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Discovery of two gravitationally lensed quasars in the Dark Energy Survey

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This paper includes data gathered with the 6.5m Baade Telescopes located at Las Campanas Observatory, Chile.

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\textbf{ABSTRACT}

We present spectroscopic confirmation of two new lensed quasars via data obtained at the 6.5m Magellan/Baade Telescope. The lens candidates have been selected from the Dark Energy Survey (DES) and WISE based on their multi-band photometry and extended morphology in DES images. Images of DES J0115–5244 show two blue point sources at either side of a red galaxy. Our long-slit data confirm that both point sources are images of the same quasar at $z_s = 1.64$. The Einstein Radius estimated from the DES images is 0.51′′. DES J2146–0047 is in the area of overlap between DES and the Sloan Digital Sky Survey (SDSS). Two blue components are visible in the DES and SDSS images. The SDSS fiber spectrum shows a quasar component at $z_s = 2.38$ and absorption compatible with Mg II and Fe II at $z_l = 0.799$, which we tentatively associate with the foreground lens galaxy. The long-slit Magellan spectra show that the blue components are resolved images of the same quasar. The Einstein Radius is 0.68″ corresponding to an enclosed mass of $1.6 \times 10^{11} M_\odot$. Three other candidates were observed and rejected, two being low-redshift pairs of starburst galaxies, and one being a quasar behind a blue star. These first confirmation results provide an important empirical validation of the data-mining and model-based selection that is being applied to the entire DES dataset.

\textbf{Key words:} gravitational lensing: strong – quasars: emission lines – methods: observational – methods: statistical
1 INTRODUCTION

Gravitationally lensed quasars provide unique insights into a variety of fundamental open problems in cosmology and extragalactic astrophysics (e.g. Courbin, Saha & Schechter 2002). When a quasar is strongly lensed by a galaxy, it results in multiple images of the same source, accompanied by arcs or rings that map the lensed host of the quasar. The light-curves of different images are offset by a measurable time-delay (e.g. Schechter et al. 1997) which depends on the cosmological distances to the lens and the source and the gravitational potential of the lens (Refsdal 1964). This enables one-step measurements of the expansion history of the Universe and the dark matter halos of the massive galaxies that act as deflectors (e.g. Suyu et al. 2014). The microlensing effect on the multiple quasar images, induced by stars in the deflector, provides a quantitative handle on the stellar content of the lens galaxies (e.g. Schechter & Wambsganss 2002; Oguri, Rusu & Falco 2014; Schechter et al. 2014). and can simultaneously provide constraints on the inner structure of the lensed quasar, both the accretion disk size and the thermal profile (e.g. Poindexter, Morgan & Kochanek 2008; Anguita et al. 2008; Eigenbrod et al. 2008; Motta et al. 2012) as well as the geometry of the broad line region (e.g. Sluse et al. 2011, Guerras et al. 2013, Braibant et al. 2014).

Futhermore, milli-lensing via the so-called flux ratio anomalies provides a unique probe of the mass function of structure and thus ultimately of the nature of dark matter (Mao & Schneider 1998; Metcalfe & Madau 2001; Metcalfe 2002; Dalal & Kochanek 2002; Nierenberg et al. 2014). Finally, source reconstruction of the lensed quasar and its host give a direct view of quasar-host coevolution up to $z \sim 2$ (Peng et al. 2006; Rusu et al. 2015).

Advancement in the field is currently limited by the paucity of known systems suitable for detailed follow-up and analysis. A large sample of new systems will be transformative. To accomplish this, the STRIDES project, a broad external collaboration of the Dark Energy Survey (DES, http://www.darkenergysurvey.org/index.shtml), aims at the discovery of the ~100 lensed quasars with primary image brighter than $i = 21$ mag predicted by Oguri & Marshall (2010) to lie within the DES footprint.

The identification of such rare systems over 5000 square degrees of DES imaging data is a classic needle-in-a-haystack problem. The challenge is possibly greater than that faced in the SDSS dataset (Oguri et al. 2006; Madg et al. 2008), as DES catalogs do not contain u-band data and there is no built-in spectroscopic dataset to aid in the quasar selection. Fortunately, the DES image quality (median seeing $\sim 0.9''$) is better than that of SDSS, so one can rely on more accurate morphological information for candidate selection. New techniques have been developed in order to address this challenge (Agnello et al. 2015; Chan et al. 2015).

Here we report on the first spectroscopic confirmation of lensed quasars from DES. We have obtained spectra of five of the 68 high-grade, small-separation candidate lensed quasars in the year-1 DES data release footprint (hereafter Y1A1, Diehl et al. 2014), covering $\approx 1200000$ square degrees in the Southern Hemisphere.

This Letter is organized as follows. Section 2 briefly illustrates the candidate-selection process and DES images of the two successful candidates from the first spectroscopic follow-up. Section 3 shows the long-slit spectroscopic data obtained for these systems. In Section 4 we present the lensing properties that can be inferred with current data and conclude in Section 5. Throughout this paper, DES and WISE magnitude are in the AB and Vega system respectively. When needed in Sect. 2, we adopt a concordance cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2 QUASAR LENS CANDIDATE SELECTION

We selected small-separation candidates from the DES Y1A1 data release, using a combination of colour cuts and data mining and model-based selection. Following Agnello et al. (2015) we adopt a multistep strategy, thereby targets are first selected from catalog data, and candidates are then selected from the targets by analysis of the actual multi-band images. This multistep procedure allows one to keep the problem computationally fast.

2.1 Preselection

Objects are preselected in the DES catalogue based on their ‘blue’ colours and extended morphology. The colour selection, satisfying $g - r < 0.6$, $r - i < 0.45$, $i - z < 0.55$, $2.5 < i - W1 < 5.5$, $0.7 < W1 - W2 < 2.0$,

$$g - i < 1.2(i - W1) - 2.8,$$  \hspace{1cm} (1)

is only used to exclude the majority of galaxies and nearby blue stars from the pool being examined. Of these, we retain those satisfying

$$\text{psf}_m - \text{model}_m \geq \text{dnmag}$$ \hspace{1cm} (2)

in DES $g, r, i$ bands simultaneously, with $\text{dnmag} = 0.125$ in $g, r$ bands and 0.2 in $i$ band. This ensures that the objects are not point-like (cf. Reed et al. 2015 who use a similar but converse criterion for point-like objects).

Out of $\sim 2 \times 10^5$ ‘blue’ systems, extended in $i-$band and with acceptable colours in DES $g, r, i, z$ and WISE $W1, W2$ magnitudes, $\sim 4000$ are brighter than limiting magnitudes $i = 21$ or $W1 = 17$ and extended also in $g, r$ bands.

2.2 Targets

Of the 4000 blue extended objects, targets are selected by neural network classifiers (ANNs) based on their photometry and multi-band morphology obtained at catalogue-level. In particular, DES model $g, r, i, z$ magnitudes and WISE $w1mpro$ ($W1$), $w2mpro$ ($W2$) magnitudes are used for the photometry and DES model position angles and axis ratios in $g, r, i, z$ are used for the morphology. ANNs produce membership probabilities for each object to belong to different classes, from which the targets are selected with cuts in output probabilities. The full procedure is discussed in detail

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1 STRong lensing Insight in the Dark Energy Survey, PI Treu, full list of Co-PIs and Co-Is at http://strides.physics.ucsb.edu
respectively. grade '3' candidates and 45, 51, 17 with grades '2', '1', '0' respectively. The final sample has 23 quantitative criteria listed above. The final sample has 23 discretion, even though the ranking is based on the four procedures (preselection, ANNs, modelling) to the investigator band. At this stage, the selection shifts from automatic procedures (preselection, ANNs, modelling) to the investigator discretion, even though the ranking is based on the four quantitative criteria listed above. The final sample has 23 grade '3' candidates and 45, 51, 17 with grades '2', '1', '0' respectively.

2.3 Candidates

The DES $g, r, i, z, Y$ image cutouts of selected targets have been modelled as combinations of point sources and galaxies to extract the SEDs of the extended and point sources. Based on the model results, we ranked candidates from '0' (not a lens) to '3' (good lens candidate), based on whether: (i) the point sources have consistent SEDs at least in $r, i, z$ bands; (ii) their SEDs are compatible with those of quasars; (iii) the fainter quasar image is also redder in $g - r$; (iv) a possible lens galaxy is detected in the residuals or in $Y$ band. At this stage, the selection shifts from automatic procedures (preselection, ANNs, modelling) to the investigator discretion, even though the ranking is based on the four quantitative criteria listed above. The final sample has 23 grade '3' candidates and 45, 51, 17 with grades '2', '1', '0' respectively.

2.4 First two confirmed lenses

Figure 1 shows DES multi-band, single-epoch images in the best seeing conditions of the two successful candidates for which we describe spectroscopic follow-up in the next Section. They are DES J0115−5244 at 01:15:57.32−52:44:23.20 (top) and DES J2146−0047 at 21:46:46.04−00:47:44.3 (bottom).

The photometry and relative astrometry of the components in our composite models are summarized in Table 1. We have used the single-epoch DES cutouts with best image quality and adopted DES models of the PSF from nearby stars. For DES J2146−0047, we also fit Moffat profiles with the same structural parameters to each quasar image and a Sérsic profile to the lensing galaxy in archival CFHT MegaCam $i, z$-band images (Programme 10BC22, PI: van Waerbeke). The resulting photometry is given in Table 1 below. The galaxy in DES J2146−0047 is above the detection limit in DES Y band and in CFHT $i, z$ bands.

![Figure 1](image-url)
3 SPECTROSCOPIC CONFIRMATION

Spectra were obtained with the Inamori Magellan Areal Camera and Spectrograph (IMACS, Dressler et al. 2011) on the Baade 6.5 m telescope on UT 2015 June 19. The f/4 camera was used with 0.70" slit mask. The data were binned factors of 2 along the slit, giving a scale of 0.22″/pixel, and 4 in the spectral direction, which combined with a 300 1/mm grating gave a dispersion of 2.92Å/pixel. Two CCDs covered the spectra over 3770 – 5260 Å and 5350 – 6880 Å. The seeing ranged between 0.8″ and 1.2″, and all our candidates were partially or completely resolved. Two spectra of 600s were taken for each object. The data were reduced using standard IRAF routines. One-dimensional (1D) spectra have been extracted by modelling the 2D spectra as superpositions of Gaussian tracks in the spatial dimension, one per component, having peak positions (p1, p2) that are linear functions of the wavelength with the same slope (dp/dλ). Even though the individual tracks are generally well separated, this procedure ensures that the resulting 1D spectra are as independent as possible from one another and exploit all the information available in the 2D tracks.

Five grade-‘3’ candidates were visible and observed. The resulting spectra are described below. The results on the two confirmed lenses are shown in Fig. 2.

3.1 DES J0115–5244

The 1D spectra of DES J0115–5244 show the same broad emission lines (C IV, He II, C III)] at z = 1.64, with a uniform ratio between the two spectra in the red, as shown in Figure 2 indicating that the low-order differences between the two spectra are due to differential reddening, or perhaps chromatic microlensing. Together with the presence of a red galaxy in the DES images, the spectra confirm DES J0115–5244 as a strongly lensed quasar, with image separation ≈ 1.04″. Unfortunately, the S/N-ratio is too low to securely detect stellar absorption lines from the deflector.

3.2 DES J2146–0047

The 1D spectra of DES J2146–0047 show two components with the same broad emission lines at z = 2.38, consistent with the public SDSS fiber spectrum. Prominent Mg II and Fe II absorption lines at zl = 0.799 are detected in both spectra (fig. 2). The ratio between the two spectra is constant, which together with the detection of a galaxy in zy bands confirms DES J2146–0047 as a strongly lensed quasar, with image separation ≈ 1.32″. We associate the lens redshift with the galaxy responsible for the absorption lines at zl. This system has been independently identified as part of the SDSS-III quasar lens sample (More et al., in prep).

3.3 False Positives

Two candidates, at 20:53:56.5 –56:09:36 and 22:17:52.5 –53:57:15 respectively, are pairs of compact, star forming galaxies. The third rejected candidate, at 22:00:24.11 +01:10:37.56, is an alignment of a z = 1.37 red quasar and a blue star, with the same r – i and i – z colours by coincidence.

In general, pairs of compact star forming galaxies at z ≈0.2–0.3 are the main residual contaminant from the candidate selection procedure, because their broad-band colours are consistent with those of quasars. This includes initial candidates that we rejected based on their available SDSS spectra. In WISE magnitudes, they tend to lie at r2 > 14 and W1 – W2 < 0.8, across the limiting locus of [Assef et al. 2013], a region that however is occupied also by spectroscopically-confirmed quasars and some of the candidates from this search.

4 LENSES PROPERTIES

Even though the current data are not sufficient for a detailed lensing model, they can be used to derive simple properties of the lens galaxies. To this aim, we adopt a Singular Isothermal Sphere (SIS) model for the mass density profile of the deflector, which is commonly considered the simplest model apt to describe galaxy-scale lenses (Treu 2010). The SIS projected surface density is

\[ \Sigma(R) = \frac{1}{2} \Sigma_{cr} (R/R_0)^{-1} \]  

with \( \Sigma_{cr} = c^2D_s/(4\pi GD_l D_s) \) in terms of angular-diameter distances to the source (\( D_s \)), to the lens (\( D_l \)) and between
Two additional candidates were ruled out by spectroscopic observations as pairs of compact, narrow-line galaxies. Another candidate was ruled out as an alignment of a quasar and a blue star. The basic characteristics of the two confirmed systems are as follows.

**DES J0115—5244**: Consists of two images of a quasar at $z_s = 1.64$ lensed by a foreground galaxy visible in the DES images. No redshift is available for the lens galaxy. The Einstein Radius is estimated to be $0.51''$.

**DES J2146—0047**: Consists of two images of a quasar at $z_s = 2.38$, with prominent Mg II absorption at $z_l = 0.799$, which we tentatively associate with the lens galaxy redshift. The redshift of the lensing galaxy is not confirmed in the spectroscopic follow-up by More et al. (in prep), since detection of the Mg II and Fe II lines depends on S/N ratio and in fact is less evident in the worse of our two exposures, where track deconvolution becomes more noisy. Thus, deeper spectroscopic data will be needed to measure the redshift of the deflector, possibly based on stellar absorption lines. The Einstein Radius is estimated to be $0.68''$.

The main class of contaminants (including candidates rejected based on their SDSS spectra) consists of groups of compact, star-forming galaxies at $z \sim 0.2 - 0.3$, because of their broad-band colours and compact morphology. With the observed sample, a strict cut in WISE $W1 - W2$ vs $W2$ would give a $100\%$ success rate, which drops at $40\%$ when the cut is relaxed. Still, with just five systems currently at hand, we would rather caution against these simple estimates.

Our search has delivered over 100 additional candidates from the Y1A1 data — and we expect many more from the next seasons of DES data. The results of this first follow-up effort are encouraging. However, a systematic follow-up campaign is needed to confirm large numbers of candidates, assess the purity of our selection technique, and carry out the many scientific investigations enabled by lensed quasars.

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