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Gravitational lenses and lens candidates identified from the COSMOS field

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ABSTRACT
A complete manual search has been carried out of the list of 285423 objects, nearly all of them galaxies, identified in the COSMOS field that are brighter than $I = 25$. Two certain and one highly probable new gravitational lenses are found, in addition to the lenses and candidate lens systems previously found by Faure et al. (2008). A further list of 112 candidate lens systems is presented. Few of these are likely to be true gravitational lens systems, most being star-forming rings or pairs of companion galaxies. It is possible to examine of order 10^6 objects by eye in a reasonable time, although reliable detection of lenses by such methods is likely to be possible only with high-resolution data. The loss of completeness involved in a rapid search is estimated as up to a factor of 2, depending on the morphology of the lens candidate.

Key words: gravitational lensing – galaxies:individual:COSMOS J100140.12+020040.9 – galaxies:individual:COSMOS J095930.94+023427.7 – galaxies:individual:COSMOS J100126.02+013714.5

1 INTRODUCTION

There are a number of reasons why gravitational lenses, systems in which a distant quasar or galaxy are multiply imaged by foreground galaxies, are important. Because lensing is a purely gravitational effect, the inverse problem can be solved in order to reconstruct the lensing mass distribution from the observed images, independently of the nature of the matter in the lens. Variable lensed sources can be monitored for time delays between variations of the images, leading to determination of the Hubble constant (Refsdal 1964, for reviews see e.g. Courbin 2003, Kochanek & Schechter 2004, Jackson 2007); non-correlated image variability allows us to study microlensing by stars in relatively high-redshift galaxies (e.g. Agol & Krolik 1999, Wambsganss 2001, Ofek & Maoz 2003, Morgan et al. 2008); lensing statistics, along with a cosmological model, allow constraints on galaxy evolution (e.g. Chae & Mao 2003, Ofek, Rix & Maoz 2003, Matsumoto & Futamase 2008); and the magnification induced by lenses allows us to study intrinsically fainter objects.

Since the discovery of the first gravitational lens by Walsh et al. (1979), over 100 lens systems have been discovered. The CASTLES compilation website (Kochanek et al. 2008) lists 100 cases in which quasars are multiply imaged by foreground galaxies. In addition, large numbers of lens systems in which the lensed sources are extended galaxies are now being produced by searches such as the SLACS survey (Bolton et al. 2006). Searches for lensed arcs in large-area sky surveys are now beginning to be successful; for example, Cabanac et al. 2007 report progress in the use of the Canada-France-Hawaii Telescope Legacy Survey for this purpose. Recently, Faure et al. (2008) report the use of the Cosmic Evolution Survey (COSMOS, Scoville et al. 2007) as a means of identifying gravitational lenses. COSMOS is a 2 square degree area in which HST/ACS imaging, together with space- and ground-based followup by telescopes at many different wavelengths, has identified over two million objects.

In the COSMOS survey there are 285423 sources brighter than 25th magnitude in the ACS I-band observations. Faure et al. (2008) considered a subset of 9452 of these objects. This sample was chosen to be the most likely to contain gravitational lens systems. The most likely lens systems are those at moderate redshift ($0.2 < z < 1.0$), with intrinsically high luminosity ($M_V < -20$) and those spectrally classified as early type galaxies. They find 20 good candidates, many of which are likely on morphological grounds to be gravitational lenses. In addition, they list 47 other objects in which detection of a single arc gives some indication of lensing by the primary galaxy.

In the present work, all of the COSMOS catalogue images are manually inspected. Two definite gravitational lenses are found, together with a third highly probable system. The search strategy is described in section 2, and the definite lens systems are presented in section 3. Finally in section 4, implications and future prospects are briefly discussed.

2 EXAMINATION OF THE COSMOS IMAGES

2.1 Method

Pseudo-colour images, 5.″25 on a side, were made in a similar way to those of Faure et al. 2008, using the COSMOS catalogue (Capak et al. 2007) and the ACS images from the COSMOS database for intensity in each pixel, and Subaru images in B, r^+ and i^+ (Taniguchi et al. 2007) for the colour coding. Colour gradients and lookup tables were optimized for fast visual inspection. A displayed intensity level I related to counts S by $I \propto S^{0.9}$ was found to give the best results. The maximum intensity level was set to the counts in the eighth brightest pixel in the central 0.″5×0.″5, or 0.2 counts s^{-1}, whichever was the smaller. This condition burns out the central region of about 5% of the brighter galaxies, but a large majority of these will appear in the compilation of Faure et al. (2008), or be too close to have a significant lensing cross section. The colour indices for each pixel were calculated by first normalising each pixel in each of the three colour images to the average pixel value for the colour image, and taking the output value for each pixel as the normalised value for that pixel raised to some power β. If we denote the three output colour values for a pixel by b, g and r, the intensity for the level of the output blue image was $3ab/(r+g+b)$ where a is the count level from the high-resolution ACS image, $3ag/(r+g+b)$ for the green level and $3ar/(r+g+b)$ for the red image. A higher value of β gives more colour contrast, and in practice $\beta = 2$ was found to be a useful value.

Cutouts were made around the position of each object in the catalogue, and the images were then mosaiced into 6×4 frames and examined by eye using the ImageMagick[1] software. Between 8000 and 10000 objects per hour can be examined in this way.

Criteria for regarding galaxies as candidate lenses included multiple images, particularly those corresponding to plausible lensing configurations, and structures similar to lensed arcs. In the case of multiple-image systems, the easiest systems to recognise are the four-image ("quad") systems produced by sources within the astroid caustic of an elliptical lens. The only reason for failure to recognise such systems should be faintness ($I_{814} > 25$) of one or more of the images. Two-image systems, especially those with a faint secondary, are much more difficult. An attempt was made to include such systems, but two-image systems with point-like sources are likely to be missed unless both components are well above the $I_{814} = 25$ level. For typical flux ratios of about 5, the survey will therefore be insensitive to double systems fainter than $I_{814} = 22-23$ unless they are accompanied by arc structures, and for this reason it is not surprising that all of the likely new lenses are quad systems. Because of the good resolution of the ACS images, components of lenses can be detected to within 200 mas of the lensing galaxy, and due to the 5.″25 size of the cutouts, lenses of Einstein radii up to 2.″5 can be detected. This range corresponds to nearly all lenses produced by single galaxies without substantial assistance from a cluster (e.g. Browne et al. 2003).

Lensed arcs from extended background objects are likely to form the majority of lensed systems. In principle these can be detected easily, the main criteria being tangential extension with respect to the lensing galaxy and curvature of the arc. The main confusion in this case is with nearby galaxies, interacting with the primary object and stretched by tidal effects associated with the interaction. Objects which have more credibility as lens candidates are those with relatively thin, long arcs, particularly those with significant colour differences from the primary galaxy and without a significant colour gradient across them. In practice, selected candidates have typical length-to-width ratios of about 3:1 or greater. In lens systems where the arcs are extended into an Einstein ring, such systems are most likely to be rejected due to confusion with star-forming rings in the primary galaxy. Colour information is sometimes of limited help here, as both lensed background objects and star-forming rings are expected to be bluer than the predominant light from the primary. The compromise between including false positives and rejecting lenses is at its most subjective in these cases.

From the list of lens candidates, objects already identified as possible lens systems by Faure et al. (2008) are excluded. The remainder are divided into two categories: candidates (possible or probable lenses) and likely lenses (very likely or certain lenses). In all, 112 candidates and 3 likely lenses survive this selection process. The lenses are discussed further in Section 3, and the candidates are presented in Fig. 1, with the coordinates of each object given in the figure itself. The candidates vary considerably in credibility. For example, 095806+021726 is a weak candidate due to the shortness of the arc; the extended component could plausibly be a companion galaxy. The arc in 100000+021545, although relatively long, is also a weak candidate because of its lack of curvature. On the other hand, arcs such as those in 095950+022057 are morphologically much stronger lensing candidates, although the possibility remains that they could also be star-forming rings within the main galaxy. Possibly the strongest candidate, 100141+021424, has an Einstein ring-like structure, but there is a colour gradient across the ring. This does not necessarily rule the object out as a lens, because it may be a lensed ring superimposed upon colour gradients within the lensing galaxy.

2.2 Completeness of the examination

Although this examination of the COSMOS images is comprehensive in the sense that every object has been looked at, it has been optimized for speed rather

[1] ImageMagick is available under the GNU Public Licence from http://www.ImageMagick.org.

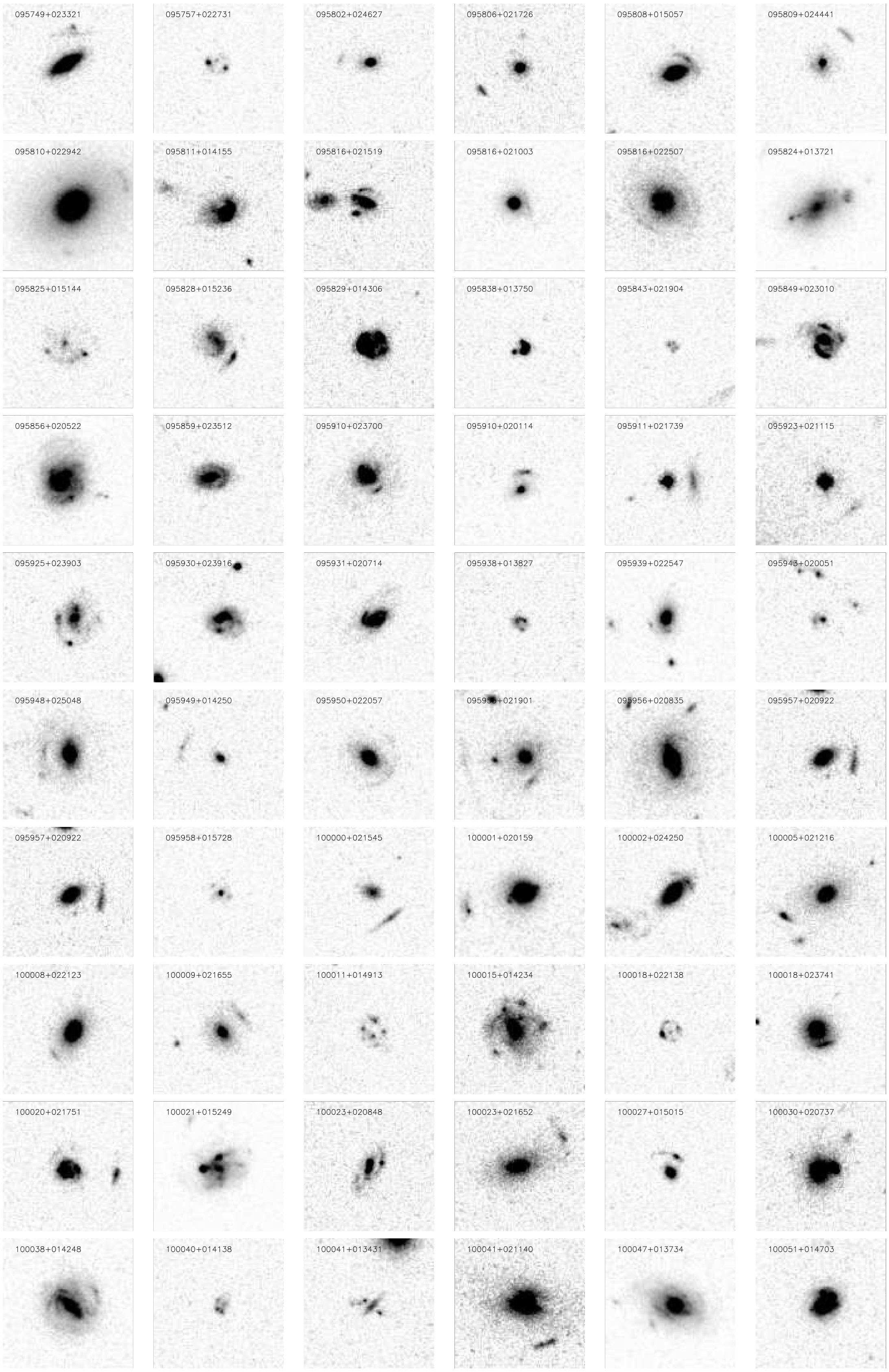

Figure 1. Candidate lens systems from the manual examination of COSMOS images, excluding candidates already presented by Faure et al. (2008). Most are single arc systems which may also be star-forming rings in the galaxy.

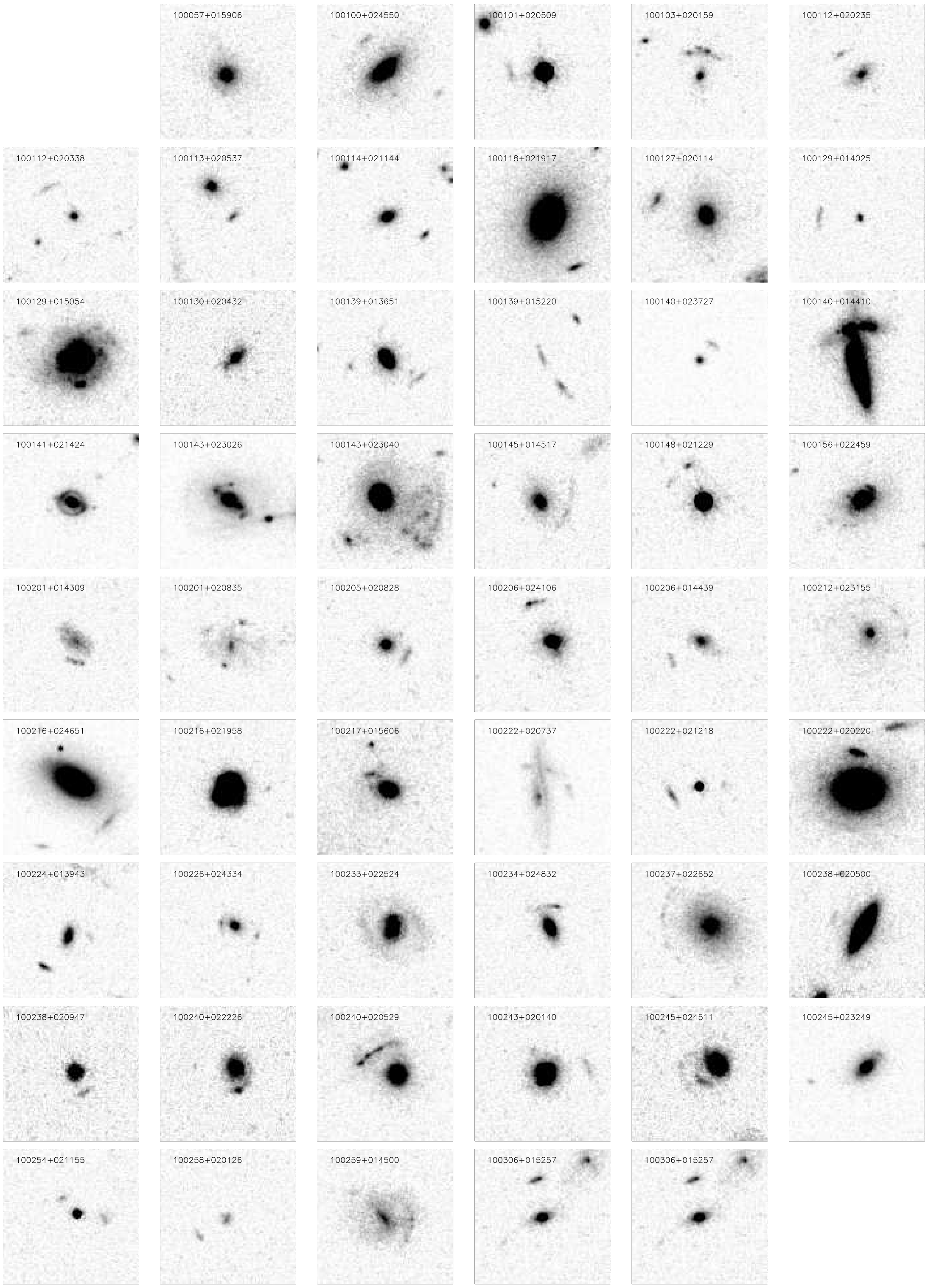

Figure 1. Candidate lens systems from the manual examination of COSMOS images (continued).

than completeness. One obvious incompleteness is that bright galaxies are examined more cursorily than in the work of Faure et al. (2008), and in particular no attempt has been made to subtract elliptical isophotes from these objects. Here we assess the completeness (extent to which real gravitational lenses are present in the sample of candidates) by comparison with Faure et al. (2008). Because Faure et al. present a much more careful manual examination of a much smaller number of candidates, their results are likely to be closer to a complete lens candidate sample; the search presented here was deliberately performed without reference to the candidate lists of Faure et al.

Faure et al. present a list of 20 "best systems". Of these, one (095737+023424) is missing from our sample because it does not have an I_{814} magnitude in the COSMOS catalogue, being outside the region of ACS coverage. Of the remaining 19, 10 are detected by the manual search presented here. ACS images of the 10 systems found and the 9 not found are presented in Figure 2.

In one of the nine cases not recovered as a candidate, the ring structure of the candidate was missed due to its large diameter and the fact that, for ease of rapid examination, the $5\farcs25$ cutout size is smaller than the $10''$ used by Faure et al. In the other eight cases, there are two main reasons for non-detection of the lens. The first is faintness of some of the arc structures, which can be missed during rapid inspection (e.g. 100049+015128). The second reason is the appearance of structures which, while they are consistent with lensing, may also be consistent with structures such as those seen in polar ring galaxies or galaxies with ring-shaped regions of star-formation (e.g. 095941+023628). The inclusion of all such objects from the whole catalogue would have resulted in a considerably increased number of candidates, and such objects are accordingly discriminated against compared to multiple-image lenses.

Encouragingly, nearly all of the Faure et al. candidates which are "obvious" candidates – those which clearly contain subsidiary flux concentrations well above the noise, and which cannot reasonably be explained by any mechanism other than lensing (e.g. 095921+020638) are recovered by this survey. Quantification of completeness is subjective, and depends on individual judgement about the candidates that were missed. For what it is worth, it is the author's opinion that at least three of the candidates of Faure et al. that were missed should definitely have been in the sample, corresponding to a completeness level of $\leq$10/13, and that two of these three were missed due to the difficulty of adjusting the colour scheme and lookup table to clearly distinguish relatively low signal-to-noise features, while still maintaining a rapid rate of inspection. This is an obvious area to optimize further.

We can also investigate the extent to which candidates are recovered by a second examination of a small subsample. Again, the recovery fraction depends on the "quality" of the lens candidate. For ordinary candidates (e.g. single arcs without long tangential extension, or weak multiple images) the recovery rate is about 50%, but this increases with increasing candidate quality; for example, in Fig. 1 the systems 100141+021424 (clear ring) and 100205+020808 (extended arc) are recovered, but 100148+021229 (small arc-like feature) and 100114+021144 (possible arc-like feature) are not. It is unlikely that further "obvious" lens systems such as J100410.12+020040.9 or J095930.94+023427.7 remain within the dataset. The lack of further obvious candidates vindicates Faure et al.'s assumption that their selection of intrinsically luminous objects at moderate redshift is an efficient way of finding lenses.

3 NEW GRAVITATIONAL LENSES

Two new objects are found which are clearly gravitational lens systems, based only on morphological and colour evidence. A third object has a morphology which resembles an Einstein Cross configuration, similar to the lens J2237+0305 (Huchra et al. 1985). Although this object is likely to be a gravitational lens, it requires confirmation. Each object is discussed separately.

3.1 COSMOS J100140.12+020040.9

Object J100140.12+020040.9 (Fig. 3) is a galaxy with an I_{814} magnitude of 21.86. It is a clear example of a four-image gravitational lens system. A pair of merging images is located $0\farcs85$ NW of the centre of the lensing galaxies, and two other images are located approximately $0\farcs9$ NE and $0\farcs7$ slightly W of S. All of these images have similar colours, and are much bluer than the lens galaxy. Of the two merging images, the south-eastern one is faint, possibly due to reddening by the second galaxy or alternatively to microlensing. The light is dominated by the galaxy in the red Subaru i^+ image, and by the lensed images in the blue (B) image. The isophotes of the lens galaxy appear almost circular.

A second galaxy is visible about $1\farcs2$ north and slightly west of the main galaxy; it is highly elongated in an N–S direction. There are a number of nearby galaxies in what appears to be a small group, the nearest being about $4''$ away to the NW.

The light profile of the system was modelled using the GALFIT software of Peng et al. (2002), fitting Sersic profiles to both the primary and secondary galaxies, and point spread functions generated with TinyTim (Krist 1993) for the images. The primary is modelled as an $I = 21.8$ object of Sersic index 3.1 (where 1 represents an exponential disk and 4 a de Vaucouleurs profile) and is likely to be a standard elliptical galaxy. The photometric redshift of 0.81 in the COSMOS database (Mobasher et al. 2007) implies an approximately L_* galaxy, but it is possible that the photometric redshift may be affected by the combination of red galaxy and blue images, and therefore that the galaxy redshift may be significantly less than 0.81.

A model can be made of the system using a singular isothermal sphere for the primary galaxy and an SIE for the second galaxy. The positions of the four images, measured using the AIPS task MAXFIT to fit to the centre of the light distributions, are given in Table 1. A

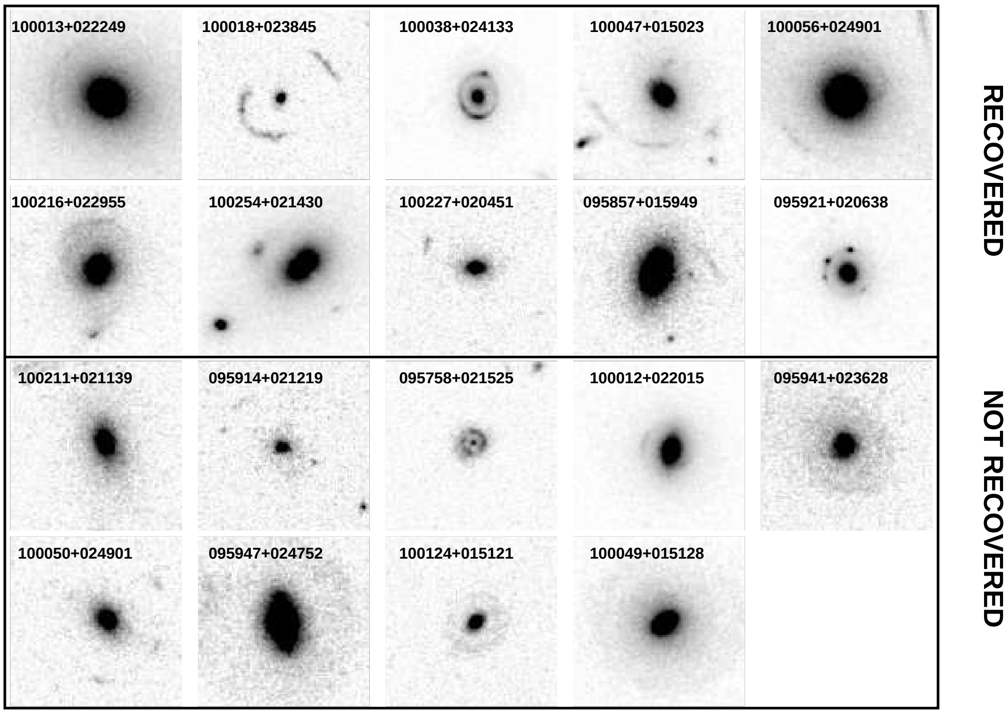

Figure 2. The 19 "best systems" of Faure et al. which have I_{814} magnitudes in the COSMOS field. 10 of these 19 are recovered in this survey (top two rows), including the majority of the "obvious" lenses. The remainder are not recovered for a variety of reasons, including lensed arcs further than 2.″5 from the primary and thus outside the cutout window, relatively faint rings or extended structure, or morphology judged during the independent search to be due to non-lensing structures; see text for further details.

Offset in RA (arcsec)	Offset in Dec (arcsec)	Relative flux
-0.7255 ± 0.001	$+0.471\pm$ 0.001	1.00
$+0.858\pm0.002$	$+0.430\pm0.002$	0.51 ± 0.03
-0.189 ± 0.003	-0.657 ± 0.003	0.42 ± 0.04
-0.444 ± 0.006	$+0.692\pm0.006$	0.06 ± 0.06

Table 1. Positions and fluxes of images in COSMOS J100140.12+020040.9. Offsets are given from the measured position of the main lens galaxy.

Quantity	Main galaxy	G2
Offset in x (″)	0.020	0.260
Offset in y (″)	0.005	1.109
Einstein radius (″)	0.787	0.068
Ellipticity	0 (fixed)	0.812
Position angle (deg)	–	7.32
External shear magnitude	0.069	
Shear angle (deg)	−11.79	

Table 2. Parameters of the lens model for COSMOS J100140.12+020040.9. Offsets are given from the measured position of the main lens galaxy.

fit to the four observed images can be made by varying the Einstein radii of both galaxies, the ellipticity of the second galaxy, plus external shear (magnitude and position) in the system. The resulting model has no degrees of freedom, although deeper observations of the arc system may provide further constraints. Reduction of χ^2 to 1 requires a small movement (about 0.″02) of the main galaxy from the measured position; this is achieved by allowing the position in both RA and Declination to move, subject to a Gaussian penalty function with σ=0.″02.

3.2 COSMOS J095930.94+023427.7

COSMOS J095930.94+023427.7 is a $I_{814} = 21.76$ object with a COSMOS photometric redshift of 1.21, and is clearly a four-image gravitational lens system. Two merging images lie about 0.″8 of a lensing galaxy, and two further images are present to the southeast and southwest, the southwestern image being noticeably further from the lensing galaxy. Again, the Subaru colour imaging clearly shows that the lensed images have a similar blue colour, and the lensing galaxy dominates the light in the i^+–band.

A lens model is more difficult to construct for this object. Using the observed point-source positions (again estimated using MAXFIT) gives eight constraints, and we can make a model with seven free parameters assuming an isothermal profile for the lensing galaxy (Einstein radius, ellipticity and position angle, external shear magnitude and direction, and source position) which does not give a good fit: $\chi^2 \sim 500$, which is unacceptable even given the likely slightly optimistic errors. Al-

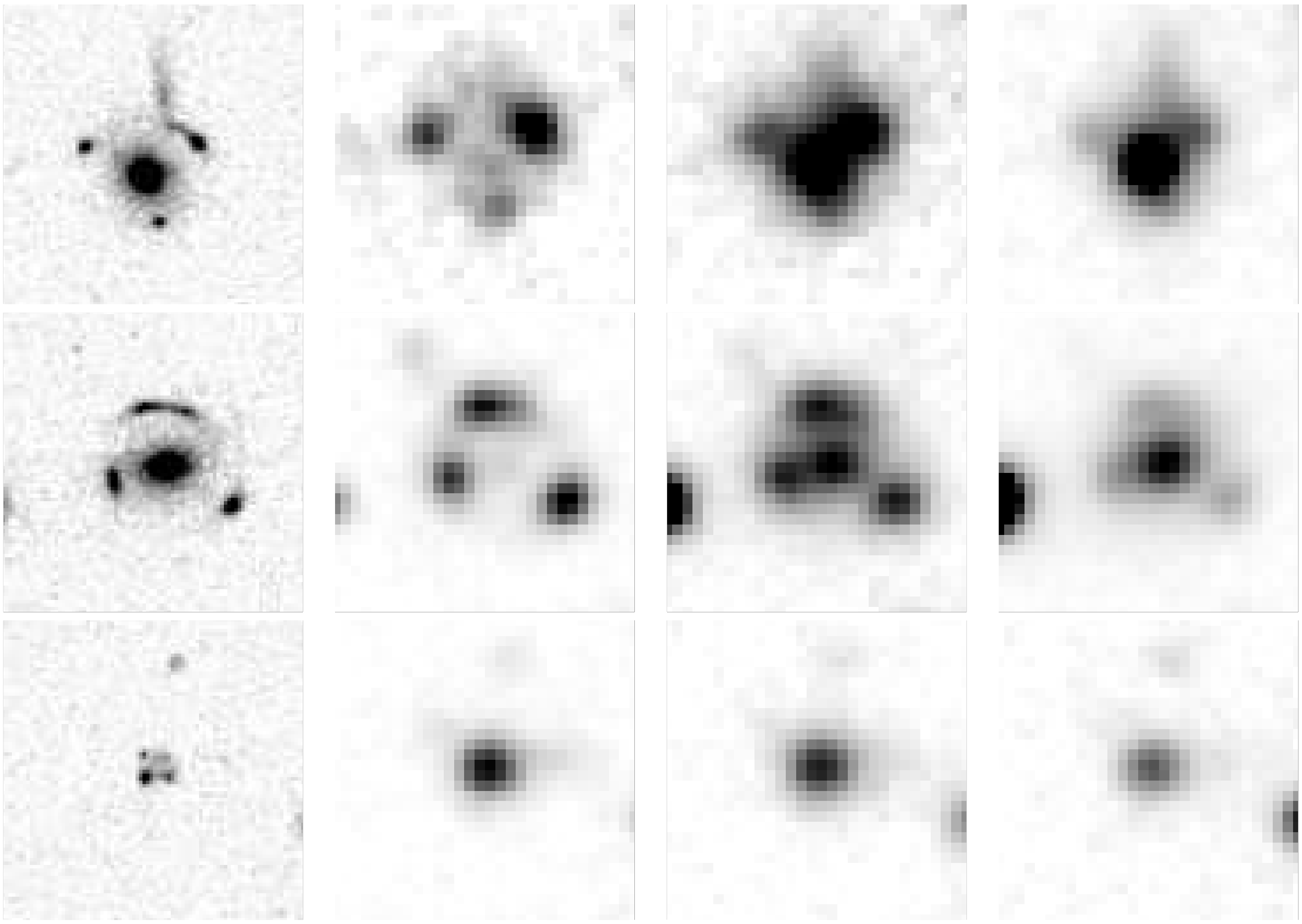

Figure 3. HST and Subaru images of the new lens systems J100140.12+020040.9 (top), J095930.93+023427.7 (middle) and J100126.02+013714.5 (bottom). The columns from left to right are HST/ACS (I-band), Subaru B, Subaru r^+, and Subaru i^+. Images are 4.″3 on a side; North is at the top and East to the right.

Offset in RA (arcsec)	Offset in Dec (arcsec)	Relative flux
+0.752±0.0050	−0.1640±0.005	1.00
−0.925±0.0050	−0.5520±0.005	0.93±0.03
−0.266±0.0050	+0.7895±0.005	0.63±0.03
+0.316±0.0050	+0.8495±0.005	0.76±0.03

Table 3. Positions and fluxes of images in COSMOS J095930.94+023427.7. Offsets are given from the measured position of the main lens galaxy.

Quantity	Main galaxy
Offset in x (″)	0.004
Offset in y (″)	0.063
Einstein radius (″)	0.888
Ellipticity	0.516
Position angle (deg)	85.12
External shear magnitude	0.254
Shear angle (deg)	−17.42

Table 4. Parameters of the lens model for COSMOS J095930.94+023427.7. Offsets are given from the measured position of the main lens galaxy.

lowing the galaxy position to vary, again by a $\sigma = 0.''02$ Gaussian penalty function, yields a better fit, at the cost of a large offset to the North of the lensing galaxy and an unrealistically large external shear ($\gamma = 0.254$ is a shear which would be produced by an isothermal perturber of the same luminosity as the primary and about 1.″5 away, or by a cluster of $\sim 1000\,\mathrm{km\,s^{-1}}$ within about an arcminute). This shear points in the direction of a bright galaxy in the field, which is however 14″ away from COSMOS J095930.94+023427.7. The problems in fitting this source are reminiscent of the difficulties in the four-image lens CLASS B0128+437 (Biggs et al. 2004) where again a large shear is required, much larger than can reasonably be ascribed to objects in the field.

3.3 COSMOS J100126.02+013714.5

COSMOS J100126.02+013714.5 (Fig. 3) is an interesting source, but is less obvious as a gravitational lens candidate. It is much fainter ($I_{814} = 23.73$) than the two definite lens systems. There are four bright condensations, arranged in a cross and strongly reminiscent of Einstein Cross lens systems such as Q2237+0305 (Huchra et al. 1985). Between these there is clearly more extended emission. This is compatible with a lensing galaxy which produces four lensed images, and also with a galaxy which happens to have four star-forming regions in a configuration resembling a lens system.

4 DISCUSSION AND CONCLUSIONS

Th number of lens systems that we should expect in the COSMOS survey is likely to be higher than the number of secure lens systems as identified by eye. For example, Miralda-Escude & Lehar (1992), in their study of lensed arcs in optical surveys, predict an approximate number of 100 per square degree in a survey to a depth of $B = 26$, which for blue objects roughly corresponds to the survey depth of the search undertaken in this work. Since the COSMOS footprint is about 1.6 square degrees, this suggests that over 100 lens systems should be present. In addition, Bolton et al. (2008) report a total of $\sim$70 clearly identified lenses from the SLACS survey, which results from the study of $\sim$50000 spectra of luminous red galaxies (LRGs). Such galaxies are more likely than the average to be gravitational lenses, because of their larger lensing cross-section; nevertheless, even if the lensing cross-section of an average galaxy is a factor of 10 lower than an LRG we would expect several dozen lens systems. Most of the systems are therefore likely to be concealed within the single-arc systems of Faure et al. (2008) or those of Figure 1.

Direct confirmation of such lenses is not easy, because it requires spectroscopy of $I = 25$ arcs to determine redshifts. This is a non-trivial task with an 8-m class telescope, and a programme is under way to investigate the best candidates. In practice, however, it is likely to be impossible to be substantially complete for lenses in a large, blind optical survey such as COSMOS.

In the future, it is likely that arc detection algorithms will be applied to large-area surveys such as COSMOS and CFHTLS, and indeed steps in this direction are described by Cabanac et al. (2007) and by Seidel & Bartelmann (2008). The latest algorithm to be used is an automated robot which explicitly fits each image as a potential lens system and adjusts the model to maximise source plane flux (Marshall et al. 2008). Other methods include searches for multiple blue objects around likely lens galaxies (Belokurov et al. 2007).

Provided that high-resolution images are available, examination by eye of large samples is likely to be a valuable adjunct, both to provide example sets for arc detection algorithms, or even for neural network versions of these algorithms. The examination performed in this work is crude, but it is surprisingly quick to perform; in fact, a sample of a million sources could be processed by one investigator with about a month of dedicated effort. The disadvantage is that many forthcoming surveys will not have diffraction-limited resolution, making galaxy-scale lens systems much more difficult to detect. Despite this, manual inspection of galaxies from forthcoming medium-deep surveys, such as the VST and VISTA KIDS/VIKING surveys, each of which will image several hundred thousand galaxies, will be useful. Lensing by galaxies assisted by groups or clusters will be detectable; such inspections will be more incomplete for lens systems such as those presented here.

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