOWLEDGMENTS

REFERENCES

Bardeen J. M., Bond J. R., Kaiser N., Szalay A. S., 1986, ApJ, 304, 15
Colless M. et al., 2003, preprint (astro-ph/0306581)
Condon J. J., Cotton W. D., Greisen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J., 1998, AJ, 115, 1693
Croom S. M., Smith R. J., Boyle B. J., Shanks T., Loaring N. S., Miller L., Lewis I. J., 2001a, MNRAS, 322, L29
Croom S. M., Shanks T., Boyle B. J., Smith R. J., Miller L., Loaring N. S., Hoyle F., 2001b, MNRAS, 325, 483
D'Odorico V., Cristiani S., D'Odorico S., Fontana A., Giallongo E., Shaver P., 1998, A&A, 339, 678
Green P. J. et al., 2002, ApJ, 571, 721
Kochanek C. S., Falco E. E., Muñoz J. A., 1999, ApJ, 510, 590
Kochanek C. S., Falco E. E., Impey C., Lehar J., McLeod B., Rix H.-W., 2002, CASTLES web site: http://cfa-www.harvard.edu/castles
Kneib J.-P., Ellis R. S., Smail I., Couch W. J., Sharples R. M., 1996, ApJ, 471, 643
Li L.-X., Ostriker J. P., 2002, ApJ, 566, 652
Lopes A. M., Miller L., 2004, MNRAS, in press (astro-ph/0306174)
Ma F., 2002, MNRAS, 335, L99
Maoz D., Rix H. W., 1993, ApJ, 416, 425
Maoz D., Rix H. W., Gal-Yam A., Gould A., 1997, ApJ, 486, 75
Mitchell P. S., 1989, PhD thesis, Univ. Edinburgh
Navarro J. F., Frenk C. S., White S. D. M., 1997, ApJ, 490, 493
Ofek E. O., Maoz D., Prada F., Kolatt T., Rix H.-W., 2001, MNRAS, 324, 463
Ofek E. O., Rix H-W., Maoz D., Prada F., 2002, MNRAS, 337, 1163
Oguri M., Lee J., Suto Y., 2004, ApJ, 599, 7
Phillips P. M., Browne I. W. A., Wilkinson P. N., 2001a, MNRAS, 321, 187
Phillips P. M. et al., 2001b, MNRAS, 328, 1001
Sahu K. C. et al., 1998, ApJ, 492, L125
Sheth R. K., Tormen G., 1999, MNRAS, 308, 119
Smail I., Couch W. J., Ellis R. S., Sharples R. M., 1995, ApJ, 440, 501
Small T. A., Sargent W. L. W., Steidel C. C., 1997, AJ, 114, 2254
Smith R. J., Croom S. M., Boyle B. J., Shanks T., Miller L., Loaring N. S., 2002, MNRAS, submitted
Spergel D. N. et al., 2003, ApJS, 148, 175
Stoughton C. et al., 2002, AJ, 123, 485
Sugiyama N., 1995, ApJS, 100, 281
Wambsganss J., Bode P., Ostriker J. P., 2004, ApJL, submitted (astro-ph/0306088)
Zhao D., Jing Y. P., Börner G., 2002, ApJ, 581, 876

This paper has been typeset from a TEX/LATEX file prepared by the author.