Satellites in the field and lens galaxies: SDSS/COSMOS versus SLACS/CLASS

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ABSTRACT

The incidence of subgalactic level substructures is an important quantity, as it is a generic prediction of high-resolution cold dark matter (CDM) models which is susceptible to observational test. Confrontation of theory with observations is currently in an uncertain state. In particular, gravitational lens systems appear to show evidence for flux ratio anomalies, which are expected from CDM substructures although not necessarily in the same range of radius as observed. However, the current small samples of lenses suggest that the lens galaxies in these systems are unusually often accompanied by luminous galaxies. Here, we investigate a large sample of unlensed elliptical galaxies from the Cosmic Evolution Survey (COSMOS) and determine the fraction of objects with satellites, in excess of background counts, as a function of satellite brightness and separation from the primary object. We find that the incidence of luminous satellites within 20 kpc is typically a few tenths of 1 per cent for satellites of a few tenths of the primary flux, comparable to what is observed for the wider but shallower Sloan Digital Sky Survey. Although the environments of lenses in the Sloan Lens ACS survey are compatible with this observation, the Cosmic Lens All-sky Survey (CLASS) radio lenses are significantly in excess of this.

Key words: gravitational lensing – galaxies: formation – galaxies: structure.

1 INTRODUCTION

The current galaxy formation model is embedded in a cosmology dominated by dark matter and dark energy [commonly referred to as the Λ cold dark matter (CDM) cosmology]. In this model, quantum fluctuations in the very early Universe are amplified by gravitational instability dominated by CDM. Further structure formation then follows a hierarchical manner in which large structures are formed by the agglomeration of smaller structures. Baryons can further condense within non-linear dark matter haloes to form visible galaxies. The model has had a high degree of success in the description of large-scale structures in the Universe (e.g. Percival et al. 2001; Tegmark et al. 2004; Cole et al. 2005; Eisenstein et al. 2005; Spergel et al. 2007).

Recently, the resolution of numerical simulations has allowed us to address the question of the predicted structure on smaller, galaxy-length, scales (Gao et al. 2004; Diemand, Kuhlen & Madau 2007). These simulations are difficult for two reasons; first, the length scales are small enough that high resolution and, consequently, large numbers of particles are required. Secondly, in the central few kiloparsecs of galaxies, baryonic matter begins to dominate, because it is able to lose energy non-gravitationally and cool into the centre of the gravitational potential wells produced by the dark matter. This complicates simulations because additional non-gravitational physics must be introduced, and this is typically done using either hydrodynamical simulations or semi-analytic models.

It is important to confront the theoretical predictions with observational evidence because doing so effectively tests our understanding of how galaxies form. Two lines of evidence are now available.

The first body of evidence is provided by studies of our own Galaxy. High-resolution simulations of a Milky Way type halo (Klypin et al. 1999; Moore et al. 1999; Gao et al. 2004; Diemand et al. 2007) predict that the Milky Way should be surrounded by hundreds of dark matter satellites down to circular velocities \( v_{\text{crit}} \approx 20 \text{ km s}^{-1} \). Until recently this was thought not to be the case, and efforts concentrated on finding mechanisms by which the satellites might have their star formation suppressed (e.g. Efstathiou 1992; Thoul & Weinberg 1996; Bullock, Kravtsov & Weinberg 2000; Gnedin 2000) and thus not be observable. In the last few years, evidence of faint satellites, many from the Sloan Digital Sky Survey (SDSS; York et al. 2000), has surfaced (e.g. Willman et al. 2005; Belokurov et al. 2006a,b; Zucker et al. 2006; Belokurov et al. 2007) and the numbers are within a factor of a few of the predicted number. However, recent ultra-high-resolution simulations indicate that the number of subhaloes can reach tens of thousands down to \( v_{\text{crit}} \approx 3 \text{ km s}^{-1} \) (e.g. Madau, Diemand & Kuhlen 2008; Springel et al. 2008), and thus it is far from clear whether the predictions and observations are consistent with each other.
The second avenue of attack is to use gravitational lensing of distant galaxies and quasars, typically by foreground galaxies at $0.1 < z < 0.6$. The effect of gravitational lensing is to produce multiple images of the background object and, importantly, in a way that depends only on the mass distribution of the lens and not on whether the mass is luminous or not. In general, we can use constraints, usually in the form of lensed image positions and fluxes, to solve an inverse problem and recover the mass distribution of the lensing galaxy.

In the first instance, the usual procedure is to fit a smooth model for the lens galaxy mass distribution. In some cases such a model fails to fit the image positions, and in many cases it fails to fit the fluxes (Kochanek 1991) of well-constrained lens systems. This problem was highlighted by Mao & Schneider (1998) who attributed the failure to perturbations in the smooth potential due to dark matter substructure at the level of a few per cent. Since then, the problem has been studied both for individual cases and statistically for ensembles of lenses (Chiba 2002; Dalal & Kochanek 2002; Metcalf 2002; Biggs et al. 2004; Kochanek & Dalal 2004). The most secure evidence is obtained from lens systems with a radio-loud source, since the image fluxes are not subject to microlensing effects and (differential) dust extinction in this case, and systems with four images which provide relatively large numbers of constraints. Dalal & Kochanek (2002) and Kochanek & Dalal (2004) studied a sample of seven radio-loud lenses, mostly those discovered in the complete radio survey CLASS (Browne et al. 2003; Myers et al. 2003), and concluded that the image flux anomalies when compared to smooth models required a contribution of between 0.6 and 7 per cent (90 per cent confidence limit) from substructures, roughly as predicted by CDM simulations.

In comparison, the CDM simulations predict that typically 5–10 per cent of the total halo mass is in substructures (e.g. Klypin et al. 1999; Moore et al. 1999; Ghigna et al. 2000). So far, so good; but there are indications that gravitational lens flux anomalies do not provide a watertight vindication of CDM expectations. First, the substructures are in the wrong place; the lens systems constrain matter distributions typically in the 5–10 kpc range, whereas the CDM substructures are predicted mostly to lie in the dark matter dominated region further out (e.g. Mao et al. 2004; Xu et al. 2009). Secondly, when the radio flux anomaly lenses are inspected more closely, it is often found that ‘substructure’ is visible and luminous. Explicitly, bright satellite galaxies which help to explain flux anomalies have been found in MG0414+0534 (Schechter & Moore 1993), 2016+112 (Schneider et al. 1985; Lawrence, Neugebauer & Matthews 1993; More et al. 2009) and CLASS 2045+265 (McKean et al. 2007) – that is, in roughly half of the known sample of four-image, radio-loud lenses studied by Dalal & Kochanek (2002). In addition, the lens system CLASS 1608+656 contains a complex lensing galaxy that is probably two galaxies in the process of interaction (Jackson et al. 1998). In a previous paper, Bryan, Mao & Kay (2008) studied the Millennium Simulation (Springel et al. 2005), together with semi-analytical models to predict the baryon distribution, and found that only 10 per cent of haloes with masses larger than $10^{12} M_\odot$ were predicted to have bright satellite galaxies within 14 kpc, and only 5 per cent within 7 kpc. Shin & Evans (2008) also addressed this problem by simulation of satellites within galaxy-mass haloes and found that the required total mass in satellites to cause flux ratio anomalies, together with the distribution of satellite masses, considerably underpredicts the observed incidence of large, luminous substructures. Both investigations thus paint a consistent picture, the solution of which may be that luminous substructures are more concentrated and hence more effective at causing flux anomalies or that the observed luminous substructures are chance projections (Shin & Evans 2008).

In this paper, we extend this work to ask the following two questions. First, what is the incidence of bright satellites around field elliptical galaxies which are not lenses? Are lens galaxies somehow untypical of the general population, a hypothesis for which there is currently no evidence or obvious explanation? Or does the explanation of some of the flux anomalies by bright substructure indicate that flux anomalies are not telling us about CDM substructure, which mostly lies at larger radius? In this case, we might expect to see that non-lens galaxies should have bright substructure at the same rate as the lens galaxies. For this work, we use the COSMOS survey (Scoville et al. 2007) which has Hubble Space Telescope (HST) imaging of comparable quality of objects at comparable redshifts to the CLASS lenses (Section 2).

Secondly, we compare the CLASS sample’s incidence of satellites with that in the largest lens sample to date, the SLACS sample (Bolton et al. 2006, 2008). This sample, of generally lower redshift lenses, is obtained by spectroscopic selection of luminous red galaxies from the SDSS, which display more than one redshift system in their spectra, and has currently more than 80 reasonably certain lens systems. In addition, we also check the predicted fraction of field galaxies with satellites in the SDSS data in similar redshifts as SLACS lenses to see whether the SLACS optical lens sample is compatible with field galaxies (Section 3). In Section 4, we briefly discuss the results from these comparisons.

2 EXTRACTION OF SATELLITE GALAXIES

2.1 Treatment of the COSMOS images

For this investigation, it is important to use images at similar resolution to those which were used to image the lens galaxies – that is, the 50-mas resolution of the HST, corresponding to about 300 pc at a redshift of 0.5. Previous work on the SDSS data base (e.g. Chen et al. 2006) yields information on scales of >1.4 arcsec, the SDSS median resolution, which corresponds to about 10 kpc; this scale is larger than the typical separation of observed CLASS satellites from the lensing galaxy. A large sample of galaxies is also needed for reasonable statistics; such a large, high-resolution sample has recently become available in the form of the COSMOS survey of about 2 deg$^2$ with the Advanced Camera for Surveys (ACS) on the HST (Capak et al. 2007; Scoville et al. 2007). We therefore use the COSMOS data for this investigation, noting that its image quality has already been proven to be useful in identifying lens systems (Faure et al. 2008; Jackson 2008) and that its distribution of redshift and magnitude is broadly similar to the lens galaxies in the CLASS sample (Fig. 1).

We use the ACS images in the F814W filter of the COSMOS field, which are available from the COSMOS website (http://irsa.ipac.caltech.edu) as reduced by Koekemoer et al. (2007). Early-type galaxies, similar to the lens galaxies in gravitational lens systems, were selected either by imposing a colour cut using the $B$ and $V$ photometry in the COSMOS catalogue or by using the $\text{TPHOT}$ parameter in the image header to select those objects identified as elliptical galaxies by requiring that $0 < \text{TPHOT} < 2$. Only objects listed as good detections, not flagged as stars, with a
The results were then used to generate a magnitude of 24.9. The CLASS redshift is unknown and a value of 0.5 is assumed in this case.

photometric redshift greater than 0.1 and with an \( I_{214} \) magnitude greater than 24.9, corresponding to about 1 mag fainter than the LMC at \( z = 0.5 \), were included.\(^2\) For each object, an image with radius of 11.14 arcsec (corresponding to 20 kpc at \( z > 0.1 \)) was initially extracted.

For each image, the SE\textsc{Extractor} program (Bertin & Arnouts 1996) was used to identify secondary objects in the aperture and record any objects with <20 kpc distance from the primary and with a magnitude brighter than \( I = 24.9 \). Secondaries were rejected if they were considered to be cosmic rays, using a criterion based on the area of the object as fitted by SE\textsc{Extractor}, and were also rejected if they were brighter than the primary. Images of potential satellites were examined by eye and rejected if they contained obvious artefacts, the usual reason being proximity to the edges of the chips. The flux scale was based on the published ACS/F814W magnitude zero-points and the calculations of Capak et al. (2007), and we checked that the fluxes we recovered matched those in the COSMOS catalogue where these overlapped, using a small adjustment from a linear fit to measured and catalogue fluxes to improve agreement with the COSMOS catalogue. Because the catalogue is based on objects detected in multicolour ground-based imaging, we could not use it directly for detecting secondaries because close secondaries would not be detectable given the poorer ground-based seeing. We could, however, regard it as reasonable to assume that all primaries would be detected in the multicolour catalogue.

2.2 Background galaxy counts and the CLASS problem

We must consider the possibility, for each detected secondary, that it is a chance coincidence along the line of sight. To do this, 10,000 random positions within the COSMOS area were adopted. For each position, a cutout was made in the same way as for the primary sample, and a centred, 3 arcsec-wide cutout of a random COSMOS object was added. This was done in order to reproduce the difficulty encountered in real images of detecting faint satellites close to the primary COSMOS object.

All objects within 11.1 arcsec (the angular distance corresponding to 20 kpc at a redshift of 0.1) were measured using the SE\textsc{Extractor} software and were visually inspected, in the case of objects close to the central position, to check that they had not been introduced by the insertion of the small cutout of the random COSMOS object. 38,715 secondaries were detected down to an \( I \) magnitude of 24.9. The results were then used to generate a grid of probability of detecting a random secondary, brighter than a certain magnitude and closer than a certain angular distance from a point (Fig. 2). Fig. 2 also shows the secondaries found in the CLASS lens systems (Table 1). Examination of archival \( HST \) images of these objects using exposures of similar depths to COSMOS and extraction in the same way with SE\textsc{Extractor} yields the result that six secondaries (MG0414+0534 = CLASS B0411+054, CLASS B0631+519, CLASS B1359+154, CLASS B1608+656, CLASS B2045+265 and CLASS B2108+213) would have been detected had they lain within the COSMOS field, the remaining being too faint, too close to the primary or both. Although ACS images are not available for some of the radio lens systems with satellites, existing Wide Field Planetary Camera 2 (WFPC2) and other images (Schneider et al. 1985; Schechter & Moore 1993; McKean et al. 2007) show that many of the satellites detected in images of CLASS radio lens systems lie above the \( I = 24.9 \) threshold, and therefore above the detection threshold of COSMOS.

In order to estimate the number of associated satellites in COSMOS objects, we need to correct the counts around COSMOS images, to be discussed below, for this possibility of chance coincidences along the line of sight. Chen et al. (2006) and Chen (2009) comment on this problem of rejection of ‘interlopers’. Their analysis in the wider, shallower SDSS survey shows that using random positions can potentially underestimate the number of interlopers, because due to clustering of galaxies, random points are more biased.

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\(^2\)The stellar flagging was accomplished by rejecting objects listed as stars and also by rejecting all objects for which the stellarity index was 1.00. Tests by eye on a selection of objects not listed as stars showed that approximately three quarters of objects of stellarity index 1.00 were stars, and three quarters of objects of stellarity index 0.99 were galaxies. This is important because it makes a significant difference (a few tens of per cent) to the background-subtracted counts, despite the relatively small numbers involved (a few per cent of the total sample).
towards voids than the sample of primary galaxies. In their simulations, a more accurate estimate of the numbers of interlopers can be achieved by a number of methods, including the estimation of the background using points relatively near to primary galaxies. The distance required is typically 400–500 kpc, corresponding to about 70 arcsec at a typical COSMOS galaxy redshift. However, the median separation of the relatively fainter COSMOS galaxies is about 50 arcsec, and it is hence likely that the random-point estimation of interlopers gives a good estimate of the background. (Incidentally, we note that underestimation of the background would worsen the discrepancy between COSMOS and CLASS which is the major result of this paper).

### Table 1. Details of secondary objects near the lensing galaxies of CLASS objects, taken from the literature.

| Lens system (#images in brackets) | Primary/secondary flux ratio | Primary/secondary separation (kpc) | Comments/references |
|-----------------------------------|-----------------------------|------------------------------------|----------------------|
| CLASS B0128+437 (4)               | –                           | –                                  | No object visible within 20 kpc in the United Kingdom Infrared Telescope K-band image of Biggs et al. (2004). |
| CLASS B0218+357 (2)               | –                           | –                                  | No object visible within 20 kpc in HST image (York et al. 2005). |
| MG0414+0534 (4)                   | 0.104                       | 12.0                               | Secondary identified by Schechter & Moore (1993) with \( I = 23.3 \), close to one of the lensed images; this is detected by SExtractor on the HST/WFPC2 I-band image first presented by Falco, Lehár & Shapiro (1997). |
| CLASS B0445+123 (2)               | 0.014                       | 9.5                                | Secondary is not identified by SExtractor on the archival HST/ACS image (Proposal 9744, PI Kochanek) due to faintness (and is in any case below the \( I = 24.9 \) mag limit). |
| CLASS B0631+519 (2)               | 0.145                       | 4.9                                | Secondary on original discovery image (York et al. 2005) shown to be at a different redshift (McKean et al. 2004); however, as it is detected by SExtractor it should be included in the statistics. |
| CLASS B0712+472 (4)               | –                           | –                                  | No secondaries within 20 kpc in WFPC2/Near Infrared Camera and Multi-Object Spectrometer images (Jackson, Xanthopoulos & Browne 2000). |
| CLASS B0739+366 (2)               | –                           | –                                  | No secondaries within 20 kpc in archival WFPC2 image (PI Impey, proposal 8268). |
| CLASS B0850+054 (2)               | –                           | –                                  | No secondaries within 20 kpc in archival HST/ACS image (PI Kochanek, proposal 9744). |
| CLASS B1030+074 (2)               | 0.100                       | 3.5                                | This lens system consists of a bright quasar lensed by an \( I = 19.6 \) galaxy (Rusin et al. 2002) with a close secondary, probably a satellite galaxy, 3.5 mag fainter. SExtractor does not detect the secondary, probably due to its faintness and closeness to the primary. |
| CLASS B1127+385 (2)               | 0.692                       | 3.0                                | Deep HST/WFPC2 I-band image in discovery paper (Koopmans et al. 1999) shows a secondary of \( I = 23.5 \), about 1 mag fainter than the primary. The secondary is detected by SExtractor on the HST image, but with a very small area which would have likely caused it to be rejected as a cosmic ray by the procedure used to examine the COSMOS images. |
| CLASS B1152+199 (2)               | 0.363                       | 3.5                                | The original discovery paper (Rusin et al. 2001) shows the system to contain three lensing galaxies in a small group. SExtractor detects all three in the HST image, and the secondaries therefore appear in the statistics. |
| CLASS B1359+154 (6)               | 0.91                        | 6.0                                | The original discovery paper (Rusin et al. 2001) shows the system to contain three lensing galaxies in a small group. SExtractor detects all three in the HST image, and the secondaries therefore appear in the statistics. |
| CLASS B1422+231 (4)               | –                           | –                                  | No secondaries are detected in high-quality HST/ACS images (e.g. Impey et al. 1996) although in principle close secondaries would stand a high chance of being hidden by bright quasar images. |
| CLASS B1555+375 (4)               | –                           | –                                  | No secondaries are detected on archival WFPC2 I-band images (Proposal 8804, PI Falco) although the lensing galaxy itself is very faint at \( I \approx 24 \). |
| CLASS B1600+434 (2)               | –                           | –                                  | The primary lens is an edge-on spiral galaxy (Jansen & Hjorth 1997) with a nearby, brighter galaxy which is, however, >20kpc from the primary. |
| CLASS B1608+656 (4)               | 0.191                       | 4.9                                | Deep HST/ACS images exist (Suyu et al. 2009) which show clearly the two galaxies responsible for the lensing. SExtractor fits these as distinct objects, and the fainter therefore should be considered as a satellite. |
| CLASS B1933+503 (4)               | –                           | –                                  | No secondaries are detected on existing HST/WFPC2 images. |
| CLASS B1938+666 (4)               | –                           | –                                  | No secondaries are detected on existing HST/WFPC2 images (King et al. 1998). |
| CLASS B2045+265 (4)               | 0.05                        | 5.1                                | A secondary galaxy is detected by McKean et al. (2007) on adaptive optics Keck images. It is also seen on archival HST/WFPC2 images and fitted by SExtractor. |
| CLASS B2108+213 (2)               | 0.076                       | 5.6                                | A secondary galaxy is detected by McKean et al. (2007) on HST/ACS images and also fitted by SExtractor. |
| CLASS B2114+022 (2?)              | –                           | –                                  | This system consists of two galaxies (Augusto et al. 2001) at redshifts 0.32 and 0.59; it is not clear what the lens configuration is here, and we do not include the object in the statistics. |
| CLASS B2319+051 (2)               | –                           | –                                  | No close secondaries are detected on existing images; a secondary galaxy G2 was imaged by Rusin et al. (2001) but is just outside the 20-kpc radius. |

*Note. I-band observations have been used for the flux ratios; in a few cases, where the lens redshift is unknown, a value of \( z = 0.5 \) has been assumed.*
2.3 COSMOS satellite counts and comparison with CLASS

We first examine the statistics for the entire $z > 0.1$ sample, using the TPHOT statistic to select the early-type galaxies as outlined above. In Fig. 3, we show some examples of satellite objects found using this process.

In the entire sample, 10,974 early-type objects were examined and 46,853 satellites identified before background subtraction, of which 4,709 are within 20 kpc of the primary. The overall detection rate corresponds to a signal of approximately 10σ over background. Fig. 4 shows the results of this first attempt. We describe the basic procedure, together with some of the selection effects, before considering the results in more detail.

We first calculated the background-subtracted cumulative counts as a function of $I$ magnitude and angular distance. This was done at each grid point ($f,d$) by calculating the fraction of primary objects which have an observed satellite brighter than $f$ and closer than $d$, together with the fraction of random background points which have observed satellites brighter and closer than these limits, and subtracting the two fractions. We also calculated the probability, at each grid point, of a detected satellite being associated with the primary and not an interloper; this probability is smoothed in Fig. 4 with a box size of 2 arcsec and 1 mag. The probability grid suffers severely from small-number statistics at low angular distances.

After background subtraction, we converted angular to linear distances using the photometric redshift in the COSMOS catalogue and magnitudes to flux ratios between detected satellites and primaries. We also used the smoothed fractional probability described above to weight the grid, finally deriving cumulative satellite counts as a function of brightness and separation (Fig. 4). This process is not unambiguous, because of the different ways that one can treat the detection limit. We approach this problem by adopting both a ‘maximalist’ and ‘minimalist’ algorithm, which will detect the greatest and smallest possible number of satellites from the given data. To illustrate this, suppose that we have six primary objects, three of which have a flux of 10 units and three of which have a flux of 5 units. A survey for satellites is done with a detection threshold of 1 unit. In one of the 10-unit primaries no satellite is detected, in the second a 1-unit satellite is detected and in the third a 2-unit satellite is detected. A similar arrangement is seen in the three 5-unit primaries.

The question is then: what is the fraction of objects which have satellites brighter than 15 per cent of the primary flux? The ‘minimalist’ approach would be to consider only the three primaries of flux 10 units, in which a 15 per cent satellite could be seen, and to conclude that the answer is 1/3. This, however, ignores the two 5-unit primary objects which obviously have satellites brighter than 15 per cent; a ‘maximalist’ approach would then indicate a fraction of 3/5. A more strictly correct approach would be to use any prior information about the distribution of galaxies in a Bayesian analysis to find the most probable value. In practice, what we do instead is to calculate fractions using the minimalist and maximalist approaches. In any case where the results agree, we can be sure of getting the correct answer. Not surprisingly, the results diverge at small secondary:primary flux ratios where many secondaries approach the $I = 24.9$ detection threshold, and this typically limits our analysis to flux ratios of about 2–2.5 mag.

Both minimalist and maximalist approaches are plotted in Fig. 4, and areas of the grid in which the two methods agree can be assigned an unambiguous value for the satellite rate. Fig. 4 shows that the statistics are robust at flux ratios of $\geq 0.1$, or about 2.5 mag. In Fig. 4, we also plot the CLASS satellites. Having established that they are unlikely to be chance background objects, this also shows that they are not representative of the incidence of satellites in the COSMOS field galaxies. In particular, three CLASS lens galaxy satellites with $f > 0.1$ lie below the 0.1 per cent probability contour on either algorithm.

We now estimate more formally the potential discrepancies between CLASS and COSMOS satellites. There are two approaches we can take, depending on whether or not we believe that the satellite in any particular CLASS object is associated or not. If it is not associated, we need to calculate the probability that a random pointing in the COSMOS field has an interloper at the same (or greater) brightness and the same (or closer) distance from the pointing centre. If it is associated, we need to use the background-subtracted COSMOS satellite probabilities, described in the last section.

In CLASS B0631+519, we know that the satellite is not associated with the primary and in CLASS B1608+656 and CLASS B1359+154, we strongly suspect on morphological grounds that the satellites are associated. For the remainder of the CLASS objects with satellites, we do not know if the satellite is associated. Table 1 shows the probability, for each CLASS object with a satellite that is detected by the setting of SExtractor used for the COSMOS images, of its occurring by chance, on the assumption of non-association and on the assumption that it is associated. Fig. 5 shows the six objects with satellites detected by SExtractor, together with three objects from the COSMOS data base closely matched to them in...
Figure 4. Representations of the incidence of satellites in the COSMOS survey objects, using objects identified as elliptical galaxies and with photometric redshift $z_{\text{phot}} > 0.1$. Top-left panel: the contours at each grid point represent the fraction of satellites brighter and closer than the brightness and angular distance of that point, corrected for the background counts. Top-right panel: the probability, at each point in brightness and primary-satellite distance, that a given satellite is associated with the primary rather than being a background object. This in general increases with increasing brightness and decreasing distance. However, it becomes negative for weak satellites close to the primary because it is more difficult to detect such a satellite close to a primary object than close to a random background point. Bottom panels: cumulative satellite counts (as a fraction of objects with satellites brighter and closer than a given flux ratio and linear distance). The two plots are calculated by the ‘minimalist’ and ‘maximalist’ algorithms described in the text and show that the counts become unreliable at low flux ratios ($<0.1$) due to statistical uncertainties associated with the detection limit. In three of the plots, filled dots represent values for CLASS objects which have satellites found by the SExtractor program, and circles represent CLASS satellites not found by SExtractor.

2.4 Limitations of the statistics

There are a number of possible problems with the comparison of the CLASS and COSMOS data.

(i) The overall resolution limit of the survey is different in linear units for objects of different redshift. For comparison with the CLASS surveys, this does not matter because CLASS data is taken using HST images, provided that we measure the HST images in the same way.

(ii) The subtraction of the background is subject to small-sample statistics at low distance from the primary.

(iii) The quasi-Bayesian problem of the detection limits, overcome as described in the previous section.

(iv) The criterion $0 < T_{\text{PHOT}} < 2$ may not be the best way of selecting early-type galaxies to compare with CLASS data.

(v) The background statistics may affect the result.

We show that in practice, these problems do not affect the result. This is done by using only fainter objects to assess effect (ii), using a colour cut ($B - V > 0.7$) to assess effect (iv) and using a different realization of the background to assess effect (v). The results are presented in Fig. 6 from which it is apparent that the effect of these corrections is less than a factor of 2 in each case.

It is also interesting to compare these results with simulations and to investigate whether the fraction of satellite galaxies varies with redshift. We can do this easily by considering two samples of galaxies, $0.4 < z < 0.6$ and $0.9 < z < 1.1$, obtaining two separate

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3This is not strictly true, as some of the CLASS images use the WFPC2 rather than the ACS.
Figure 5. Six CLASS lenses with detected substructure are shown in the left-hand column (from top to bottom: MG0414+0534; CLASS B0631+519; CLASS B1359+154; CLASS B1608+656; CLASS B2045+265; CLASS B2108+213). For each lens, we have selected three objects from COSMOS matching it as closely as possible in redshift and brightness. The figure illustrates satellites that are found by circles; note that we have excluded lensed images from the lens systems by this process. The large circle in each diagram has a radius of 20 kpc. Only satellites fainter than the primary are considered. Note that although satellites are found in COSMOS objects, few are found close to the primary object in the way that seems to be common in CLASS.

results for low- and high- redshift galaxies which are shown in Fig. 7.

For comparison, we have (as in Bryan et al. 2008) used the De Lucia & Blaizot (2007) semi-analytic models run on the Millennium Simulation. Haloes were selected from the galaxy catalogue by imposing a minimum mass cut of $10^{12}h^{-1} M_\odot$. All galaxies satisfying the same cut-offs in brightness and colour selection (discussed before) were considered. We search within the virial radius of each halo for a companion galaxy. While Bryan et al. (2008) considered only central galaxies, we have included all galaxies satisfying the
imposed cuts. The sample is, however, still dominated by central objects due to the small number of satellites satisfying the mass cuts (Fig. 8).

It can be seen that, for the mass range considered, the simulations give typical satellite fractions of about eight times that of the COSMOS values, but even then underpredict the satellite frequency observed in the CLASS samples. However, the satellite population consists of exclusively ‘orphan’ galaxies which have been stripped of their dark matter haloes (see Bryan et al. 2008 for further discussion). The fraction found in simulations does however depend on the lower mass limit imposed when selecting host haloes; higher mass haloes are more likely to host a companion galaxy. Increasing the mass cut to $10^{11} \, h^{-1} \, M_{\odot}$ increases the fraction by a factor of $\sim 2$. We find we are able to reproduce the number density of the COSMOS sample by imposing a minimum mass cut of $\sim 3 \times 10^{11} \, h^{-1} \, M_{\odot}$ (on non-central galaxies), in doing so our fraction of galaxies found to host a companion is reduced by less than a factor of two (i.e. the fractions are comparable within the level of uncertainty of the observations).

### 3 NEIGHBOUR COUNTS AROUND EARLY-TYPE FIELD AND LENS GALAXIES AT LOW REDSHIFTS

In this section, we study the fraction of galaxies with satellites for both field and lens galaxies selected from SDSS. Both sets of galaxies are selected from redshift 0.05 to 0.4.

#### 3.1 Satellites in field galaxies

For comparison, we have performed a similar analysis on a sample of galaxies in the low-redshift Universe drawn from the SDSS. For this, we take data from Sample DR72 of the New York University Value Added Catalogue (NYU-VAGC). This is an update of the catalogue constructed by Blanton et al. (2005b), is based on the seventh data release of the SDSS (DR7; Adelman-McCarthy et al. 2008) and is publicly available on the NYU-VAGC website. Starting from Sample DR72, we select all galaxies with $r < 18$ and spectroscopically measured redshifts $z < 0.5$. Here, $r$ is the $r$-band Petrosian apparent magnitude, corrected for Galactic extinction. We then trim this sample so that it has roughly the same distribution in both redshift and stellar mass as the SLACS sample. This gives rise to a final sample of 75 839 galaxies. Detailed description of the NYU-VAGC can be found in Blanton et al. (2005b), and the methodology of estimating the stellar mass for SDSS galaxies is described in Blanton & Rowes (2007).

In order to count the companions around these galaxies, we first construct a photometric reference sample, from datasweep of the NYU-VAGC (version DR7, see the NYU-VAGC website), by selecting all galaxies with $r < 21$. The resulting sample includes $\sim 26$ million galaxies. We then construct a set of 10 random samples that have the same selection effects as the reference sample (a detailed account of the observational selection effects accompanies the NYU-VAGC release). For each object in our sample, we count the number of companions in the reference sample, and in each of the random samples, with a given value of the projected radius $R_p$ and with a minimum value of luminosity ratio $r_{\text{Lmin}}$, determined by the difference in the $r$-band apparent magnitude between the companions and the galaxy in question. The average correlated neighbour counts $N_r$ per galaxy, as functions of $R_p$ and $r_{\text{Lmin}}$, are then given by the difference between the result from the reference sample and the average one from the random samples. By evaluating and subtracting the counts in the random samples, we can make a statistical correction for chance projections of foreground and background galaxies that lie along the line-of-sight. This method is similar to that used in Li et al. (2006), Li et al. (2008a,b), where the authors computed neighbour counts around active galaxy nuclei (AGN) and star-forming galaxies (SFGs) from SDSS and examined the connections of star formation and AGN activity with tidal interactions. The reader is referred to those papers for detailed description and tests of this method.

The result is shown in Fig. 9, where we plot the contours of the average correlated neighbour counts around our early-type galaxies in the plane of $R_p$ and $r_{\text{Lmin}}$. It can be seen from the figure that the SDSS fractions are comparable to those seen in SLACS (and COSMOS), within the statistical noise.

#### 3.2 Satellites in SLACS lenses

The major satellite anomaly detected to date has been the excess of light substructure in CLASS lenses compared to normal elliptical galaxies. However, the largest survey for gravitational lenses to date has been the SLACS survey (Bolton et al. 2006) which targets luminous red galaxies in the SDSS and examines the SDSS data for systems which contain more than one spectroscopic redshift within a $\sim 3$ arcsec fibre. The intrinsic efficiency of this procedure has resulted in the discovery of nearly 100 lens systems. All of these are systems in which a background galaxy is imaged by a foreground galaxy; because of the SLACS selection of bright objects, most of the systems have a lens redshift of 0.1–0.3, somewhat lower than that of CLASS.

Fields of the 64 most certain SLACS lenses from the most recent compilation (Bolton et al. 2008; lens category YES) have been examined; in most cases these fields extend to 20 kpc, or nearly 20 kpc, from the centre of the lens galaxy. SEExtractor has again been used to detect all satellites out to a 7 arcsec radius, with the exception of objects in the regions covered by source structure; these regions are identified by SLACS mask images and can be blanked out. They do not significantly affect the statistics, as most such regions are within about 5 kpc of the lens galaxy (Fig. 10). Fig. 11 shows the satellites in the SLACS images as a function of linear and angular distance.

Over most of the range of brightness and angular distance, the distribution of SLACS satellites is statistically indistinguishable from background (for example, 29 satellites are expected with...
Figure 6. Cumulative background-subtracted satellite counts for the COSMOS sample under several different assumptions: (left-hand panel) using a different realization of the background; (right-hand panel) using a colour cut instead of a galaxy classification; (bottom panel) using only fainter $I > 20$ galaxies to assess the effect of removing the difficulty of finding faint objects close to bright ones in the COSMOS data. The maximalist counts are shown in each case.

Figure 7. Cumulative background-subtracted COSMOS counts for two redshift ranges, $0.4 < z < 0.6$ and $0.9 < z < 1.1$.

$I_{r14} < 24$, $d < 6$ arcsec and 34 are observed, with a further 3–4 probably missed due to limited sensitivity). A few satellites are likely to be genuinely associated with the primary, including for example the satellite of SLACS 0808+4706; this object lies at a cumulative probability of 0.005, implying that only 0.3 satellites of this brightness and distance should occur in the SLACS sample. Nevertheless, these satellites do not lie in the region of flux ratio linear distance space that is strongly discrepant with the COSMOS statistics (right-hand side of Fig. 11) as we see in the CLASS images.

4 DISCUSSION AND CONCLUSIONS

The current work sharpens the problem which arises from the presence of excess satellites around lensing galaxies in the CLASS survey. It appears that the frequency of satellite galaxies, predicted...
Satellites in the field and lens galaxies

Figure 8. The contours show the proportion of galaxies which contain satellites at less than a certain distance \( d \) and brighter than a flux ratio \( f \), from the primary, using the Millennium Simulation and the method of Bryan et al. (2008). At each grid point, the contoured quantity represents the proportion of primary galaxies which have secondaries at flux ratio \( f \) or brighter, at a distance \( d \) or closer. The left-hand plot shows the results for all galaxies with redshifts \( 0.4 < z < 0.6 \) and the right-hand plot for \( 0.9 < z < 1.1 \).

Figure 9. Cumulative detection rate of SDSS satellites, as a function of secondary/primary flux ratio and linear distance.

Figure 10. Sensitivity to SLACS satellites as a function of linear distance, due to masking of lensed source structure and the edges of the images.

by current simulations based on CDM/semi-analytic models are in excess of the actual frequency of satellites observed in the COSMOS survey and also in the wider but shallower SDSS survey, given the limits imposed by resolution and depth. Though the sample statistics are still small, lensing galaxies in the SLACS survey are also consistent with early-type, non-lensing galaxies in COSMOS. This is interesting as the SLACS survey lens galaxy sample has a much lower median redshift (\( z = 0.20 \)) than the COSMOS survey galaxies. This leaves the CLASS lens galaxies as the anomalies, containing significantly higher rates of luminous substructure than either simulations or field galaxies in SDSS and COSMOS. The major significant difference between CLASS and SLACS lenses is that the redshift of lens (and source) is typically larger in the CLASS lenses. However, the difficulty then becomes the difference between lensing galaxies (CLASS) and non-lensing galaxies (COSMOS) in broadly similar redshift ranges.

One possibility is that, although the incidence of satellites in the CLASS lens systems appears anomalously high, the
The comparison with simulations would benefit a great deal from the use of higher resolution simulations involving a realistic treatment of the gas processes, but we highlight the fact that studying the central regions of haloes may provide important additional constraints to theoretical models. This is because the models may reproduce the overall luminosity function of (more numerous) satellite galaxies, but fail for the small fraction of projected central galaxies which are most sensitive to numerical effects (e.g. resolutions) and physical processes such as tidal stripping.

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