THE SLOAN BRIGHT ARCS SURVEY: SIX STRONGLY LENSED GALAXIES AT $z = 0.4–1.4$

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ABSTRACT

We present new results of our program to systematically search for strongly lensed galaxies in the Sloan Digital Sky Survey (SDSS) imaging data. In this study six strong lens systems are presented which we have confirmed with follow-up spectroscopy and imaging using the 3.5 m telescope at the Apache Point Observatory. Preliminary mass models indicate that the lenses are group-scale systems with velocity dispersions ranging from 464 to 882 km s$^{-1}$ at $z = 0.17 – 0.45$ which are strongly lensing source galaxies at $z = 0.4 – 1.4$. Galaxy groups are a relatively new mass scale just beginning to be probed with strong lensing. Our sample of lenses roughly doubles the confirmed number of group-scale lenses in the SDSS and complements ongoing strong lens searches in other imaging surveys. As our arcs were discovered in the SDSS imaging data they are all bright ($r \lesssim 22$), making them ideally suited for detailed follow-up studies.

Key words: gravitational lensing

1. INTRODUCTION

Gravitational lens systems provide the opportunity to study in detail the properties of distant galaxies through the magnification provided by lensing. Models of these systems also provide insight into the underlying mass distribution in the foreground lens. New samples of strong lenses have been enabled by the Sloan Digital Sky Survey (SDSS; York et al. 2000) with systems initially discovered in the SDSS spectroscopic data (Bolton et al. 2006). Because of the nature of the selection these are smaller separation systems ($< 3'$, the SDSS fiber diameter) consisting of a single Luminous Red Galaxy (LRG) lensing a background source galaxy. An additional parameter space to discover strong lenses is also provided by the SDSS imaging data, and a number of complementary programs are now underway in the SDSS to search for these systems (Belokurov et al. 2007; Estrada et al. 2007; Hennawi et al. 2008; Shin et al. 2008; Wen et al. 2009). Because of the moderate imaging quality (1′′FWHM in $r$) in the SDSS these systems typically have a larger lens–arc separation (greater than 3′′) which is outside of the regime probed by the SDSS spectroscopic lens survey. Motivated by the discovery of the 8 o’clock arc (Allam et al. 2007), the brightest lensed Lyman Break galaxy (LBG) currently known ($z = 2.73$), we have also initiated a program to systematically search for strong lens systems in the SDSS. Our program is focused on searching for lensed high-redshift galaxies in particular $z > 2$ lensed LBGs similar to the 8 o’clock arc. Since fall 2006 we have been following up candidate systems with imaging and spectroscopy using the 3.5 m telescope at Apache Point Observatory (APO) in New Mexico. The first lensed system discovered in our systematic search, a lensed LBG at $z = 2.0$ which we named the “Clone,” was recently reported in Lin et al. (2008). In addition to these lensed high-redshift galaxies we are also discovering a number of interesting lensed galaxies at lower redshift. In this paper, we present our first results on six of these lower-redshift systems which we have spectroscopically confirmed to be lensed galaxies, ranging in redshift from $z = 0.4 – 1.4$.

This Letter is organized as follows: details of initial candidate selection and follow-up imaging/spectroscopy are described in Section 2. Preliminary mass models of each system are presented in Section 3. In Section 4, we summarize our work and describe future directions of our survey. Throughout we assume a standard cosmology of $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2. DATA

2.1. Lens Search

The SDSS is an 8000 deg$^2$ spectroscopic and imaging survey using a dedicated 2.5 m telescope at APO (York et al. 2000). We searched for candidate strong lens systems using two systematic searches on the SDSS Data Release Five (DR5; Adelman-McCarthy et al. 2007) and Data Release Six (DR6; Adelman-McCarthy et al. 2008).

Our first candidate list is generated using the SDSS Catalog Archive Server (CAS) database. As described in Kubik (2007) and Lin et al. (2008) we performed two separate queries which searched for blue objects ($g – r < 1$ and $r – i < 1$) around a catalog of 221,000 Luminous Red Galaxies (LRGs; Eisenstein et al. 2001) and around a catalog of 29,000 Brightest Cluster Galaxies (BCGs) based on a version of the maxBCG cluster finder algorithm (Hansen et al. 2005). We separated systems into groups depending on the number of blue objects, $n$, around each LRG or BCG. This query produced 1081 objects with $n \geq 3$ which were visually examined by four separate inspectors. Systems were flagged by each inspector if they exhibited an arc-like morphology, consistent with a strongly lensed galaxy. Systems which the inspectors agreed were the most promising were then chosen for follow-up. Three confirmed systems discovered in this search are presented in Section 3.

Our second list of candidates is generated by searching a catalog of merging galaxies using the method described in Allam et al. (2004). This method was used in the initial discovery of the 8 o’clock arc (Allam et al. 2007). A candidate merging galaxy pair is defined here as two galaxies in the magnitude range $16.0 < g < 21.0$ separated by less than the sum of their respective Petrosian radii (Stoughton et al. 2002). This algorithm was run on imaging data from the SDSS DR6 and the resulting catalog was visually examined and classified. In total 5739 lensing candidates were initially flagged by the algorithm,
and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been and upon visual inspection this initial list was further reduced to a final list of 2761 objects having morphologies and colors similar to a strong lens. Three of these systems have been spectroscopically confirmed to be bona fide strong lens systems similar to a strong lens. Three of these systems have been

2.2. APO Imaging and Spectroscopy

We followed up candidates with both imaging and spectroscopy using the APO 3.5 m telescope. Imaging is obtained with the SPICAM CCD imager which has a field of view of 4.8′ × 4.8′ and a plate scale of 0.28′ per pixel. Each target in our program is imaged in three SDSS filters gri each with 3 × 300 s dithered exposures. As described in Lin et al. (2008) images are reduced using standard IRAF tasks, and are co-added using the SWarp package (Bertin 2006). The SPICAM images are photometrically calibrated by matching unsaturated stars in the co-added images to the photometry in the SDSS.

Follow-up spectroscopy of candidate arcs was performed with the Dual Imaging Spectrograph (DIS III), a medium dispersion double spectrograph which has separate red and blue channels. We used the standard medium red/low blue grating setup which covers a spectral range of 3600–9600 Å with a resolution of 2.43 Å per pixel in the blue and 2.26 Å per pixel in the red. Each arc in our sample was targeted with an exposure time of 3 × 900 s. We used a 1′.5 or 2′.0 slit which was typically oriented along the brightest segment of each arc in order to maximize the signal-to-noise ratio. Spectra were also reduced using standard IRAF tasks, described further in Lin et al. (2008). Dates for our follow-up observations were spread over two nights in 2007 (March 19 and November 14) and six nights in 2008 (January 30, February 8, April 5, April 30, May 27, and June 11).

3. LENS SAMPLE

Using the search techniques described in Section 2.1 we have followed-up and confirmed a sample of six strong lens systems. In Figures 1 and 2 (top row), we show color composite images of these six systems derived from our SPICAM gri imaging. Most systems have only a single visible arc, with the exception of SDSS J1113 which has a visible second arc.

Unfortunately, the resolution of our SPICAM imaging is relatively poor ∼1′.3–1′.6 so detailed models of the systems are not possible. Instead we adopt a simple model typically used to measure cluster scale lenses where we assume that each system consists of two foreground LRGs, the brightest of which, SDSS J103843.59 + 484917.7, has a spectroscopic redshift of z = 0.4256 ± 0.0003 from the SDSS database. The system contains two prominent arcs shown in Figure 1. We independently obtained DIS spectroscopy of the bright knot along the southern arc (the G knot in Belokurov et al. 2007) and measured the redshifted [O ii] 3727 line shown in Figure 1. This places the primary arc at a redshift of z, the arc would have dropped out from the g-band image due to the redshifted Lyman alpha break.

3.1. SDSS J1038 + 4849

SDSS J1038 + 4849 has been previously reported on by Belokurov et al. (2007) but also independently appeared in our n = 4 sample in our search around LRGs. The system consists of two foreground LRGs, the brightest of which, SDSS J103843.59 + 484917.7, has a spectroscopic redshift of z = 0.4256 ± 0.0003 from the SDSS database. The system contains two prominent arcs shown in Figure 1. We independently obtained DIS spectroscopy of the bright knot along the southern arc (the G knot in Belokurov et al. 2007) and measured the redshifted [O ii] 3727 line shown in Figure 1. This places the primary arc at a redshift of z, which Belokurov et al. (2007) noted is likely a different lensed source galaxy due to the absence of any [O ii] 3727 in the spectrum. They use a lack of this emission line to place a redshift limit on this arc of z > 1.4. We estimate an Einstein radius for this system of 8, which gives a velocity dispersion of σv = 768 km s−1 and an enclosed mass of 14.0 × 1012 M⊙.

3.2. SDSS J1049 + 4420

SDSS J1049 + 4420 was selected from our n = 3 sample in our search around BCGs. The system contains one BCG with a spectroscopic redshift of z = 0.2303 ± 0.0002 from the SDSS database, with a small blue r = 21.20 arc (SDSS J10493.32 + 44203.2) to the east (Figure 1). In our follow-up DIS spectroscopy of the blue arc we identify five strong emission lines, specifically [O ii] 3727, Hβ, [O iii] 4959, [O iii] 5007, and Hα (Figure 1) from which we obtain a secure redshift of z, the source galaxy is the lowest redshift arc in our entire sample, but the lensing hypothesis is still valid. We estimate an Einstein radius of 7.2 for this system, which gives a velocity dispersion of 805 km s−1 and an enclosed mass of 8.8 × 1012 M⊙.

3.3. SDSS J1113 + 2356

SDSS J1113 + 2356 was identified from the merging galaxy catalog described in Section 2.1 and is a small group consisting of one LRG and two bright red galaxies (r = 16.46, 20.57, 18.31 from east to west) with a bright 12′6 long arc to the southeast (Figure 1). The SDSS database places the redshift of the LRG at z = 0.3361 ± 0.0002 (Table 1). Photometric redshifts of the two neighboring red galaxies from the SDSS Photoz2 database (Oyaizu et al. 2008) are within 2σ of the LRG redshift. For spectroscopic confirmation we oriented the slit along the brightest segment of the arc and measured redshifted [O ii] 3727 emission line in the DIS spectrum (Figure 1). This places the redshift of the arc at z, confirming this as a lens system. The deeper SPICAM imaging also reveals a possible fainter extension of the arc to the west but spectra of this portion of the arc was not measured. The measured Einstein angle of the system is θE = 11′.5 which corresponds to a σv = 882 km s−1 and an enclosed mass of 21.7 × 1012 M⊙.

3.4. SDSS J1137 + 4936

SDSS J1137 + 4936 was also selected from our merging galaxy catalog. The system is comprised of a single LRG at z = 0.4483 ± 0.0002 with a blue arc located to the east. In
the SDSS imaging the arc is split into two knots, the brightest (SDSS J113740.44 + 493635.8) with $r = 20.43$ and a fainter knot (SDSS J113740.26 + 493638.9) with $r = 22.33$ (Figure 2). The fainter knot is misclassified by the SDSS database as a star. DIS spectroscopy of the source was measured along the bright knot and we obtain a redshift $z = 1.411$ based on a strong [O ii] 3727 emission line (Figure 2). This single emission line is corroborated by a number of Mg and Fe absorption features commonly observed in the optical spectra of galaxies at similar redshifts, e.g., see Figure 9 of Abraham et al. (2004). As shown in Figure 3, we see strong absorption due to Mg ii 2798, Mg ii 2803, Mg i 2852, Fe ii 2586, and Fe ii 2600, as well as weaker absorption from Fe ii 2344, Fe ii 2374, and Fe ii 2382, all at $z = 1.41$, consistent with the [O ii] 3727 redshift. In addition, we also see strong absorption from Fe ii 2586, 2600 and Mg ii 2798, 2803 from an apparent second source galaxy at $z = 1.38$. As far as we can tell from our DIS spectroscopy (done under 2″ seeing), there is no spatial separation between the $z = 1.41$ and $z = 1.38$ absorption features, and we will need spectroscopy under better seeing conditions in order to improve the spatial
resolution. Given the present data, we interpret this system as two sources, with redshifts $z = 1.411$ and $z = 1.38$, both being lensed by a foreground LRG at $z = 0.4483$. As the bulk of the spectroscopic features are at $z = 1.411$, we adopt that value in the velocity dispersion calculation. For this system we measure an Einstein radius of 3.7, which gives a corresponding $\sigma_v = 464 \text{ km s}^{-1}$ and an enclosed mass of $2.3 \times 10^{12} \, M_\odot$.

3.5. SDSS J1511 + 4713

SDSS J1511 + 4713 was discovered in our search around SDSS LRGs and fell into our $n = 3$ sample. It consists of a foreground LRG with a spectroscopic redshift from the SDSS database of $z = 0.4517 \pm 0.0003$, with an extended blue arc (SDSS J1511 + 4713) directed to the south (Figure 2). The arc contains three bright knots having a total estimated length of 10 prim. For spectroscopic followup we oriented the slit along the brightest segment of the arc and measured the redshifted [O ii] 3727 emission line (Figure 2). This places the arc at a redshift of $z = 0.985$, confirming this as a lens system. We estimate the Einstein radius for the system to be 5.4 which gives a velocity dispersion of $\sigma_v = 631 \text{ km s}^{-1}$. This corresponds to an enclosed mass of $6.3 \times 10^{12} \, M_\odot$.

3.6. SDSS J1629 + 3528

Our final system, SDSS J1629 + 3528 was also selected from our merging galaxy catalog and contains one primary LRG with a bright ($r = 19.09$) blue arc to the west. A spectroscopic redshift for the LRG is not available in the SDSS database as its magnitude ($r = 19.09$) is too faint to be included in the main spectroscopic survey. We have obtained DIS spectroscopy of the LRG showing strong absorption features that yield a redshift of $z = 0.170$ (not shown). For the blue arc we measure the redshifted [O ii] 3727 emission line shown in Figure 2 which places the arc at a redshift $z_s = 0.850$. We have also measured the [O ii] 4958 and [O iii] 5007 emissions lines (not shown) which further corroborate this redshift and confirm this as a lens system. From our estimate of the Einstein radius (5.8) this gives a velocity dispersion of $\sigma_v = 510 \text{ km s}^{-1}$ and an enclosed mass of $2.1 \times 10^{12} \, M_\odot$. We note that the SDSS imaging also indicates a small companion galaxy which is embedded within the brighter LRG, however in our current imaging resolution we cannot estimate its magnitude.

4. SUMMARY

We have presented six confirmed group-scale strong lenses from our search program in the SDSS. Although the focus of our survey is to confirm high-redshift ($z \sim 2$) lensed galaxies similar to the 8 o’clock arc (Allam et al. 2007) and the Clone (Lin et al. 2008), we are discovering a number of lensed galaxies lying at lower redshift. These systems were initially discovered via two systematic searches of the SDSS DR5 database and from a separate search of a catalog of candidate merging galaxies based on the SDSS DR6. The arcs in our confirmed systems are relatively bright $r < 22$, making them ideal candidates for detailed follow-up studies.

Our initial follow-up APO SPICAM imaging has relatively poor resolution but preliminary modeling indicates that these systems are group-scale lenses, an intermediate regime between isolated galaxies and galaxy clusters. This is a relatively new regime that imaging surveys are just beginning to probe with
strong lensing (Cabanac et al. 2007). In the SDSS a handful of other group-scale lenses have been recently reported (Belokurov et al. 2007; Shin et al. 2008) and our work roughly doubles the number of these systems discovered in the SDSS. Additional high-resolution imaging will allow for more detailed models of these systems which will yield precise measurements of the mass distribution in the lens and detailed studies of the source galaxy in each system. Future papers in this series will describe our sample of confirmed lensed $z = 2 - 3$ galaxies as well as the results of our ongoing follow-up programs using HST, Spitzer, and other telescopes.

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