TWO LENSED LYMAN-α EMITTING GALAXIES AT $z \sim 5^*$

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ABSTRACT

We present observations of two strongly lensed $z \sim 5$ Lyman-α emitting galaxies that were discovered in the Sloan Giant Arcs Survey (SGAS). We identify the two sources as SGAS J091541+382655 at $z = 5.200$ and SGAS J134331+415455 at $z = 4.994$. We measure their AB magnitudes at $(i, z) = (23.34 \pm 0.09, 23.29 \pm 0.13)$ mag and $(i, z) = (23.78 \pm 0.18, 24.24^{+0.18}_{-0.16})$ mag and the rest-frame equivalent widths of the Lyman-α emission at 25.3 ± 4.1 Å and 135.6 ± 20.3 Å for SGAS J091541+382655 and SGAS J134331+415455, respectively. Each source is strongly lensed by a massive galaxy cluster in the foreground, and the magnifications due to gravitational lensing are recovered from strong lens modeling of the foreground lensing potentials. We use the magnification to calculate the intrinsic, unlensed Lyman-α and UV continuum luminosities for both sources, as well as the implied star formation rates. We find SGAS J091541+382655 and SGAS J134331+415455 to be galaxies with $(L_{Ly-\alpha}, L_{UV}) \leq (0.6 L_{Ly-\alpha}^*, 2 L_{UV}^*)$ and $(L_{Ly-\alpha}, L_{UV}) = (0.5 L_{Ly-\alpha}^*, 0.9 L_{UV}^*)$, respectively. Comparison of the spectral energy distributions of both sources against stellar population models produces estimates of the mass in young stars in each galaxy; we report an upper limit of $M_{stars} \leq 7.9^{+3.7}_{-2.5} \times 10^7 M_\odot$ for SGAS J091531+382655 and a range of viable masses for SGAS J134331+415455 of $2 \times 10^8 M_\odot < M_{stars} < 6 \times 10^9 M_\odot$.

Key words: galaxies: high-redshift – galaxies: individual (SGAS J091541+382655, SGAS J134331+415455) – gravitational lensing: strong

Online-only material: color figures

1. INTRODUCTION

Understanding the evolution of galaxies—especially the first generation of galaxies—remains one of the most important topics in astrophysics and cosmology. Populations of galaxies in the distant universe are identified over a wide range of wavelengths, including Distant Red Galaxies, Ultra Luminous Infra-Red Galaxies, and Sub-Millimeter Galaxies. Many efforts to study the properties of high redshift galaxies at optical wavelengths focus on two distinct classes selected by their restframe UV properties: (1) Lyman-Break Galaxies (LBGs) and (2) Lyman-α Emitters (LAEs). LBGs are selected via deep wide-band photometry, identified by the “Lyman limit” continuum break that appears at 912 Å in the rest frame (Steidel et al. 1996a, 1996b; Lowenthal et al. 1997), though for sources at higher redshift this spectral break moves redward, approaching 1216 Å in the rest frame due to the Lyman-α forest (Steidel & Sargent 1987; Rauch 1998) absorption by intergalactic neutral hydrogen. LAEs are selected by either narrow-band imaging (Cowie & Hu 1998; Rhoads et al. 2000, 2003; Ajiki et al. 2004; Gawiser et al. 2006; Yamada et al. 2005) or blind spectroscopy (Kurk et al. 2004; Sawicki et al. 2008) tuned to detect Lyman-α line emission redshifted into near-ultraviolet, optical, or near-infrared wavelengths. Over the past decade, large samples of LBGs and LAEs have driven studies of star-forming galaxies at $z \gtrsim 2.5$.

Surveys for LBGs and LAEs are efficient for collecting statistical samples of high-redshift galaxies, but at $z \gtrsim 3$ they produce objects which are generally too faint to have their galactic continuum emission studied spectroscopically. The standard approach for studying the properties of these galaxy samples relies on stacking the photometric signal from many objects and fitting the observed mean spectral energy distribution (SED) against a variety of stellar population synthesis models in order to constrain parameters such as the ages and masses of the underlying stellar populations, as well as the amount of dust extinction (Shapley et al. 2003; Chary et al. 2005; Pirzkal et al. 2007; Lai et al. 2007; Finkelstein et al. 2008, 2010; Nilsson et al. 2009; Yabe et al. 2009). In principal, stellar population synthesis modeling can also provide information about dust properties (i.e., the shape of the dust law) and metallicity, but even the stacked SED signal at $z \gtrsim 3$ is insufficient to constrain these additional parameters with much confidence. Broadly speaking, galaxies selected as LBGs are believed to sample more massive star-forming galaxies with an underlying older stellar population, and possibly higher dust content, while LAE selected galaxies tend to be lower mass galaxies with low metallicities and very little dust (Giavalisco 2002; Venemans et al. 2005; Gawiser et al. 2007). Hubble Space Telescope imaging studies of high redshift LAE galaxies imply that these sources are compact and likely either disk-like or irregular in structure (Pirzkal et al. 2007; Taniguchi et al. 2009). Recently, Finkelstein et al. (2009b) modeled individual SEDs of 14 bright $z \sim 4.5$ LAEs from the...
Chandra Deep Field South and found a broad range in stellar population age, stellar mass, and dust extinction, which suggests that stacking SED analyses of high redshift galaxies may not be the best approach.

The main hurdle involved in studying any high redshift source is the general lack of signal. Distant galaxies are faint and therefore difficult to detect, and those which are identified are rarely—if ever—amenable to detailed follow-up. Furthermore, there are drawn from the extreme bright tail of the luminosity function of high redshift galaxies and are therefore not necessarily representative of the bulk of the populations. In this paper, we present two serendipitously discovered, strongly lensed high redshift galaxies: SGAS J091541+382655 spectroscopically confirmed at \( z = 5.200 \pm 0.001 \), with \( r_{\text{AB}} = 24.68 \pm 0.25 \) mag, \( i_{\text{AB}} = 22.92 \pm 0.09 \) mag, and \( z_{\text{AB}} = 22.75 \pm 0.13 \) mag, and SGAS J134330+415455 spectroscopically confirmed at \( z = 4.994 \pm 0.001 \), with \( r_{\text{AB}} \geq 25.47 \) mag, \( i_{\text{AB}} = 23.36 \pm 0.18 \) mag, and \( z_{\text{AB}} = 23.70^{+0.18}_{-0.16} \) mag. Both objects have \( riz \) colors and magnitudes that satisfy selection criteria for \( r \)-band dropouts in \( z \sim 5 \) dropout surveys, as well as Lyman-\( \alpha \) equivalent widths (see Section 2) sufficiently large to be selected in surveys for Lyman-\( \alpha \) excess. At \( z \gtrsim 5 \) these objects are the two brightest LAEs in the literature to date, and both sources are projected on the sky within \( 30'' \) of the cores of confirmed strong lensing galaxy clusters. This means that the sources—one corrected for the lensing magnification—are intrinsically much fainter than the observed flux implies and therefore provide a rare opportunity to study individual LAE properties at the fainter end of the luminosity function. There is a small but growing number of magnified galaxies at high redshift that are excellent candidates for high-resolution spectroscopic follow-up (Koester et al. 2010; Wuyts et al. 2010); some of these galaxies have been observed in detail at optical and near-infrared wavelengths, including cB58 (Pettini et al. 2000), “the 8 O’clock Arc” (Allam et al. 2007; Finkelstein et al. 2009a), and “the Cosmic Eye” (Smail et al. 2007; Siana et al. 2009; Quider et al. 2010). The two galaxies discussed in this paper are the first \( z \sim 5 \) galaxies that present similar opportunities for detailed study via follow-up spectroscopy.

Where necessary, we calculate cosmological distances assuming a flat cosmology with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\) and matter density \( \Omega_M = 0.3 \). All magnitudes are AB.

2. OBSERVATIONS

2.1. Data

The two sources presented here were first identified as \( r \)-band dropouts in \( gri \) imaging of two different strong lensing galaxy clusters and subsequently confirmed by spectroscopy to have strong Lyman-\( \alpha \) emission features. The two galaxy clusters were identified as part of the Sloan Giant Arcs Survey (SGAS; Hennawi et al. 2008), a blind survey for strong lensing systems in optically selected massive clusters at \( 0.1 \leq z \leq 0.6 \) detected via the Red-Sequence Cluster algorithm (Gladders & Yee 2000) adapted to run on the Sloan Digital Sky Survey (SDSS; York et al. 2000) public data release catalogs. Strong lensing clusters are identified by visual inspection of imaging in \( g \) band on 2 m to 4 m-class telescopes for 600 s in \( <1'' \) seeing, and the most spectacular systems have been followed up with multi-band imaging and spectroscopy on 8 m-class telescopes. One of the clusters discussed here, SDSS J1343+4155, appears in a recent small sample of strong lensing clusters discovered in the SDSS by Diehl et al. (2009). The other cluster, SDSS J0915+3826, does not appear in any prior published work. Imaging and spectroscopic observations were conducted with the Frederick C. Gillett Telescope (Gemini North) between the months of 2008 February and 2008 July. The GMOS imaging observations were pre-imaging conducted for the purpose of spectroscopic mask design. Both imaging and spectroscopy were part of Gemini program GN-2008A-Q-25. The primary goal of the spectroscopic observations was to obtain redshifts of arcs to facilitate strong lensing modeling. We briefly summarize the spectroscopy here and refer the reader to M. Bayliss et al. (2010, in preparation), for additional details.

Gemini North/GMOS \( gri \) photometry for both cluster fields are derived from 2 \( \times \) 150 s dithered exposures, which were executed in queue mode in February and March of 2008. These pre-imaging data were used for spectroscopic mask design and target prioritization. GMOS \( z \)-band observations consisted of 6 \( \times \) 180 s dithered exposures which were scheduled as follow-up, primarily in order to measure the continuum flux of the LAEs, and were executed in queue mode in February of 2010. The GMOS images were reduced using the Gemini IRAF\(^5\) package.

In addition to the GMOS-\( N \) photometry and spectroscopy, we obtained near-infrared (NIR) imaging of the two lensing clusters in the \( z/JH \) filters with the Near-Infrared Camera and Fabry-Perot Spectrometer (NIC-FPS) of the 3.5 m telescope at the Apache Point Observatory (APO) in New Mexico. The detector is a Rockwell Hawaii 1-RG 1024 \( \times \) 1024 HgCdTe device with a pixel scale of \( 0.273 \) pixel\(^{-1}\) and a 4.58 \( \times \) 4.58 arcmin\(^2\) unvignetted field of view. The APO/NIC-FPS \( z' \) data differ from the Gemini/GMOS \( z \) significantly due to the different wavelength responses of the NIC-FPS and GMOS detectors. The effective wavelengths of the two filters are offset by \( \sim 1000 \) Å and we use the prime (’) throughout this paper to distinguish the APO/NIC-FPS \( z' \) from the Gemini/GMOS \( z \). The NIR data were taken on three different nights in the Winter and Spring of 2009. The conditions during the observing nights varied, with subarcsecond seeing for the SDSS J1343+4155 \( z' \)-band and both \( J \)-band images. The SDSS J0915+3826 \( z' \)-band and both \( H \)-band images were taken in \( \sim 2'' \) seeing. The observations consisted of five-point dithers around a 40\('\) box and were reduced, registered, and stacked using a custom IRAF pipeline. Total exposure times are \( 5400 \) s, \( 6960 \) s, and \( 3500 \) s for \( z', J', \) and \( H' \)-band observations of SDSS J0915+3826 and 7800 s, 5160 s, and 2625 s for \( z', J', \) and \( H' \)-band observations of SDSS J1343+4155.

The SDSS was used to calibrate the four optical bands and the Two Micron All Sky Survey was used to calibrate the NIR observations. Prior to making any photometric measurements, we first transform images in all bands to the reference frame of the \( i \)-band image, \( 0.3 \)\,1454 pixel\(^{-1}\) (GMOS-North detector, binned 2 \( \times \) 2). We then construct an empirical, normalized point-spread function (PSF) for each image based on a well-defined, non-saturated reference star. We create photometric apertures by drawing a ridge line that covers the high-redshift LAE and convolving it with the appropriate PSF for each image. Apertures are defined by an equivalent radius, which corresponds to the radius of a circular aperture that goes out to the same isophot. We make the final magnitude measurement using a detailed sequence of sky subtraction and outlier masking steps; first we subtract a general sky measurement and then

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\(^5\) 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.
compute the median pixel value and standard deviation inside annuli of fixed width at increasing radial distances from the source. Far enough out, these median values converge to zero for an accurate sky subtraction. We average the median values at large radii and subtract this average from the image to correct the general sky subtraction. Outliers are defined as pixel values that deviate by more than 5σ from the median in the respective annuli and are replaced by the median value plus an appropriate noise term. The final magnitude is measured at an equivalent radius of twice the FWHM of the PSF and corrected to an equivalent radius of 6′′ based on the curve of growth of the PSF. By defining the radius as twice the FWHM, we make sure that our apertures always cover the same physical region on the sky.

In the case of SGAS J091541+382655, a foreground galaxy lies very close to and partially on top of the LAE galaxy. We use the GALFIT package (Peng et al. 2002) to fit a Sersic profile to this galaxy in the imaging data where the LAE has no measurable flux and then scale the galaxy model by the peak flux in each band and subtract it out before measuring the LAE magnitudes. When the LAEs are not detected (in gH for SGAS J091541+382655 and grH for SGAS J134331+415455), we measure a limiting magnitude, derived from the total sky noise in the aperture. We define a sky noise per pixel σsky as the standard deviation of our overall sky measurement plus a contribution from the poisson error made in this measurement. A pixel value of 2σsky is added in quadrature for each pixel in our final aperture with an equivalent radius equal to twice the FWHM. The limiting magnitudes are also aperture corrected to an equivalent radius of 6′′. This method constrains the source to be fainter than the limiting magnitudes at 95% confidence in the relevant bandpasses.

All spectroscopic observations were carried out using the Gemini Multi-Object Spectrograph (Hook et al. 2004) using custom slitmasks that were designed to target lensed sources based on their color, morphology, and position in the GMOS imaging. After targeting all of the arc candidates, any remaining slits were placed on cluster members, easily identified by their red sequence colors. Spectra were taken using the macroscopic nod-and-shuffle (N&S) mode available on GMOS. The reasons for using N&S are threefold. First, many of the emission or absorption features that are used to determine galaxy redshifts in the range z = 1.0–3.0 characteristic of the giant arcs are in the redder part of the optical where sky lines are problematic, and N&S facilitates more accurate sky-subtraction (Glazebrook & Bland-Hawthorn 2001), particularly at low spectral resolution. Second, N&S sky-subtraction allows us to use very small 1′ × 1′ microslits that can be densely packed into the cluster core (∼30′′), allowing us to target as many arcs, arclets, and cluster galaxies as possible (Gilbank et al. 2008). Third, as we are primarily interested in a number of objects around the cluster center, the density of objects and the limited field of interest are perfect for block-shuffling N&S observations. Spectra were taken with the R150_G5306 grating in first order which gives a dispersion of 3.5 Å per pixel (binned spectrally by two), with six pixels per resolution element resulting in a spectral FWHM ∼ 940 km s−1. Although the R150 grating offers broad spectral range from the atmospheric cutoff to λ > 1 µm, the drop in sensitivity at the blue and red extremes, due both to the GMOS CCD and the R150 grating efficiency, results in effective spectral coverage of ∼ 4000–9500 Å.

The N&S technique employed in our program is nonstandard in that it involves a nod distance on the sky that is half the size of the macroscopic shuffle. The mask is designed to incorporate two submasks, each of which is a set of slits covering an area one third the size of the detector. Slits for the two submasks overlap on the sky in an area that is one sixth the size of the detector (because the nod distance is set to half the shuffle distance). This design allows us to place science slits for the primary target—the core of a strong lensing cluster in this case—on both submasks and obtain useful spectra for the entire duration of the N&S exposure, whereas standard macroscopic N&S results in science spectra for only half of the total exposure time. Our integration times were 2400 s resulting in a 1200 s effective integration for each of the two submasks. Two exposures were taken for each target. Thus, if an arc was targeted on both submasks (typical for the most prominent arcs) the total integration time was 4800 s. N&S facilitates straightforward sky subtraction by differencing two sections of the detector—each 1/3 the size of the full detector. The spectra presented here were wavelength calibrated, stacked, extracted, and analyzed using a custom pipeline based on the XIDL software package.6

2.2. SGAS J091541+382655

SDSS J0915+3826 is a new strong lensing cluster that was discovered in the SGAS, discussed above. We measure redshifts for 16 cluster members in our Gemini/GMOS spectroscopy and combine this new data with a redshift for the brightest cluster galaxy (BCG) measured in the SDSS to identify a mean cluster redshift of z = 0.397 and a velocity dispersion of 870 ± 169 km s−1. The most prominent strong lensing feature around this cluster is a bright blue arc that we identify as a background galaxy at z = 1.501 from O [\[\lambda\]1577, C [\[\lambda\]1215, C [\[\lambda\]1344, H [\[\lambda\]397, and a velocity dispersion of 501 km s−1. Although the R150 grating offers broad characteristic of the giant arcs are in the

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6 http://www.ucolick.org/~xavier/IDL/index.html
Figure 1. GMOS griz (from left to right) 8′′ × 8′′ cutout images centered on SGAS J091541+386254 and SGAS J134331+415455. Both objects exhibit obvious drop-out behavior from the i to r bands. The z-band detection of SGAS J091541+386254 appears at lower significance than its counterpart for SGAS J134331+415455 because its z data were taken during bright time and the sky background noise is ∼30% higher.

Figure 2. GMOS spectrum of the Lyman-α emitter behind cluster lens SDSS J0915+3826. The LAE spectrum plotted over a range of 7150–8350 Å is smoothed to a scale comparable to the spectral resolution of 940 km s⁻¹ in order to emphasize the low-significance candidate absorption features, with the composite Lyman Break Galaxy absorption-emission spectrum from Shapley et al. (2003) overplotted in green. Dashed vertical lines indicate the location of prominent UV continuum metal absorption lines at the LAE redshift, which coincide with the low-significance features in our continuum spectrum. The Lyman-α emission feature is also shown in the inset, without smoothing. A typical spectral flux error bar is displayed on the right side of the figure, in the white space above the continuum. (A color version of this figure is available in the online journal.)

The relevant part of the extracted spectrum is displayed in Figure 2, and despite the low dispersion grating used for our observations the line is measurably asymmetric. We also detect continuum signal redward of the emission line and no significant signal blueward of it. This source has a strong photometric r−i break—even after subtracting the emission line flux from the i-band photometry. It is also very blue in i − z and is not detected in NIC-FIPS imaging to a 2σ limiting magnitude of $J_{AB} \geq 22.49$, indicating that the continuum spectral slope redward of the emission feature is blue. The blue continuum redward of the emission feature and the strong r − i break along with the non-detection in g and the asymmetry of the line confirm the interpretation of the source as a Lyman-α emitting galaxy at high redshift. The most likely candidate emission lines which confuse searches for high-redshift LAEs are O [ii]λ3727 Å, [O iii] λ5007 Å and H-α, but for each of these other candidate lines we would expect accompanying emission features to fall within the wavelength coverage of our spectroscopy. We measure the equivalent width of the Lyman-α emission by fitting a simple power law to the continuum spectrum redward of the emission line over a wavelength range of 7575–8275 Å and subtracting the underlying continuum flux from the emission line. Over the relatively small wavelength range used the continuum level is consistent with a constant value. We note that our spectral flux calibration uses a standard from the Gemini archive to correct roughly for the detector sensitivity as a function of wavelength but is not suitable for measuring absolute fluxes from the spectral data. Taking into account the underlying continuum and the source redshift, we measure a rest-frame EW for the Lyman-α emission of 25 ± 4 Å and combine the EW measurement with our i−band photometry to calculate an observed Lyman-α line flux of $2.1 \pm 0.7 \times 10^{-16}$ erg s⁻¹ cm⁻².

2.3. SGAS J134331+415455

The second lensed LAE presented here is located near the strong lensing cluster SDSS J1343+4155, which was previously identified as a strong lensing cluster in the SDSS by Wen et al. (2009) and Diehl et al. (2009). We combine our Gemini/GMOS spectroscopy with two cluster member redshifts from the SDSS to measure a mean cluster redshift of $z = 0.418$ and a velocity dispersion of $1077 \pm 266$ km s⁻¹ from seven cluster member galaxies. The bright arc around this lens is spectroscopically
identified by Diehl et al. (2009) as a background galaxy at $z = 2.091$. Pre-imaging of this cluster reveals a source near the cluster core that exhibits a dramatic drop in flux from the $i$- to $r$-band, shown in Figure 1. We measure this source at $i_{AB} \geq 25.97$, $r_{AB} \geq 25.64$, $i_{AB} = 23.78 \pm 0.12$, and $z_{AB} = 24.24 \pm 0.16$. We placed slits on this source in each of the two submasks for our spectroscopic N&S observations of this cluster. The spectra corresponding to these slits exhibit a bright emission line at 7289 Å, which we interpret as Lyman-$\alpha$. The extracted spectrum around the emission feature is displayed in Figure 3. The emission feature is significantly asymmetric and we measure continuum emission redward of the line, but no continuum blueward. The source is undetected in NIC-FIPS imaging down to a 2σ limiting magnitude of $J_{AB} \geq 22.22$. Similarly to the case of SGAS J091541+382655, this source has a blue $i - z$ color and our NIR photometry implies that it has a blue continuum spectral slope redward of the emission feature. The most likely candidate emission line which could be misinterpreted as Lyman-$\alpha$ in this spectrum is O [\textsc{iii}] $\lambda 3727$ Å, but we rule this out as a realistic interpretation based on the absence of H-$\beta$ $\lambda 4862$ Å and O [\textsc{iii}] $\lambda 4960, 5007$ Å, both of which should fall just within the spectral range covered by our data if the source were a very red galaxy at lower redshift. Other common contaminants in searches for high-redshift LAEs include [O [\textsc{iii}]] $\lambda 5007$ Å and H-$\alpha$, but in each of these cases we would also expect to observe other accompanying emission features given the wavelength coverage of our spectroscopy. We measure the equivalent width of the Lyman-$\alpha$ emission by fitting a simple power law to the continuum spectrum redward of the emission line over a wavelength range of 7400–8275 Å and subtracting the underlying continuum flux from the integrated flux from the emission line. Similar to the continuum fit for SGAS J091541+382655, the continuum level for SGAS J134331+41555 is consistent with a constant value. Taking into account the continuum and the source redshift, we measure a rest-frame EW for the Lyman-$\alpha$ emission of 136 ± 20 Å and combine the EW measurement with our $i$-band photometry to calculate an observed Lyman-$\alpha$ line flux of $2.1 \pm 0.5 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$.

3. ANALYSIS

3.1. Lens Models and Intrinsic Source Properties

Using the measured equivalent widths and $i$ magnitudes, we also calculate lensed isotropic Lyman-$\alpha$ line luminosities of $L_{Ly-\alpha} = 5.9 \pm 1.1 \times 10^{43}$ erg s$^{-1}$h$_{70}^{-1}$ and $L_{Ly-\alpha} = 5.4 \pm 0.9 \times 10^{43}$ erg s$^{-1}$h$_{70}^{-1}$ for SGAS J091541+382655 and SGAS J134331+415455, respectively. These are not the true isotropic luminosities because both sources are lensed by foreground galaxy clusters and are therefore significantly magnified. To measure the intrinsic luminosities of the LAEs, we estimate the magnification due to strong lensing by the intervening clusters. The mass models are constructed using the publicly available software, LENSTOOL (Jullo et al. 2007), with Monte Carlo Markov Chain minimization in the source plane, and are shown in Figure 4. For SDSS J1343+4155, we compute a simple mass model using as constraints the giant blue arc at $z = 2.09$, the LAE at $z = 4.994$, and its putative counterimage predicted by the lensing model are identified by white triangles. The center of the dark matter halo and BCG mass components are indicated by a square and cross, respectively. Other sources in the field—background objects and cluster members—are labeled with their spectroscopic redshifts. Color images are created from Gemini+GMOS-North grii 300 s pre-imaging data.

(A color version of this figure is available in the online journal.)
J134331+415455 to be SFR$_{Ly-\alpha} = 4.1 \pm 0.6 \, M_\odot \, yr^{-1} h_{0.7}^{-1}$. Applying a magnification correction to the apparent magnitude in $z$-band, we find the intrinsic $z$-band AB magnitude to be $z = 27$. We can also estimate the SFR from the UV continuum flux density at 1500 Å according to Equation (1) from Kennicutt (1998), which results in SFR$_{UV} = 18 \pm 3 \, M_\odot \, yr^{-1} h_{0.7}^{-1}$.

The strong lensing model for SDSS J0915+3826 is constrained by the positions of the components of the giant arc. We do not identify a clear counter image for the LAE and therefore do not use it as a constraint. We represent the lens with a single PIEMD and allow all its parameters to vary, which produces a velocity dispersion estimate that is similar to the value we measure from spectroscopy of cluster members (see Section 2.2). The critical curves for our best-fit model are plotted in Figure 5. Since the available constraints are internal to the radial projection of the LAE, the predicted LAE magnification is highly uncertain. In particular, if we compute a set of models with parameters in the range allowed by the uncertainties, the location of the critical curve for the LAE varies significantly and there is practically no upper limit for the implied magnification. In all cases the magnification is higher than $\sim 10$, we adopt this number as our working order-of-magnitude estimate and determine an upper limit for the intrinsic isotropic Lyman-$\alpha$ line luminosity for SGAS J091541+382655 of $L_{Ly-\alpha} \lesssim 5.9 \pm 1.1 \times 10^{42} \, erg \, s^{-1} h_{0.7}^2$ and a corresponding SFR$_{Ly-\alpha} \lesssim 5.3 \pm 1.0 \, M_\odot \, yr^{-1} h_{0.7}^{-1}$. Correcting the $z$-band magnitude for the lensing magnification, we recover an intrinsic magnitude of $z \gtrsim 25.75$ mag, from which we measure SFR$_{UV} \lesssim 51 \pm 7 \, M_\odot \, yr^{-1} h_{0.7}^{-1}$ using Equation (1) from Kennicutt (1998).

We note that SFR$_{Ly-\alpha}$ and SFR$_{UV}$ differ significantly for both sources. For SGAS J134331+415455 SFR$_{Ly-\alpha}$ is lower than SFR$_{UV}$ by a factor of 4.5, which is consistent with previous studies finding that the SFR calculated from Lyman-$\alpha$ emission is often systematically lower than other SFR metrics—such as UV continuum flux density at 1500 Å—by a factor of $\sim 5$ or more (Tapken et al. 2007). The disagreement between the two SFR estimates is more extreme for SGAS J091541+382655, with SFR$_{UV} \sim 9 \times$ larger than SFR$_{Ly-\alpha}$. In a study of LAEs at $z = 3.1$ identified in the Chandra Deep Field South, Gronwall et al. (2007) find on average, SFR$_{UV}$/SFR$_{Ly-\alpha} \sim 3$ with a large scatter about the mean, including several objects with SFR$_{UV}$/SFR$_{Ly-\alpha}$ as large as we measure for SGAS J091541+382655. Significant differences between these two SFR calibrations are understandable considering the potential systematic errors involved in measuring the SFR from both UV continuum and Lyman-$\alpha$ emission. For example, resonant scattering of Lyman-$\alpha$ photons off of neutral hydrogen can suppress observed Lyman-$\alpha$ emission if there is even a very small amount of dust in the source galaxy, thus producing an underestimate of SFR$_{Ly-\alpha}$. Additionally, Kennicutt (1998) identifies several caveats associated with the SFR$_{UV}$ calibration, including assumptions about the IMF and the timescale and manner of star formation (e.g., constant vs. burst). Specifically, Equation (1) in Kennicutt (1998) recovers SFR from the rest-frame UV flux by assuming that a galaxy has undergone continuous star formation for $10^9$ years or longer and originates from a Salpeter IMF with mass limits of 0.1 and 10 $M_\odot$. If the properties of the underlying stellar populations in either of these galaxies differ significantly from the parameters assumed in Equation (1) from Kennicutt (1998), then there will be systematic differences between the SFRs estimated from the rest-frame UV flux and the true SFRs.

We have also considered the possibility that the Lyman-$\alpha$ emission in one or both of these objects could be due all or in part to active galactic nucleus (AGN) activity. Given the lack of detection of significant emission from highly ionized species, such as N[V] and C[IV], we conclude that it is unlikely that AGNs are playing a significant role in the observed Lyman-$\alpha$ emission. The disagreements between the two SFR estimates for the two sources discussed here highlight the difficulty in making robust SFR measurements from source-frame UV observables.
Having accounted for the magnification due to gravitational lensing, we can also compare the luminosities of these two sources to large samples of LAEs and LBGs at comparable redshifts (e.g., Hu et al. 2004; Shimasaku et al. 2006; Bouwens et al. 2007; Dawson et al. 2007; Murayama et al. 2007; Ouchi et al. 2008; McLure et al. 2009). Studies of luminosity functions at high redshift are challenging, and parameters such as $L^*$ and $\alpha$ are not nearly so well measured as they are in the nearby universe. For comparing Lyman-$\alpha$ luminosities, we take the average of six different measurements of $L_{L_{\alpha}}^{\text{Ly}^*}$ values from Ouchi et al. (2008) that were fit using samples of LAEs at $z \sim 3.7$ and $z \sim 5.7$, assuming three possible values of the faint end slope of the luminosity function, $\alpha$. For the purpose of comparing continuum luminosities, we take $L_{L_{\alpha}}^{\text{ Ly}^*}$ as the average of the two $L_{1500}^*$ best-fit values for LAEs at $z \sim 3.7$ and $z \sim 5.7$ from Ouchi et al. (2008). SGAS J091541+382655 is ($L_{L_{\alpha}}^{\text{Ly}^*}$, $L_{\text{Ly}^*}^*$) = (0.6 $L_{L_{\alpha}}^{\text{Ly}^*}$, 2 $L_{\text{Ly}^*}^{\text{Ly}^*}$) and SGAS J134331+415455 is ($L_{L_{\alpha}}^{\text{Ly}^*}$, $L_{\text{Ly}^*}^*$) = (0.5 $L_{L_{\alpha}}^{\text{Ly}^*}$, 0.9 $L_{\text{Ly}^*}^{\text{Ly}^*}$). Both of these galaxies live at $\lesssim L^*$ on the luminosity function for similar galaxies at comparable redshifts, which makes them interesting targets for studying the properties of typical LAEs at $z \sim 5$ on an individual basis (Figure 6).

We also attempt to measure the morphologies of both lensed LAEs in our Gemini/GMOS imaging and place constraints on the intrinsic sizes of these two galaxies. Neither source is detected at S/N $\gtrsim 12$, which limits our ability to make detailed morphological measurements or shape fits, but we can check the object profiles against the image PSFs and use our estimates of the magnification due to lensing to place some rough constraints on the physical sizes of these galaxies. Studies of LAE morphologies at $z = 3.1$ using HST imaging find that the Lyman-$\alpha$ and rest-frame UV emission from these sources are spatially coincident and have half-light radii $\lesssim 1.5$ kpc (Bond et al. 2009, 2010). Bond et al. (2009) argue that S/N $\gtrsim 30$ is necessary to make robust measurements of half-light radii for LAEs and find that it is difficult to distinguish between resolved and unresolved compact cores at S/N $\lesssim 30$. The two lensed LAEs are best detected in our Gemini/GMOS $i$-band imaging, so these are the data we use for our morphological measurements.

SGAS J134331+315455 is slightly elongated in the tangential direction with respect to the center of the cluster. We measure its profile to be consistent with a Gaussian along the tangential axis with an FWHM = 1$^\prime$.1 and consistent with a Gaussian of FWHM = 0$^\prime$.57 along the radial axis. The FWHM of the PSF measured from stars in the image is $\sim 0^\prime$.57, suggesting that the LAE is unresolved along one axis and resolved along the other. This kind of morphology is natural for a strongly lensed background source where the magnification is generally much greater along one axis than the other; a source located on the tangential caustic will be highly magnified in the tangential direction with respect to the center of the lensing potential and magnified very little or not at all in the radial direction. We conclude that SGAS J134331+415455 is unresolved in the radial direction and barely resolved in the tangential direction. Assuming that all of the magnification factor of $m = 12$ is applied in the tangential direction, we convert an FWHM of 1$^\prime$.1 into a physical linear size of $\sim 0.6$ kpc, which indicates that most of the emission from this galaxy originates from a region very compact in size. This constraint must be taken with the caveat that the data are lower S/N than would be optimal, but the significant linear magnification of these sources due to gravitational lensing does enable us to probe very physically interesting scales even with ground-based imaging. We also measure the locations of SGAS J134331+415455 to be identical in the Gemini/GMOS $i$- and $z$-band images to the accuracy of our astrometry, $\sim 0^\prime$.2, corresponding to physical scales of $\sim 100$ pc. Based on the observer frame equivalent width of this source, the flux in the $i$-band filter is $\sim 60$ Lyman-$\alpha$ line emission, whereas the $z$-band filter measures only rest-frame UV continuum emission. Given the spatial coincidence of the LAE in the $i$ and $z$ bands, we conclude that the UV continuum and Lyman-$\alpha$ emission cannot originate from regions separated by more than an order $\sim 100$ pc projected onto the sky. We have no measurement of the relative velocities of the UV continuum and the Lyman-$\alpha$ emission and therefore cannot constrain a possible separation in velocity.

SGAS J091541+382655 is similar to SGAS J134331+415455 in that the LAE is elongated on the tangential axis relative to the center of the lensing cluster. Using the GALFIT subtracted $r$-band image, we measure the LAE to be resolved in the tangential direction, having a shape consistent with a Gaussian of FWHM = 1$^\prime$.82, which equates to a constraint on the physical scale of $\lesssim 1.2$ kpc, where the lower limit on the magnification of this source translates to an upper limit in the physical size (and again assuming that the magnification is entirely along the tangential direction). We also measure the LAE to have a Gaussian shape with FWHM = 0$^\prime$.75 in the radial direction, which—given the FWHM $\sim 0^\prime$.73 measured from the PSFs of stars in the image—is consistent with the source being unresolved in the radial direction. In the observer frame the equivalent width of the Lyman-$\alpha$ emission for this source is EW$_{\text{Ly}^*}$ = 157 Å, from which we estimate that Lyman-$\alpha$ photons are contributing less than 20% of the $i$-band flux, so that we cannot make any attempt to measure a spatial offset between the Lyman-$\alpha$ and UV continuum emission. Our size constraints for both sources are in good agreement with the literature, in that we find the sizes of the LAEs to be consistent with compact sources of size $\lesssim 1.5$ kpc.

### 3.2. Stellar Mass and UV Continuum Properties

With several photometric measurements in hand for each of our sources, it becomes interesting to investigate the spectral energy distributions of the LAEs to try and recover the properties (e.g., stellar mass, age, SFR, and dust content) of the underlying stellar populations in a way that does not rely on as many problematic assumptions as, for example, the SFR estimated from the rest-frame UV continuum flux that we calculate in Section 3.1 above. We compare our photometry for these sources against modified stellar population synthesis models. More details can be found in Wuyts et al. (2010); we only summarize the main procedure here. We use the revised templates of Bruzual and Charlot (CB07, based on Bruzual & Charlot 2003) with solar metallicity, a Chabrier initial mass function (Chabrier 2003), and Calzetti (2000) dust extinction law. We investigate a range of exponentially declining star formation histories of the form $\text{SFR}(t) \sim \exp(t/\tau)$, with $e$-folding times $\tau = 0.01, 0.05, 0.1, 0.2, 0.5, 1, 2$, and $5$ Gyr, as well as single bursts (SSP) and continuous star formation models (CSF). An updated version of the code Hyperz (Bolzonella 2000) is used to obtain the best-fit SED at the fixed spectroscopic redshift of the source via a maximum likelihood procedure.

The best-fit SED for SGAS J091541+382655 is shown in Figure 7 and corresponds to a dust-free single burst with an age of 1.4 Myr. It is important to supplement the best-fit stellar population parameters with confidence intervals allowed by the
photometric uncertainties. We create 1000 fake realizations of the observed SED by perturbing each broadband magnitude measurement in a manner consistent with its error bars. This set of fake SEDs is fit in exactly the same manner as described above for the observed SED; bad fits with $\chi^2 > 3$ are excluded. This procedure results in a very young (age $\leq 5$ Myr) and dust-free ($E(B-V) \leq 0.01$) stellar populations. Though we can place constraints on the age of the observed stellar population, these data are not sufficient for the SED fits to simultaneously constrain the star formation history and consequently the current star formation rate for this galaxy. After correcting for a lensing magnification factor of $\geq 10$, we find a Chabrier stellar mass of $M_{\text{stars}} \lesssim 7.9_{-2.5}^{+1.7} \times 10^7 M_\odot h_{100}^{-1}$.

SGAS J134331+415455 is detected in only two bands, which is insufficient to produce a robust best-fit stellar population. Instead, we compare the photometry to single burst, dust-free CB07 models of different ages to obtain some constraints on the age and stellar mass. The results are shown in Figure 8. The age of the observed stellar population lies in the range between 100 Myr and 400 Myr, which makes SGAS J134331+415455

Figure 7. Best-fit SED for SGAS J091541+382655 is plotted with a solid line on top of the photometric data. The dotted and dashed lines are dust-free, single burst models from CB07 with ages of 10 Myr and 50 Myr, respectively, scaled to match the observed $z$-band flux. This illustrates that the photometry favors a young (i.e., blue) stellar population, the 50 Myr model already deviates considerably from the best-fit SED. Filter transmission curves corresponding to the $r$, $i$, $z$, and $J$ photometry are plotted in the bottom panel.

Figure 8. Dust-free single burst CB07 models are scaled to match the $z$-band flux and plotted on top of the photometric data for SGAS J134331+415455. Models with ages anywhere in the range of 100 Myr to 400 Myr are potentially good fits for the limited data in-hand. Filter transmission curves corresponding to the $r$, $i$, $z$, and $J$ photometry are plotted in the bottom panel.
significantly older than the very young stellar population seen in SGAS J091541+382655. After correcting for a lensing effect, the stellar mass is estimated to be in the range $2 \times 10^8 M_\odot < M_{\text{stars}} < 6 \times 10^8 M_\odot$. All of our photometric data for both of these sources sample light blueward of the 4000 Å break in the source frame, so that the stellar population parameters obtained from the SED fitting procedures correspond to the most recent episode of star formation in each LAE; we have no power to constrain stellar mass that may be present in an underlying population of older stars.

In addition to SED modeling of the photometry of both LAEs, we also examine the modest continuum signal that is detected for SGAS J091541+382655. Cross-correlation of our GMOS spectrum for this source over a wavelength range of 1230–1350 Å (source frame) against the composite LBG spectrum from Shapley et al. (2003) results in a peak at $z \sim 5.2$, in agreement with the redshift measured from the Lyman-$\alpha$ emission. We explicitly exclude the Lyman-$\alpha$ emission portion of the spectrum in this analysis so that the cross-correlation signal that we detect is entirely due to low-significance continuum features redward of Lyman-$\alpha$. The composite LBG from Shapley et al. (2003) is plotted with our GMOS spectra for both targets in Figures 2 and 3, and visual comparison of the continuum against the LBG composite spectrum suggests the presence of several strong UV metal absorption lines that are observed in well-studied LBGs at lower redshifts (e.g., Pettini et al. 2000). The features are at too low a significance in our data to claim a robust detection of individual absorption lines, but the cross-correlation signal alone is encouraging given our low-resolution spectra and limited integration time. Both of the sources presented here are excellent candidates for a more aggressive spectroscopic follow-up effort to explore the gas properties and stellar metallicity in representative low-mass star-forming galaxies at $z \sim 5$.

4. SUMMARY AND CONCLUSIONS

We have identified two lensed Lyman-$\alpha$ emitting galaxies at $z \sim 5$ near the cores of strong lensing selected galaxy clusters. These sources are among the brightest galaxies identified at such high redshift, but their intrinsic luminosities are much lower than the observed flux due to magnification by the gravitational potential of foreground galaxy clusters. We use the available data to investigate the underlying stellar populations for these galaxies and find that the light—continuum and line emission—for SGAS 091541+382655 likely originates from a population of young stars with low dust content. Both sources are in the process of undergoing active star formation. Our analysis of these two LAEs corroborates our current understanding of the nature of Lyman-$\alpha$ emitting galaxies at high redshift, and the large magnification of these sources due to gravitational lensing makes them excellent candidates for studying the individual properties of galaxies on the faint end of the $L_{\text{Ly}–\alpha}$ and $L_{\text{UV}}$ luminosity functions at $z \sim 5$. We encourage efforts to follow up these sources aggressively on 8–10 m-class telescopes in order to better study the properties of the underlying stellar populations via continuum light. These sources are also excellent targets for space-based observations, both with current HST instruments and with JWST in the future.

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