TWO LENSED $z \simeq 3$ LYMAN BREAK GALAXIES DISCOVERED IN THE SDSS GIANT ARCS SURVEY

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ABSTRACT

We report the discovery of two strongly lensed $z \simeq 3$ Lyman break galaxies (LBGs) discovered as $u$-band dropouts as part of the SDSS Giant Arcs Survey (SGAS). The first, SGAS J122651.3+215220 at $z = 2.9233$, is lensed by one of several sub-clusters, SDSS J1226+2152, in a complex massive cluster at $z = 0.43$. Its $(g, r, i)$ magnitudes are $(21.14, 20.60, 20.51)$ which translate to surface brightnesses, $\mu_{g,r,i},$ of $(23.78, 23.11, 22.81)$. The second, SGAS J152745.1+065219, is an LBG at $z = 2.7593$ lensed by the foreground SDSS J1527+0652 at $z = 0.39$, with $(g, r, z) = (20.90, 20.52, 20.58)$ and $\mu_{g,r,z} = (25.15, 24.52, 24.12)$. Moderate resolution spectroscopy confirms the redshifts suggested by photometric breaks and shows both absorption and emission features typical of LBGs. Lens mass models derived from combined imaging and spectroscopy reveal that SGAS J152745.1+065219 is highly magnified source ($M \simeq 40$), while SGAS J152745.1+065219 is magnified by no more than $M \simeq 15$. Compared with LG survey results, the luminosities and lensing-corrected magnitudes suggest that SGAS J122651.3+215220 is a highly luminous LBG at $z \sim 3$ and is lensed by a massive cluster at $z \sim 0.43$. The second, SGAS J152745.1+065219, on the other hand, has an unlensed $r$-band apparent magnitude similar to that of the “Cosmic Eye,” which places it near the mean of LBG survey results over similar redshifts.

Key words: early universe – galaxies: formation – galaxies: high-redshift – gravitational lensing: strong

Online-only material: color figures

1. INTRODUCTION

In the sequence of gravitational collapse, heating, stellar ignition, and death that govern the evolution of baryons in the earliest overdensities, Lyman break galaxies (LBGs) serve as high-redshift way points on the path to the $z \sim 0$ galaxies we observe today (e.g., Adelberger et al. 1998; Steidel et al. 2003). In star-forming galaxies at $z \sim 3$, the Lyman continuum break at 912 Å resides in blue optical bands ($u, g$), while the continuum itself can be detected at redder wavelengths ($g, r$). These features have motivated the construction of photometric surveys that rely on this “dropout” technique (Steidel et al. 1995, and references therein) to select hundreds of likely LBGs at $z \sim 3$ (Steidel et al. 1996, 2003; Adelberger et al. 2003). However, typical samples of LBGs consist of tens of objects with fluxes too faint to permit detailed spectroscopic observations (e.g., Nesvadba et al. 2006) of individual systems. Shapley et al. (2003) addressed this shortcoming by creating a high signal-to-noise ratio ($S/N$) composite spectra from low $S/N$ spectra of $\sim 1000$ LBGs to infer the properties of the average LBG.

Alternatively, since the discoveries of MS1512-cB58 at $z = 2.7$ (cB58; Yee et al. 1996) and A2218-384 at $z = 2.515$ (Ebbels et al. 1996) strongly lensed LBGs magnified tens of times have offered a high $S/N$ window (Teplitz et al. 2000; Pettini et al. 2002) into the conditions of individual star-forming galaxies when the universe was less than 2 Gyr old. For example, the presence of ultraviolet absorption lines in cB58 (Pettini et al. 2000, 2002) reveals a chemically diverse interstellar medium (ISM), which suggests that most of the metal enrichment occurred within the previous $\sim 300$ Myr and that the energetic star formation drives a bulk outflow of the ISM that exceeds the star formation rate. Studies of cB58 with Spitzer (e.g., Siana et al. 2008) have recently brought the IR observations into the picture, suggesting that the UV-inferred star formation rate is a factor of $\sim 3$ lower than that measured in the IR.

Following the discoveries of cB58 and A2218-384, several additional strongly lensed LBGs have been added to literature: 1E0657-56 at $z = 3.24$ (Mehlert et al. 2001), the Einstein Ring at $z = 3.773$ (Cabanac et al. 2005), J1011+0143 at $z = 2.701$ (Bolton et al. 2006), the Sextet Arcs at $z = 3.038$ (Frye et al. 2007), the Cosmic Horseshoe at $z = 2.379$ (Belokurov et al. 2007), the 8 o’clock arc (Allam et al. 2007) at $z = 2.73$, and the Cosmic Eye at $z = 3.07$ (Small et al. 2007). The success of this growing sample of magnified LBGs continues to spawn more detailed observations, as spectroscopy (e.g., Finkelstein et al. 2009), space-based IR (e.g., Siana et al. 2009), and millimeter (e.g., Coppin et al. 2007) observations are now beginning to paint a detailed picture of $z \sim 3$ LBGs but still leave many unanswered questions.

In this Letter, we report the discovery of two more strongly lensed LBGs and include a description of their basic properties. Given the burgeoning rate of discovery of large samples of lensed sources (e.g., Gladders 2005; Cabanac et al. 2007; Hennawi et al. 2008), we refrain from assigning nicknames to the sources discussed here; instead, we introduce designations of the form SGAS $JHMMSS.s+DDMSS$ to denote lensed sources and SDSS $JHMM+DDMM$ to denote the cluster lenses. Where necessary, we assume a flat ($\Omega_m, \Omega_{\Lambda} = (0.27, 0.73)$ cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$. 
Beginning in 2005 May, we initiated the SDSS Giant Arcs Survey (SGAS; Hennawi et al. 2008), a blind survey for strong-lensing systems in massive clusters at $0.1 < z < 0.6$ detected in the Sloan Digital Sky Survey (SDSS; York et al. 2000) using the SDSS adaptation of the Red-Sequence Cluster algorithm (Gladders & Yee 2000). Clusters are blindly chosen and imaged in the $g$ band at 2 m to 4 m class telescopes for 600 s in $<1''$ seeing and then visually inspected for giant arcs. For the most promising sources, follow-up imaging and low-resolution spectroscopy at 8 m class telescopes are used to study the sources in detail, and to secure the redshift of the putative lensed source. In some cases, we have obtained medium-resolution spectroscopy to begin to explore the intrinsic properties of the arcs themselves. As of 2009 May, the blind survey includes nearly 600 clusters with initial imaging follow-up, tens of which are new strong lenses. SGAS 152745+065219 was discovered in 2005 May on the 3.5 m WIYN telescope at Kitt Peak and presented as a probable lensing system in Hennawi et al. (2008). As part of the spectroscopic follow-up program (see below), we obtained redshifts for 13 cluster members that set the redshift of the cluster lens at $z = 0.39$, with $\sigma_z \simeq 908$ km s$^{-1}$. In 2007 December, SGAS 122651+215220 was discovered at the 2.5 m Nordic Optical Telescope. The lens photometric redshift, $z = 0.43$, for SDSS J1226+2152 has since been confirmed by several objects from the SDSS spectroscopic survey and GMOS spectroscopy. Notably, a separate arc in this same system was deemed a "probable" lensing galaxy by Wen et al. (2009) (NSCS J122648.0+215157). The lens itself is one of several sub-clusters that includes MACS J1226.8+2153 which is centered $\simeq 2.5'$ to the south. A summary of the source properties is given in Table 1.

### Table 1

| Lens or Source Property | SGAS J122651.3+215220 | SGAS J152745.1+065219 |
|-------------------------|------------------------|------------------------|
| Cluster lens            | SDSS J1226+2152        | SDSS J1527+0652        |
| Cluster centroid         | (12:26:51.74,+21:52:25.57) | (15:27:45.15,+06:52:25.70) |
| Arc ($\alpha, \delta$)  | (12:26:51.34,+21:52:20.26) | (15:27:45.17,+06:52:19.17) |
| Arc total mag$^a$ ($g, r, i/z$) | (21.14,20.60,20.51) | (20.90,20.52,20.58) |
| Lens magnification       | $\simeq 40$            | $\lesssim 15$          |
| Arc source mag$^b$ ($g, r, i/z$) | (25.16,24.61,24.52) | (23.90,23.52,23.5) |
| Arc $\mu$ (mag arcsec$^{-2}$) | (23.78,23.11,22.81) | (25.15,24.52,24.12) |

**Notes.**

$^a$ The BCG coordinates are given for SDSS J1226+2152, while the luminosity-weighted centroid coordinates are used for SDSS J1527+0652.

$^b$ SGAS J122651.3+215220 is measured in $g, r, i$ and SGAS J152745.1+065219 in $g, r, z$; errors on magnitudes are typically $\pm 0.05$ mag.

$^c$ Source magnitude corrected for assumed lens magnification.

### 2. DATA

#### 2.1. SGAS

### 2.2. Image and Photometric Calibration

In preparation for initial spectroscopy of probable arcs, deeper multi-band imaging was acquired in addition to pre-existing SGAS discovery images. Pre-imaging exposures totaling 5 minutes in length in $g, r, i$ acquired with the GMOS instrument on the 8 m Gemini North telescope were used to design slit masks for the cluster SDSS J1226+2152. GMOS images were reduced using the Gemini IRAF$^9$ package. A composite color image is shown in Figure 1. SDSS J1527+0652 serendipitously falls in a Red-Sequence Cluster Survey-2 (RCS2) field, which supplies 4, 8, and 6 minute exposures in $g, r, z$ with MegaCam on the 3.6 m Canada–France–Hawaii Telescope (CFHT) telescope; the composite color image is also shown in Figure 1.

The images are transformed to a common reference frame in the $i$ band for SGAS 122651+215220 and the $r$ band for SGAS J152745.1+065219, and calibrated against the SDSS. We construct an empirical, normalized point-spread function (PSF) for each image based on a well-defined, non-saturated, isolated reference star. The three bands have nearly identical seeing, and PSF mismatches are non-existent and can be safely ignored. Apertures are created by first defining a curve along the long axis of the extended source and convolving this curve with the appropriate PSF. The effective aperture is then defined as a contour of this convolution that is at exactly 2.5 times the FWHM of the PSF. Both sources lie close to one or more members of the foreground galaxy cluster in projection. We use the GALFIT package (Peng et al. 2002) to fit a Sersic profile to these cluster members in each of the images and subtract their flux. After carefully removing the sky level and masking any remaining outliers in the outskirts of the apertures (pixel values more extreme than $\pm 5\sigma$), the final magnitude is measured in the effective aperture defined above and corrected to an equivalent radius of 6" based on the curve of growth of the PSF star.

#### 2.3. Spectroscopy

Spectra (Figure 2) of the 3100–8000 Å region were obtained with the Magellan Echellette (MagE) spectrograph (Marshall et al. 2008) on the Magellan Clay 6.5 m telescope, using a 2\arcsec slit. The spectrum for SGAS J122651.3+215220 is a combination of three observations from 2008 February 9, 2009 April 22, and 2009 April 23 UT, with a total integration of 6.1 hr. The spectrum for SGAS J152745.1+065219 is from the night of 2009 April 23 UT, with a total integration of 1.5 hr. The data were bias-subtracted, flat-fielded, sky-subtracted, optimally extracted, and wavelength-corrected following the methods in Kelson (2003). Our implementation of these methods is custom-built code written in Python, similar to the MIKE pipeline. Each slit was aligned with the parallactic angle and positioned at the

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8 IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatory, which is operated by AURA, Inc., under cooperative agreement with the National Science Foundation.

9 http://obs.carnegiescience.edu/Code/mike
peak brightness in $g$ band. Each spectrum shows a damped Ly$\alpha$ emission line along with characteristic UV metal absorption lines (C$\text{II}$, Si$\text{II}$, Si$\text{III}$, Si$\text{IV}$) all consistent with redshifts of $z = 2.7593$ and $z = 2.9233$, for SGAS J152745.1+065219 and SGAS J122651.3+215220, respectively.

3. LENS PROPERTIES AND MASS MODELING

To understand luminosity-dependent source properties, a lens mass model is needed to correct for the magnification effect, $M$. The redshift, morphology, and position of the lensed LBG relative to the cluster center permit simple modeling of the cluster lens, as has been done in other systems. However, unlike other lensed LBGs (e.g., Cosmic Eye, 8 o’clock arc), neither source is multiply imaged, which reduces the robustness of the lens model. Moreover, the fact that these lenses were originally selected as massive galaxy clusters highlights the complexity of the lens relative to lensing by a single galaxy. The lens modeling is executed via lenstool (Jullo et al. 2007).

The cluster SDSS J1226+2152 (Figure 3) is dominated by a central brightest cluster galaxy (BCG), around which several lensed features are detected. As part of our spectroscopic follow-up campaign, redshifts were secured for some of these background sources. In addition to the LBG, SGAS J122651.3+215220, at $z = 2.9233$, we have secured the redshift of a giant arc at $z = 2.923$, a source that Wen et al. (2009) noted is a “probable” lensed galaxy; this is suggestive of a high-redshift galaxy pair or group. Other background sources appear at $z = 0.772$ and $z = 0.732$. Possible counter-images for any of these sources, if they exist, were not identified in the data.
The SDSS J1226+1252 lens model is composed of a cluster halo that is represented by a Navarro–Frenk–White (NFW; Navarro et al. 1996) profile: the BCG is represented by a pseudo-isothermal ellipsoid mass distribution (PIEMD; Jullo et al. 2007), with parameters that follow the observed light distribution of the galaxy. External shear is also included from the neighboring cluster MACS J1226.8+2153, 153′12 south and 8′6 west of the BCG, represented as a circular PIEMD with $\sigma_c \sim 1000 \kms$. We allowting the parameters of the NFW halo to vary as well as the velocity dispersion of the BCG and the external shear. The best-fit model is determined using Markov Chain Monte Carlo (MCMC), and the minimization is done in the source plane. We use the redshift and position of the giant arc and its counter image as constraints. The ellipticity ($e$), position angle (P.A.), scale radius ($r_s$), slope ($\alpha$), and concentration ($c$) of the generalized NFW profile that obeys these constraints has ($e$, P.A., $r_s$, $\alpha$, $c$) $\simeq (0.26 \pm 0.17, 52.9 \pm 2.5, 27.3 \pm 8.9, 1.3 \pm 0.23, 5.6 \pm 2.0)$ and a PIEMD BCG velocity dispersion of $189 \pm 118$, where errors are given by MCMC.

The critical curve given by this model approximately bisects the giant arc (Figure 3). However, with no other constraints, the critical curve falls radially outside the BCG source, a scenario that predicts counter images brighter than the observed image. Only when the critical curve is forced radially inward until it passes directly through the LBG do we get a model consistent with the data at hand, which suggests that the observed arc is the result of a merging pair. Models that produce this configuration typically have magnifications of $M \gtrsim 40$. Until space-based data is available to confirm the merging pair nature of this image, the fact that the LBG image is near the critical curve will render magnification measurements uncertain.

In the case of SDSS J1527+2152, there are fewer lensing constraints, as no other lensed features are accessible in RCS2 imaging. Furthermore, the core of SDSS J1527+2152 is dominated by two bright galaxies of approximately the same brightness—not by a dominant BCG—preventing the common assumption that the cluster halo is centered on the BCG. We therefore do not attempt to fit a model to the cluster, but instead we explore a large set of lens models spanning a wide range in parameter values. We take advantage of the known cluster velocity dispersion, $\sigma_v = 908 \pm 150 \kms$, as computed from GMOS spectroscopy of 13 cluster members and represent the cluster with a PIEMD. The parameter space we explore includes the position of the halo, its ellipticity and P.A., and the core and cut radii (see Limousin et al. 2005 for a full description of the PIEMD parameters). We examine two families of models. In the simplest case, we assume that the halo is circular and centered on a line connecting the two central galaxies. For each model, we compute the locations and relative magnifications of predicted counter images for the LBG. Since we do not observe counter images at RCS2 depths, we rule out models that predict counter images brighter than our detection limit, which consequently restricts the magnification to be under $\sim 15$ for any model from this family. However, the more complicated case, in which we allow models with high ellipticity, the requirement that the model should not produce counter images above our brightness limit provides little or no constraint on the magnification. Hence, we proceed by taking $M = 15$ as an upper bound on the magnification of SGAS J152745.1+065219 and employ $M = 15$ in later analyses.

4. SOURCE PROPERTIES

An important feature of both of these sources is that the total magnitude of each source is not spread among many images. In this sense, multiple imaging is a double-edged sword: lens modeling suffers, but the effective surface brightness is greatly enhanced over multiply imaged objects, making our sources especially amenable to detailed spectroscopy. As examples, the Sextet Arcs have a total magnitude of $r_{65} = 21.7$, which is spread out among six images, where $r_{65} = 22.55$ is the brightest image. The Cosmic Eye has a total magnitude $R_{606} = 20.54 \pm 0.02$ spread over a pair of highly elongated arcs.

To place SGAS J122651.3+215220 and SGAS J152745.1+065219 and other lensed-LBGs in context, we compare to the LBG sample presented in Steidel et al. (2003, hereafter S03). That catalog is constructed from a photometric survey that targeted $z \sim 3$ LBGs. The mean redshift of the S03 spectroscopic sample is $z = 2.96 \pm 0.29$. For comparison, we select objects classified as galaxies with spectroscopic redshifts $2.7 < z < 3.3$, or $\pm 1\sigma$ of the mean. These redshift limits also approximately correspond to the target window for the Lyman Break technique. A total of 237 LBGs remain from a sample of 940 objects presented in S03. For uniformity, we apply the same redshift cuts to bright, strongly lensed LBGs noted in the literature. This includes the LBGs presented in this Letter, as well as the 8 o’clock arc (Allam et al. 2007), the Cosmic Eye (Smail et al. 2007), cB58 (Yee et al. 1996), and the brightest of the Sextet Arcs (Frye et al. 2007). The high magnification ($> 10$) of each of these sources makes them unique and well suited to detailed spectroscopic follow-up.

In the absence of the lensing interpretation, both LBGs in this study sit 2 mag brighter, or about a factor of $\sim 6$ brighter than the brightest object in the S03 sample. The apparent arc magnitudes in each band are given in Table 1, as are the lens magnifications, the lensing-corrected apparent magnitudes, and coordinates. Because the $r$-band samples the continuum redward of both the characteristic strong Ly$\alpha$ emission and

Figure 3. SDSS J1226+2152 lens model. Background objects with redshifts are labeled, including the newly discovered LBG SGAS J122651.3+215220 ($z = 2.923$). The source of interest is 5′ SW of the BCG. To the south a source at the same redshift appears lensed as a giant arc. Source redshifts and positions are used to construct a PIEMD mass model (see the text), whose radial and tangential critical curves (inner and outer red lines) are overplotted. (A color version of this figure is available in the online journal.)
Lyman break spectral features (e.g., Steidel et al. 1995), we consider only $r$-band quantities in all comparisons. Using the published magnifications and observed total magnitudes of the brightest of the multiple images of both the 8 o’clock arc and the Cosmic Eye, the lensing-corrected apparent magnitudes are $r = 22.93$ and $r = 24.16$, respectively. Assuming a magnification, $M = 15$, SGAS J152745.1+065219 has a similar lensing-corrected $r$-band magnitude of $r = 23.52$. However, SGAS J122651.3+215220, $r = 24.61$, is about a magnitude fainter. Thus, while all these sources are at similar redshifts, it is evident that SGAS J122651.3+215220 is quite faint and is in fact similar in brightness to cB58, which experiences a magnification of $M \approx 30$ (Seitz et al. 1998; Pettini et al. 2000), or a lensing-corrected magnitude of $r = 24.77$.

When placed in the context of the S03 LBG survey, it is apparent that the recently discovered bright, lensed LBG sources consistent with criteria defined above include objects that form a sparse, but wide-ranging sample of the underlying LBG population. In the brightest quartile, the unlensed apparent $r$-band magnitude ($r \approx 22.9$) of the 8 o’clock arc source galaxy is among the $\approx 10\%$ brightest LBGs in S03, and SGAS J152745.1+065219 ($r \approx 23.5$) is among the brightest 25%. The Cosmic Eye ($r \approx 24.2$) and cB58 ($r \approx 24.3$) both are found in the third quartile, and SGAS J122651.3+215220 ($r \approx 24.6$) is fainter than 80% of the galaxies in the S03 sample. The Sextet Arc source ($r \approx 25.3$) is $\approx 0.1$ mag dimmer than anything in the portion of the S03 outlined at the start of this section. The two sources presented in this discovery paper and the handful of lensed LBGs in the literature fill out a sample of highly magnified high-redshift galaxies whose unlensed apparent magnitudes form a somewhat representative sample of high-redshift survey populations like that in S03.

5. CONCLUSION

While we require additional deep imaging to better constrain the lens models for SGAS J122651.3+215220 and SGAS J152745.1+065219, the existing MagE spectra, other spectroscopy, and additional IR and UV imaging form a basis for a series of forthcoming papers that investigate the intrinsic properties of the LBGs in this study (J. R. Rigby et al. 2010, in preparation).

These discoveries continue to build the existing sample of lensed LBGs. The ambitious follow-up program built into SGAS will continue to grow the $z \sim 3$ lensed-LBG sample as well as other lensed source populations (e.g., Lyα emitters; Bayliss et al. 2010). The systematic nature of this program offers the possibility of building large samples of strongly lensed high-redshift galaxies whose high fluxes enable both the acquisition of high S/N spectra and a look at the faint end of the luminosity function.

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Based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada–France–Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Science de l’Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This work is based in part on data products produced at TERAPIX and the Canadian Astronomy Data Centre as part of the Canada–France–Hawaii Telescope Legacy Survey, a collaborative project of NRC and CNRS.

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