The environments of SLACS gravitational lenses

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ABSTRACT

We report on an investigation of the environments of the Sloan Lens ACS Survey (SLACS) sample of gravitational lenses. The local and global environments of the lenses are characterized using Sloan Digital Sky Survey (SDSS) photometry and, when available, spectroscopy. We find that the lens systems that are best modelled with steeper than isothermal density profiles are more likely to have close companions than lenses with shallower than isothermal profiles. This suggests that the profile steepening may be caused by interactions with a companion galaxy as indicated by N-body simulations of group galaxies. The global environments of the SLACS lenses are typical of non-lensing SDSS galaxies with comparable properties to the lenses, and the richnesses of the lens groups are not as strongly correlated with the lens density profiles as are the local environments. Furthermore, we investigate the possibility of line-of-sight contamination affecting the lens models, but do not find a significant over-density of sources compared to lines of sight without lenses.

Key words: gravitational lensing – galaxies: elliptical and lenticular, cD – galaxies: interactions – galaxies: structure.

1 INTRODUCTION

The Sloan Lens ACS Survey (SLACS; Bolton et al. 2006) is a large sample of strong gravitational lenses derived from the Sloan Digital Sky Survey (SDSS). The lens sample has proved to be particularly useful because of the high quality of the data: all of the SLACS lenses have known lens and source redshifts, stellar velocity dispersions for the lensing galaxies have been measured from the SDSS spectra, all of the systems have Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) imaging in two bands for accurate non-parametric lens modelling, and all of the sources are extended and therefore provide additional constraints on the mass profile of the lensing galaxy. Furthermore, the density of background sources in the HST imaging allows a weak lensing analysis of the ensemble sample of lenses (Gavazzi et al. 2007); the major drawback of the lens sample is that it is unlikely to find any variable sources that would provide time delays.

Koopmans et al. (2006) have used the SLACS lenses to show that early-type galaxies have isothermal total inner density profiles with very little intrinsic scatter (approximately 6 per cent) assuming a uniformity in the environments of the lenses that has not been rigorously tested. While the SLACS lenses seem to lie on the Fundamental Plane (Bolton et al. 2006, 2007; Treu et al. 2006) and do not differ noticeably from other SDSS galaxies with similar luminosities and stellar velocity dispersions, the local environments of the lenses might affect the mass profiles of the lensing galaxies (e.g. Rusin et al. 2002; Dobke, King & Fellhauer 2007; Auger et al. 2007b). If some of the lenses are being perturbed by neighbouring galaxies, the intrinsic scatter of the density slope for isolated early-type galaxies might be even smaller than 6 per cent. Furthermore, it has been suggested that line-of-sight (LOS) contamination significantly affects the SLACS lenses (Guimaraes & Sodrê 2007) and the density slope might be expected to be shallower than originally reported.

We report on a spectroscopic and photometric evaluation of the environments and LOSs of the 15 SLACS lenses investigated by Koopmans et al. (2006). A weighting scheme is used to determine the effective number of potential perturbing companions to each lens galaxy. We also characterize the ‘richness’ of the global environment of each lens field and quantify the number of galaxies along the LOS to the lens. Throughout this Letter the term ‘global environment’ is used to describe the group, cluster or field in which the lens resides, while the ‘local environment’ describes the environment within ≈ 100 h⁻¹ kpc of the lensing galaxy. A Λ cold dark matter cosmology with Ω_M = 0.27 and Ω_Λ = 0.73 is used to determine all physical distances, which are measured in h⁻¹ units.

2 DATA SAMPLES

2.1 Lens systems

Our primary intent is to investigate a correlation between the inner density profile of the lensing galaxy and its local environment. We therefore limit our sample to the subset of SLACS lenses with published inner density slopes. This sample consists of 15 early-type galaxies with lens redshifts between z = 0.063 and 0.332, and stellar...
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Table 1. Properties of the 15 SLACS gravitational lenses investigated in this work. Columns: (1) lens name; (2) lens redshift; (3) lens stellar velocity dispersion; (4) lens mass slope; (5) photometric estimate for the number of close companions; (6) proxy for the richness of the local environment.

| Name        | $z$  | $\sigma^a_{SDSS}$ | $\alpha^r$ | $N_{wrt}$ | $R$  |
|-------------|------|------------------|------------|-----------|------|
| SDSS J0037−0942 | 0.1954 | 265             | 2.05      | 0.11     | 3.2  |
| SDSS J0216−0813 | 0.3317 | 332             | 2.05      | 0.02     | 1.4  |
| SDSS J0737+3216 | 0.3223 | 310             | 2.34      | 0.86     | 2.3  |
| SDSS J0912+0029 | 0.1642 | 313             | 1.82      | 0.03     | 3.7  |
| SDSS J0956+5100 | 0.2405 | 299             | 2.04      | 1.98     | 8.2  |
| SDSS J0959+0410 | 0.1260 | 212             | 2.18      | 0.80     | 22.5 |
| SDSS J1250+0523 | 0.2318 | 254             | 2.26      | 0.01     | 6.1  |
| SDSS J1330−0148 | 0.0808 | 178             | 2.18      | 5.80     | 87.1 |
| SDSS J1402+6321 | 0.2046 | 275             | 1.95      | 0.24     | 2.8  |
| SDSS J1420+6019 | 0.0629 | 194             | 2.03      | 0.00     | 4.8  |
| SDSS J1627−0053 | 0.2076 | 275             | 2.21      | 0.96     | 7.1  |
| SDSS J1630+4520 | 0.2479 | 260             | 1.85      | 0.00     | 4.1  |
| SDSS J2300+0022 | 0.2285 | 283             | 2.07      | 0.91     | 7.2  |
| SDSS J2303+1422 | 0.1553 | 260             | 1.82      | 0.00     | 2.9  |
| SDSS J2321−0939 | 0.0819 | 236             | 1.87      | 0.05     | 4.0  |

*Data from Koopmans et al. (2006).*

velocity dispersions from $\sigma = 178$ to 330 km s$^{-1}$ (Koopmans et al. 2006). The density slopes range from $\alpha = 1.82$ to 2.34 where $\rho \propto r^{-\alpha}$, and the typical error on $\alpha$ for a given system is approximately 5 per cent (Koopmans et al. 2006). Four of the systems have shallower than isothermal density slopes (i.e. $\alpha < 2$), six are approximately consistent with isothermal, and five lenses have steeper than isothermal profiles. The lens characteristics are summarized in Table 1.

2.2 Lens environments

Photometric and spectroscopic data from the SDSS Data Release 6 (Adelman-McCarthy et al. 2007) are used to quantify the environments of the lensing galaxies. Catalogues are made of all SDSS primary galaxies with $r < 22.1$ mag that lie within 1.2 h$^{-1}$ Mpc of the lensing galaxy. These catalogues include the five-band SDSS photometry, photometric redshifts from the SDSS catalogue, and spectroscopic redshifts for those galaxies targeted by SDSS. Because of the range in redshifts spanned by the lenses, the spectroscopic completeness varies significantly from system to system. Only the systems with $z < 0.1$ contain sufficient spectroscopic redshifts to characterize adequately the global environments of the lenses.

2.2.1 Local environment

We use the colours of the field galaxies and their offsets from the lens to determine the likelihood that a neighbouring galaxy is physically associated with the lens. Only galaxies that are less than 1 mag brighter or 2.5 mag fainter than the lens are used in the analysis. Fiducial colours of galaxies at the lens redshift are determined by querying all spectroscopic galaxies in the SDSS data base that have redshifts within 1200 km s$^{-1}$ of the redshift of the lensing galaxy. These empirical colour distributions are used to determine Gaussian weights for each of the field galaxies, which are also weighted by their distance from the lens system. The colour distributions for a $z = 0.25$ galaxy are shown in Fig. 1; note that there are long tails at the blue end of each distribution. These tails are due to late-type galaxies and are clipped from our analysis when determining the location and width of the distributions. The clipping biases us against finding late-type companion galaxies; however, this is not a strong bias because early-type galaxies are known to cluster much more strongly than late-type galaxies (Meneux et al. 2006).

The final weighting scheme used is

$$w_{gal} = f(d) \prod_i \exp \left( -\frac{\Delta c^2}{2\sigma^2} \right),$$

where $w_{gal}$ is the weight for each galaxy and $f(d)$ is given by

$$f(d) = \begin{cases} 1 & d < 90 \ h^{-1} \ kpc \\ \exp\left(\frac{-d^2}{2\sigma^2}\right) & d > 90 \ h^{-1} \ kpc, \end{cases}$$

where $d$ is the distance of the galaxy from the lens and $d_0$ is set to 20 h$^{-1}$ kpc for an effective distance of approximately 100 h$^{-1}$ kpc (i.e. several truncation radii, Limousin et al. 2007). The product is taken over the set of colours $c = \{g-r, r-i, i-z\}$. $\Delta c$ is the difference between the mean of the empirical colour distribution and the measured colour of the galaxy, and $\sigma_c$ is the quadrature sum of the width of the colour distribution and the errors on the SDSS photometry. The $\sigma$ filter is not used in our analysis because of its poor sensitivity, and all of the galaxies in our sample have the three-colour photometry $\{g-r, r-i, i-z\}$ available from the SDSS data base. We sum the weights of all of the galaxies in the field to determine an effective number of galaxies physically associated with the lensing galaxy, $N_\text{eff}$. The photometric weighting is not equivalent to determining a photometric redshift for each galaxy; photometric redshifts characterize the most likely redshift of a source, while our weights are a proxy for the likelihood of a source being at a given redshift (although the full probability distribution from a photometric redshift analysis could approximately provide the same information).

Our weighting algorithm was tested on low-redshift ($0.025 < z < 0.075$) SDSS galaxies that have luminosities and stellar velocity dispersions that are comparable to the SLACS lenses. These low-redshift galaxies have nearly complete spectroscopy for all neighbouring field galaxies with $r_{\text{field}} < r_{\text{gal}} + 2.5$. The weighting algorithm was employed as above, and a comparison was made.
The lens density slope ($\alpha$) versus the number of photometrically estimated companions ($N_w$) inferred from lensing plus stellar dynamics models for 15 SLACS lenses. The two systems with $N_w > 1$ have been set to 1 to emphasize the bimodality. The dashed line at $\alpha = 2$ indicates an isothermal density profile and the dotted lines are 1σ deviations from isothermal.

Figure 2. The lens density slope ($\alpha$) versus the number of photometrically estimated companions ($N_w$) inferred from lensing plus stellar dynamics models for 15 SLACS lenses. The two systems with $N_w > 1$ have been set to 1 to emphasize the bimodality. The dashed line at $\alpha = 2$ indicates an isothermal density profile and the dotted lines are 1σ deviations from isothermal.

between $N_w$ and the number of spectroscopically confirmed neighbours. $N_w$ correctly estimated the total number of companions within 100 $h^{-1}$ kpc of the target galaxy for 64 per cent of the systems, where $N_w$ was rounded to the nearest integer to make the comparison. For the incorrectly matched systems, $N_w$ does not show a bias for over- or underestimating the number of companions: 18 per cent were incorrectly matched in either case. However, $N_w$ is more robust as a binary indicator of whether there are any companions or not. Our simulations show that 67 per cent of systems with $N_w > 0.75$ have at least one spectroscopically confirmed companion, while 76 per cent of the systems with $N_w < 0.75$ do not have any companions. We suspect that many of the incorrect associations are due to late-type galaxies that are not identified well by our colour distributions.

$N_w$ for each lens system is recorded in Table 1. There is a noticeable trend for lenses with steeper density profiles to have higher values of $N_w$ (Fig. 2). Furthermore, none of the shallower than isothermal lenses is found to be associated with a companion galaxy. A simple linear regression of the data (after setting $N_w = 1$ for the systems with $N_w > 1$) finds that the trend is real with 98.3 per cent confidence. A comparison sample of non-lens fields was made for each lens system to provide an external comparison. For each lens, the same analysis as described above was performed on 200 SDSS galaxies at the same redshift as the SLACS lens and with a measured stellar velocity dispersion within 20 km/ s$^{-1}$ of the lens velocity dispersion. In some cases the number of comparison fields meeting these criteria is less than 200, in which case we used all fields that do meet the criteria. The composite distribution of $N_w$ for all of the SDSS comparison fields is shown in Fig. 3; a Kolmogorov–Smirnov test cannot distinguish between the distributions. The lenses lie in typical environments and there is not a strong correlation between the global richness and the density slope for the SLACS lenses.

2.2.2 Global environment

A proper characterization of the global environment of a lens system would determine the velocity dispersion for the group in which the lens resides as well as the distance of the lens from the centre of the group. Neither of these can be quantified without spectroscopically defining the group membership; we are only able to perform this analysis for the lowest redshift lenses (Section 2.2.3). Nevertheless, we attempt to characterize the ‘richness’ of the global environment by employing a weighting scheme similar to the one used for the local environment. The same colour distributions are used and the analysis only differs by the weight term used to penalize the radial offset from the lens; the distance weighting for the global environment is

$$f(d) = \frac{1}{\frac{d}{d_0} + 1}$$

with $d_0$ set to 350 $h^{-1}$ kpc, approximately the virial radius for moderate-redshift groups (e.g. Auger et al. 2007a). The group richness, $R$, is the sum of all of the individual weights and is recorded in Table 1. While $N_w$ can be interpreted approximately as the number of neighbouring galaxies for each lens, $R$ should not be interpreted as the number of galaxies in the group, although it is a proxy for the density of early-type galaxies at a particular redshift. Fig. 4 shows the distribution of richness for the SLACS lenses and the SDSS comparison sample; a K–S test cannot distinguish between the distributions. The lenses lie in typical environments and there is not a strong correlation between the global richness and the density slope for the SLACS lenses.

2.2.3 Spectroscopic sample

Three of the systems, SDSS J1330−0148, J1420 + 6019 and J2321−0939, are at lower redshifts than the other lenses and their fields have nearly complete SDSS spectroscopy down to $r = r_{lim}$ + 2.5. We use the SDSS redshifts to determine group properties for these lens fields. There is one spectroscopically identified companion within 100 $h^{-1}$ kpc of SDSS J1330−0148 but no spectroscopic neighbours are found for the other two systems, tentatively confirming the binary interpretation of $N_w$ for these three systems. However, because of the inability to closely pack fibres on the SDSS spectrograph, the local environments of these lenses are not completely probed spectroscopically. One of the systems, SDSS J1420 + 6019, appears to be isolated and no group is found to be associated with the lens. For the remaining two lens systems, we determine the group velocity dispersion using the biweight estimate of the velocity dispersion.
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3 DISCUSSION

We find that the global environments of the SLACS lenses are typical of other massive early-type galaxies found in the SDSS. Two of the steeper than isothermal systems lie in very over-dense regions but the remaining lenses all have richness values that fall near the peak of the richness distribution (Fig. 4). Furthermore, the suggestion that the SLACS lenses are affected by LOS contamination does not seem to be supported by the data. While there are other galaxies along the LOSs to the lens systems, the LOS densities do not significantly deviate from the densities along comparable LOSs. We therefore expect that the parameter estimates should not be affected as proposed by Guimarães & Sodrê (2007).

The SDSS photometric data indicate that the SLACS lenses are only slightly more likely to be associated with companion galaxies than comparable lenses selected from the SDSS, although the uncertainty of the photometric identifications makes the difference negligible. We therefore conclude that SLACS lenses do lie in typical environments both globally and locally. However, we also find that lens systems with steeper than isothermal density slopes are preferentially associated with companion galaxies compared to lenses with shallower density slopes. \textit{N}-body simulations suggest that interactions with neighbouring galaxies can induce a steepening in the density slope (Dobke et al. 2007), and there are other lens systems with companion galaxies that are found to be best modelled with steeper than isothermal profiles (e.g. Rusin et al. 2002; Auger et al. 2007b). The interaction-induced steepening is a transient effect and the density profile of the galaxy will return to isothermal approximately 0.5–2 Gyr after the encounter with the neighbour (Dobke et al. 2007). This may account for the large range of $N_w$ for lenses with nearly isothermal profiles; isothermal lenses with a companion may be in the relaxed state before or after an encounter with the neighbouring galaxy. This stripping mechanism may also account for local observations of dark matter deficient galaxies (e.g. Romanowsky et al. 2003; Proctor et al. 2005).

We note that one steeper profile system, SDSS J1250 $+$ 0523, is not photometrically associated with any neighbouring galaxies; this perhaps illustrates the limits of using photometry to find perturbing companions, or demonstrates that other factors also influence the slope of the density profile. Additionally, we have not found an environmental bias to account for the shallower lenses. However, if a lens galaxy is embedded in a cluster, the joint profile of the cluster and galaxy would tend to be modelled with a shallower than isothermal profile if a single-component power law was used (ignoring

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**Table 2.** Group properties for the low-redshift SLACS lenses that lie in spectroscopically confirmed groups. Columns: (1) lens name; (2) number of spectroscopically confirmed group members; (3) distance from the lensing galaxy to the group centre; (4) group velocity dispersion.

| Name       | $N_{grp}$ | Offset (arcsec) | $\sigma$ (km/$s$) |
|------------|-----------|-----------------|-------------------|
| SDSS J1330$-$0148 | 87        | 167             | 905 $\pm$ 84     |
| SDSS J2321$-$0939 | 13        | 41              | 411 $\pm$ 58     |

**Figure 4.** The distribution of $R$ for all of the SDSS comparison fields (black line) and 14 of the SLACS lenses. The lenses largely have richnesses near the peak of the distribution at $R \sim 5$. One lens, SDSS J1330$-$0148, is in a cluster with $R = 87$ and has been omitted for clarity.

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**Table 3.** The number of non-local galaxies along the LOSs to SLACS lenses compared to similar, non-lensing SDSS galaxies. Columns: (1) lens name; (2) number of galaxies along LOS to the lens; (3) mean number of galaxies along LOS to non-lensing SDSS galaxies; (4) median number of galaxies along LOS to non-lensing SDSS galaxies; (5) standard deviation of number of galaxies along LOS to non-lensing SDSS galaxies.

| Name       | $N_{lens}$ | $N_{mean}$ | $N_{med}$ | $\sigma_N$ |
|------------|------------|------------|-----------|------------|
| SDSS J0037$-$0942 | 5         | 5.4        | 5.0       | 3.2        |
| SDSS J0216$-$0813 | 11        | 8.0        | 7.0       | 4.6        |
| SDSS J0737 $+$ 3216 | 6        | 7.3        | 7.0       | 4.0        |
| SDSS J0912 $+$ 0029 | 9        | 7.3        | 7.0       | 3.6        |
| SDSS J0956 $+$ 5100 | 10       | 7.7        | 7.0       | 3.9        |
| SDSS J0959 $+$ 0410 | 5        | 4.1        | 4.0       | 2.4        |
| SDSS J1250 $+$ 0523 | 5        | 5.9        | 5.0       | 3.2        |
| SDSS J1330$-$0148 | 5        | 3.8        | 3.0       | 2.5        |
| SDSS J1402 $+$ 6321 | 6        | 6.0        | 5.0       | 3.2        |
| SDSS J1420 $+$ 6019 | 3        | 5.1        | 4.0       | 3.6        |
| SDSS J1627$-$0053 | 9        | 6.0        | 6.0       | 3.1        |
| SDSS J1630 $+$ 4520 | 4        | 6.0        | 6.0       | 3.3        |
| SDSS J2300$+$ 0022 | 11       | 6.4        | 6.0       | 3.4        |
| SDSS J2303 $+$ 1422 | 6        | 5.2        | 5.0       | 3.0        |
| SDSS J2321$-$0939 | 9        | 5.2        | 5.0       | 3.2        |
interactions between the two haloes). This effect is dependent on the location of the lens with respect to the centre of the cluster, which our photometric analysis is unable to address. More complete field spectroscopy would better characterize the global environments of these lens systems and allow correlations between the mass slopes and cluster centre offsets to be investigated. Furthermore, a spectroscopic investigation of the local environments of the complete sample of SLACS early-type lenses would confirm the correlation indicated by our photometric analysis and provide strong evidence for truncation caused by galaxy interactions.

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