

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 3.5m telescope at the Apache Point Observatory. Preliminary mass models indicate that the lenses are group-scale systems with velocity dispersions ranging from $466 - 878 \text{ km s}^{-1}$ 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 such as the CFHTLS (Cabanac et al. 2007). 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.

Subject headings: 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 (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 width of the SDSS fiber radius) 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

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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. 2008). Because of the moderate imaging quality ($1.4''$ FWHM in r) in the SDSS these systems typically have a larger lens-arc separation ($> 3.0''$) 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 LBG's similar to the 8 o'clock arc. Since Fall 2006 we have been following up candidate systems with imaging and spectroscopy using the 3.5m 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 §2. Preliminary mass models of each system are presented in §3. In §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 square degree spectroscopic and imaging survey using a dedicated 2.5m 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).

Our first candidate list was 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 (LRG's) (Eisenstein et al. 2001) and around a catalog of 29,000 Bright Cluster Galaxies (BCG's) based on the maxBCG cluster finder algorithm (Koester 2007). We separated systems into groups depending on the number of blue objects found

around each LRG or BCG where the number of blue objects, n , was 2, 3, or ≥ 4 . Each list was visually inspected by four separate inspectors. Based on their morphology, candidates were then ranked on their likelihood of being an arc. The most promising systems in this search were chosen for follow-up. Three confirmed systems discovered in this search are presented in §3.

Our second list of candidates is generated from 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). In this technique a candidate merging galaxy pair is defined 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. Lensing candidates were flagged by the algorithm if their morphologies and colors were similar to a strong lens. Three of these systems have been spectroscopically confirmed to be strong lens systems and are discussed in §3.

2.2. APO Imaging and Spectroscopy

We followed-up candidates with both imaging and spectroscopy using the APO 3.5m telescope. Imaging is obtained with the SPICAM CCD imager which has a field of view of $4.8' \times 4.8'$ and a plate scale of $0.28''$ per pixel. Each target in our program is imaged in three SDSS filters gri each with $3 \times 300s$ 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 $3600 - 9600\text{\AA}$ with a resolution of 2.43\AA per pixel in the blue and 2.26\AA per pixel in the red. Each arc in our sample was targeted with an exposure time of $3 \times 900s$. 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 all of our follow-up observations with SPICAM and DIS are summarized in Table 1.

3. Lens Sample

Using the search techniques described in §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 J103843.59 + 484917.7 which has a visible second arc. The lens-arc separation in the systems range from $\sim 3.7'' - 11.5''$ indicating that the lens galaxies are not isolated galaxies. The color SPICAM imaging reveals several nearby galaxies in most of the systems indicating that these lenses are likely in groups or poor cluster environments.

Unfortunately the resolution of our SPICAM imaging is relatively poor $\sim 1.3 - 1.6''$ so detailed models of the systems are not possible. Instead we adopt a simple model typically used to measure cluster scale lenses (Gladders, Yee, Ellingson 2002) where we assume that each system can be described by a singular isothermal sphere (SIS). The Einstein radius of an SIS is given by

$$\theta_E = 4\pi \frac{\sigma^2 D_{ls}}{c^2 D_s} \quad (1)$$

where D_{ls} is the angular diameter distance between the lens-source and D_s is the angular diameter distance to the source. As in Kubik (2007), we estimate the Einstein radius from the measured lens-arc separation and knowing the lens and source redshift in each system we can calculate the velocity dispersion. The resulting velocity dispersions are given in Table 2 which range from $\sim 466 - 887 \text{ kms}^{-1}$, typical for group scale objects. We also estimate the corresponding mass within the Einstein radius of each system from

$$M(< \theta_E) = \frac{c^2}{4G} \frac{D_s D_l}{D_{ls}} \theta_E^2. \quad (2)$$

Below we briefly comment on each individual system, but we note here that redshifts of four of the systems rely on a single strong emission line seen in the red DIS spectrum. In each case the line is best interpreted as [OII] 3727, whereas if the line were H α or [OIII] 5007, we do not see the expected strong [OII] 3727 in the blue spectrum. Similarly, if the line were Lyman alpha at high redshifts $z > 4$, the arc would have dropped out from the g-band image due to the redshifted Lyman 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 $n \geq 4$ sample in our search around LRG's. The system

consists of two foreground LRG’s, the brightest of which, SDSS J103843.58+484917.7, has a spectroscopic redshift of $z = 0.4256 \pm 0.0003$ 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 segment (the G knot in Belokurov et al. (2007)) and measured the redshifted [OII] 3727 line shown in Figure 1. This places the primary arc at a redshift of $z_s = 0.966$ which is in excellent agreement with the redshift reported by Belokurov et al. (2007). We did not obtain a spectroscopic redshift of the second arc, which Belokurov et al. (2007) noted is likely a different lensed source galaxy. We estimate an Einstein radius for this system of $8.4''$ which gives a velocity dispersion of $\sigma_v = 768 \text{ km s}^{-1}$ and an enclosed mass of $14.0 \times 10^{12} M_\odot$.

3.2. SDSS J1049 + 4420

SDSS J1049 + 4420 was selected from our $n = 3$ sample in our search around BCG’s. The system contains one BCG with a spectroscopic redshift of $z = 0.2303 \pm 0.0002$ from the SDSS database, with a small blue $r = 21.20$ arc (SDSS J104943.82 + 442034.2) to the East (Figure 1). In our follow-up DIS spectroscopy of the blue arc we identify five strong emission lines, specifically [OII] 3727, $H\beta$, [OIII] 4959, [OIII] 5007, and $H\alpha$ (Figure 1) from which we obtain a secure redshift of $z_s = 0.389$. The relative strength of the [OIII] doublet is in the expected 1:3 ratio. 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 $8.8 \times 10^{12} M_\odot$.

3.3. SDSS J1113 + 2356

SDSS J1113 + 2356 was identified from the merging galaxy catalog described in §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 $z = 0.3361 \pm 0.0002$ (Table 2). Redshifts of the two red galaxies are unknown but have the same color as the LRG and are therefore likely at the same redshift. For spectroscopic confirmation we oriented the slit along the brightest segment of the arc and measure redshifted [OII] 3727 emission line in the DIS spectrum (Figure 1). This places the redshift of arc at $z_s = 0.766$, 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 $\theta_E = 11.5''$ which corresponds to a $\sigma_v = 882 \text{ km s}^{-1}$ and an enclosed mass of

$21.7 \times 10^{12} M_{\odot}$.

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 $z = 0.4483 \pm 0.0002$ 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 [OII] 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 Fig. 9 of Abraham et al. (2004). As shown in Figure 3, we see strong absorption due to MgII 2798, MgII 2803, MgI 2852, FeII 2586, and FeII 2600, as well as weaker absorption from FeII 2344, FeII 2374, and FeII 2382, all at $z = 1.41$, consistent with the [OII] 3727 redshift. In addition, we also see strong absorption from FeII 2586,2600 and MgII 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 LRG's 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 $10.1''$. For spectroscopic follow-up we oriented the slit along the brightest segment of the arc and measured the redshifted [OII] 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 $\sigma_v = 631 \text{ km s}^{-1}$ assuming an

SIS model. 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 [OII] 3727 emission line shown in Figure 2, which places the arc at a redshift $z_s = 0.850$, confirming 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 at 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 ($z = 2 \sim 3$) 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. 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). 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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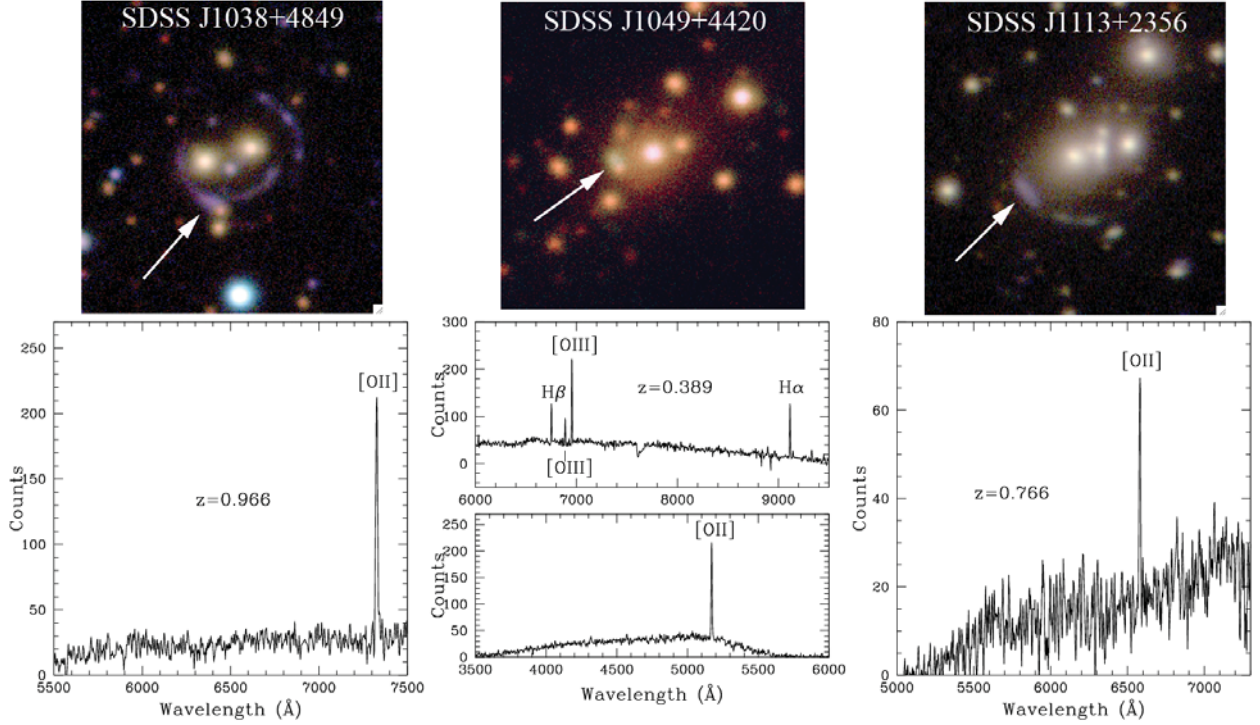


Fig. 1.— (Top row) : Color composite images of our strong lens systems derived from our SPICAM *gri* imaging. In each the arrow points to the knot in the lensed background galaxy for which we obtained spectroscopy. Images have dimensions $1' \times 1'$. (Bottom row): DIS spectroscopy of the corresponding lensed source galaxy. A strong [OII] 3727 emission line is measured in each lensed source galaxy.

Table 1. Observing Log

System	SPICAM Imaging	DIS Spectroscopy
SDSS J1038 + 4849	2008 Jan 3	2008 Feb 8
SDSS J1049 + 4420	2008 Jan 3	2007 Mar 19
SDSS J1113 + 2356	2008 Jan 3	2007 Nov 14
SDSS J1137 + 4936	2008 Apr 5	2008 May 27
SDSS J1511 + 4713	2008 Jun 11	2007 Mar 19
SDSS J1629 + 3528	2008 Jun 11	2008 Apr 30

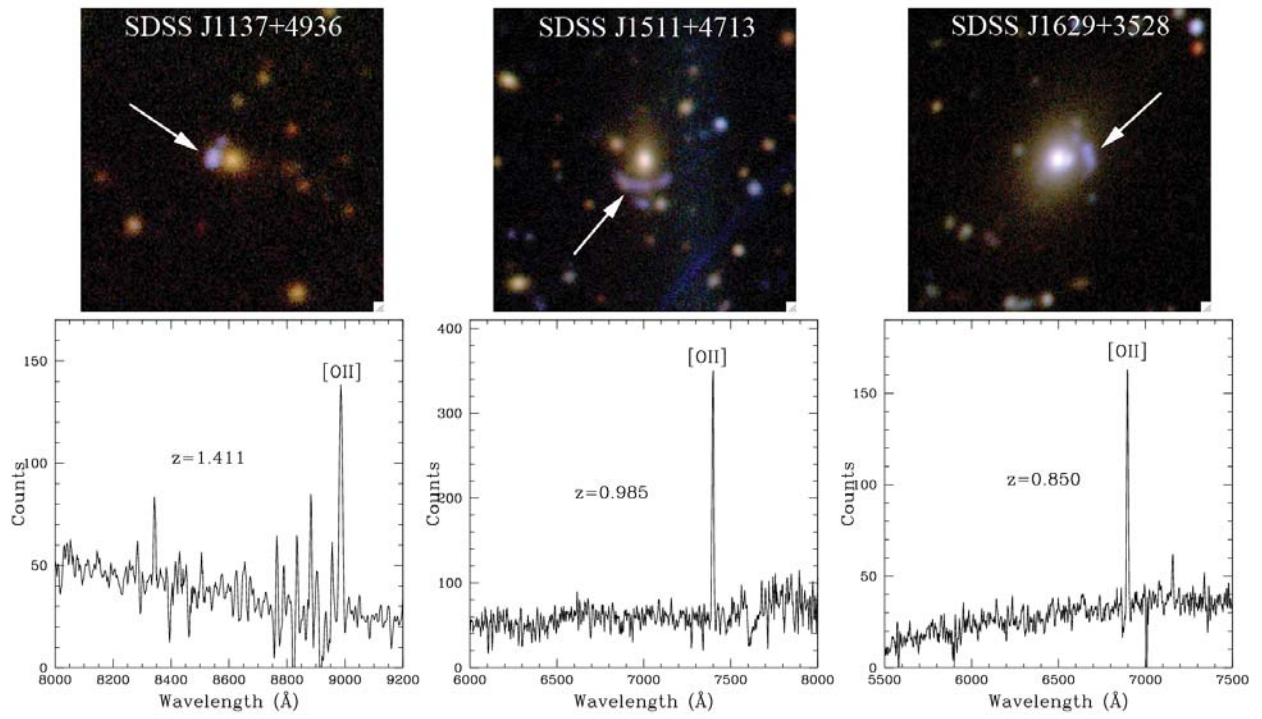


Fig. 2.— Same as in Figure 1. Additional spectral features for SDSS J1137 + 4936 are shown in Figure 3.

SDSS J1137+4936

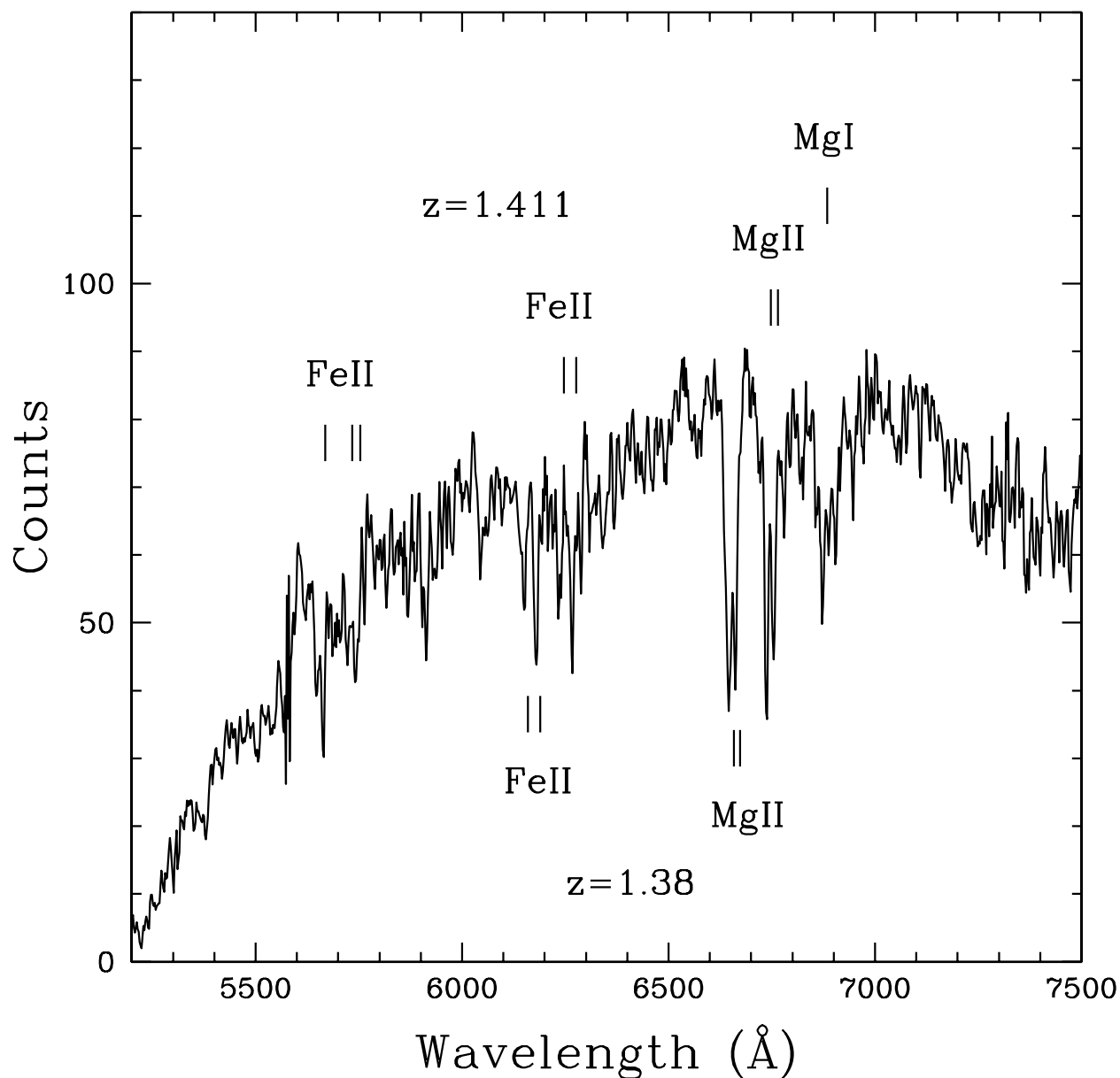


Fig. 3.— Additional spectra lines of the lensed galaxy in SDSS J1137 + 4936. Strong absorption due to MgII 2798, MgII 2803, MgI 2852, FeII 2586, and FeII 2600 are seen, as well as weaker absorption from FeII 2344, FeII 2374, and FeII 2382, all at $z = 1.41$. This is consistent with the [OII] 3727 redshift in Figure 2. Strong absorption from FeII 2586,2600 and MgII 2798,2803 from an apparent second source galaxy at $z = 1.38$ is also seen. With our current level of data our interpretation is that there are two source galaxies with redshifts $z = 1.411$ and $z = 1.38$, being lensed by a foreground LRG at $z = 0.4483$.

Table 2. Lens Parameters for Each System

System	R.A. (deg)	Decl. (deg)	z_l	z_s^b	θ_E (")	σ_v (km s ⁻¹)	$M(< \theta_E)$ (10 ¹² h ⁻¹ M _⊙)	length (")	$(g, r, i)_{\text{lens}}^c$
SDSS J1038 + 4849	159.6816	48.8216	0.4256 ^a	0.966	8.4	768	14.0	16.6	(20.33,18.59,17.87)
SDSS J1049 + 4420	162.4298	44.3432	0.2303 ^a	0.389	7.2	805	8.8	3.6	(18.56,16.96,16.47)
SDSS J1113 + 2356	168.2944	23.9443	0.3361 ^a	0.766	11.5	882	21.7	12.6	(18.18,16.46,15.83)
SDSS J1137 + 4936	174.4169	49.6099	0.4483 ^a	1.411	3.7	464	2.3	5.3	(21.18,19.38,18.64)
SDSS J1511 + 4713	227.8281	47.2279	0.4517 ^a	0.985	5.4	631	6.3	10.1	(20.12,18.37,17.55)
SDSS J1629 + 3528	247.4773	35.4776	0.17 ^b	0.850	5.8	510	2.3	3.0	(18.15,16.91,16.42)

^aSpectroscopic redshift from the SDSS database

^bSpectroscopic redshift determined using DIS on the APO 3.5m

^cGalaxy model magnitude (Stoughton et al. 2002) from the SDSS database