DISCOVERY OF A VERY BRIGHT, STRONGLY LENSED $z = 2$ GALAXY IN THE SDSS DR5

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ABSTRACT

We report on the discovery of a very bright $z = 2.00$ star-forming galaxy that is strongly lensed by a foreground $z = 0.422$ luminous red galaxy (LRG), SDSS J120602.09+514229.5. This system, nicknamed the “Clone,” was found in a systematic search for bright arcs lensed by LRGs and brightest cluster galaxies in the Sloan Digital Sky Survey Data Release 5 sample. Follow-up observations on the Subaru 8.2 m telescope on Mauna Kea and the Astrophysical Research Consortium 3.5 m telescope at Apache Point Observatory confirmed the lensing nature of this system. A simple lens model for the system, assuming a singular isothermal ellipsoid mass distribution, yields an Einstein radius of $\theta_{\text{E}} = 3.82 \pm 0.03$ or $14.8 \pm 0.1$ $h^{-1}$ kpc at the lens redshift. The total projected mass enclosed within the Einstein radius is $2.10 \pm 0.03 \times 10^{12}$ $h^{-1}$ $M_{\odot}$, and the magnification factor for the source galaxy is $27 \pm 1$. Combining the lens model with our $gVRiz$ photometry, we find a (unlensed) star formation rate (SFR) for the source galaxy of $32$ $h^{-1}$ $M_{\odot}$ yr$^{-1}$, adopting a fiducial constant SFR model with an age of 100 Myr and $E(B - V) = 0.25$. With an apparent magnitude of $r = 19.8$, this system is among the very brightest lensed $z \geq 2$ galaxies, and provides an excellent opportunity to pursue detailed studies of the physical properties of an individual high-redshift star-forming galaxy.

Key words: galaxies: high-redshift – gravitational lensing

Online-only material: color figures

1. INTRODUCTION

Strong lensing systems provide the dual opportunity to study both the foreground mass distribution along the line of sight to the lens and the physical properties of the background object that is being lensed. The latter is especially useful in studies of high-redshift galaxies, for which lensing provides a vital boost in the apparent brightness of these faint objects, which are otherwise difficult to study in detail.

For many years, the $z = 2.72$ system cB58 (Yee et al. 1996) served as the prototypical lensed high-redshift Lyman break galaxy (LBG; e.g., Steidel et al. 2003). At $r = 20.4$, it is very bright and thereby allowed a number of detailed studies of the physical properties of a single LBG to be carried out (e.g., Pettini et al. 2000; Teplitz et al. 2000). Recently, a number of high-redshift lensed systems have been discovered, either serendipitously or in systematic searches, that are brighter than cB58 (Smail et al. 2007; Belokurov et al. 2007; Ofek et al. 2008), including the current record holder, the “8 o’clock arc,” at $r = 19.2$ (Allam et al. 2007). These discoveries have often been enabled by the Sloan Digital Sky Survey (SDSS; York et al. 2000), which provides the very large search area needed to systematically find these rare examples of extremely bright lensed high-redshift galaxies.

In this paper, we report on the discovery of another remarkably bright ($r = 19.8$) strongly lensed $z = 2.00$ galaxy, the first system we have confirmed from a systematic search program for very bright lensed arcs that we are carrying out using the SDSS data. This paper is organized as follows: Section 2 describes the arc search and the discovery, Section 3 describes the follow-up imaging and spectroscopy that led to confirmation of the system as a gravitational lens, Section 4 describes the modeling of the system including the photometry measurements, Section 5 describes the source galaxy star formation rate (SFR) measurements, and finally Section 6 presents our conclusions. We assume a flat cosmology with $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 100$ $h$ km s$^{-1}$ Mpc$^{-1}$, unless otherwise noted.

2. ARC SEARCH SAMPLE

The SDSS (York et al. 2000) is a digital imaging and spectroscopic survey that, over the course of five years, mapped nearly one quarter of the celestial sphere in five filter bands (ugriz; Fukugita et al. 1996) down to $r = 22.2$ and obtained spectra for $\approx 10^6$ astronomical objects (Adelman-McCarthy et al. 2007). The SDSS completed its first phase of operations in 2005 June and recently completed a three-year extension known as SDSS-II in 2008 July (for more details, please consult www.sdss.org.).

We previously reported the serendipitous discovery in the SDSS Data Release 4 (DR4; Adelman-McCarthy et al. 2006) of the brightest lensed LBG currently known, the 8 o’clock arc (Allam et al. 2007). The LBG in that system is at a redshift of 2.73 and is lensed by a luminous red galaxy (LRG) at a redshift of 0.38. The three bright gravitationally lensed images have a total magnitude of $r = 19.2$ and are quite blue ($g - r = 0.7$). Motivated by this discovery and using the characteristics of the 8 o’clock arc system as our starting point, we have conducted a systematic search (Kubik 2007) for similar systems in the

http://www.physics.niu.edu/physics/academic/grad/theses/Donna.pdf
The search started from two catalogs: the first consisting of 221,000 LRGs derived from the SDSS database and the second consisting of 29,000 brightest cluster galaxies (BCGs) compiled by one of us (J. Annis) using an earlier version (Hansen et al. 2005) of the maxBCG cluster finding technique (Koester et al. 2007). We defined a database query which was run on the DR5 Catalog Archive Server (CAS) database. This query searched for LRGs and BCGs which have one or more neighboring blue objects, defined using color cuts $g - r < 1$ and $r - i < 1$, that were detected by the SDSS photometric pipeline within a search radius of $10''$. We note that due to issues of seeing and object deblending in the SDSS, our search will effectively find systems with Einstein radii larger than about 2'' or so. Our search is therefore complementary to a spectroscopic lensing survey like the Sloan Lens ACS Survey (SLACS; Bolton et al. 2006), which is limited to systems with image separations smaller than the 3'' SDSS spectroscopic fiber diameter. Our sample is also distinct from the previous SDSS spectroscopic sample of candidate LBGs of Bentz et al. (2004), though those objects turned out to be broad absorption line quasars (Bentz et al. 2008).

Our query returned 57,485 systems, which were then ranked by the number of blue objects, $n$. The 1081 systems with $n \geq 3$ were inspected by four separate inspectors who looked for arc-like morphology in the SDSS CAS $gri$ color jpeg images. The 14 final candidates found in this sample have already been described in Kubik (2007), including an initial analysis of their Einstein radii and mass-to-light ratios. To date, we have spectroscopically confirmed six of them as lensed, including three with source redshifts $z \geq 2$. Additional details of follow-up observations and lens modeling for these systems, as well as for other systems found in a separate search of a sample of SDSS interacting/merging galaxies, are the subject of other papers (Kubo et al. 2009; Diehl et al. 2009). One inspector also examined the 7442 systems in the $n = 2$ sample, which yielded the object described in this paper. This system was the brightest and most striking arc candidate from the $n = 2$ list, and we dubbed the system the “Clone” as it was very similar to the 8 o’clock arc in morphology and brightness. In Figure 1, we show the discovery SDSS image of this system. The lensing LRG is the object SDSS J120602.09+514229.5, and Figure 2 shows its SDSS spectrum, indicating absorption features of an LRG.

3. FOLLOW-UP IMAGING AND SPECTROSCOPY

In order to confirm the Clone system as a gravitational lens, we have carried out a follow-up program of imaging and spectroscopy using the Astrophysical Research Consortium (ARC) 3.5 m telescope at Apache Point Observatory (APO) and the 8.2 m Subaru telescope on Mauna Kea. We first describe our Subaru data in Section 3.1 and then our APO data in Section 3.2. Note that some details of the APO data reductions mentioned in Section 3.2 will also be relevant to the Subaru reductions.

3.1. Subaru Imaging and Spectroscopy

Initial follow-up imaging and long-slit spectroscopy were carried out with the Faint Object Camera and Spectrograph (FOCAS) instrument on the Subaru 8.2 m telescope (Kashikawa et al. 2002); see the observation log in Table 1. The instrument has a 6''-diameter circular field of view and the pixel scale is 0.208 pixel per pixel (when binned by 2 × 2).

Three 15 s $V$-band exposures were taken using the FOCAS instrument, under good seeing conditions of 0.53 FWHM as measured from stars in the images. The images were bias subtracted and flat-fielded using standard routines from the IRAF7 package. We then ran the SExtractor v2.5 code (Bertin & Arnouts 1996) on the reduced images to generate object catalogs, and we matched objects from image to image to determine relative photometric zero points, using SExtractor MAG_AUTO magnitudes. We also astrometrically aligned the world coordinate system (WCS) of each image to that of the first image, using the IRAF ccmap task to derive the WCS parameters to put into the image headers. The images were then remapped and co-added, specifically median combined, with account made for the relative flux scalings between the images, using the $\mathcal{S}$warp v2.16 package.8 We note that using a simple median of the three images works well in rejecting cosmic rays and bad pixels from the final co-added image. As we had no $V$-band standard star observations available, the final photometric zero point was derived by matching objects detected by SExtractor in the co-added $V$-band image with those in the calibrated $g$- and $r$-band images from the APO 3.5 m telescope; the APO images were themselves calibrated using SDSS matches, as described below in Section 3.2. Note that this bootstrapping method gives a more robust photometric zero point as it provides twice the number of objects compared to directly matching the Subaru and SDSS data, due to the small size of the Subaru image and the shallow depth of the SDSS data. The $g$-band SExtractor

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7 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
8 http://terapix.iap.fr/ rubrique.php?id_rubrique=49
Table 1
Observation Log

| Filter/Grating       | UT Date     | Exposure  | Seeing | Notes                                      |
|----------------------|-------------|-----------|--------|--------------------------------------------|
| Subaru 8.2 m/FOCAS imaging V | 2007 Jan 23 | 3 × 15 s | 0′.53  |                                            |
| Subaru 8.2 m/FOCAS spectroscopy 300B+L600 | 2007 Jan 23 | 1 × 600 s | 0′.5   | Slit includes knots A2, A3                  |
| APO 3.5 m/SPICam imaging g | 2008 Jan 11 | 3 × 300 s | 1′0    |                                            |
| APO 3.5 m/SPICam imaging r | 2008 Jan 11 | 3 × 300 s | 1′2    |                                            |
| APO 3.5 m/SPICam imaging i | 2008 Jan 11 | 3 × 300 s | 0′9    |                                            |
| APO 3.5 m/SPICam imaging z | 2007 Oct 28 | 3 × 300 s | 1′1    |                                            |
| APO 3.5 m/DIS spectroscopy B400/R300 | 2007 Nov 19 | 2 × 600 s | ~ 1′5  | Slit includes knots A1, A2                  |

Figure 2. SDSS spectrum (provided by the SDSS SkyServer) of the LRG, showing an early-type galaxy spectrum with a redshift \( z = 0.4224 \pm 0.0002 \). The labels and vertical green lines indicate potential spectral features (whether present or not) at the LRG redshift. Note that the prominent emission feature at \( \sim 5577 \) Å is really a strong night sky line subtraction residual, as indicated by the vertical magenta lines.

(A color version of this figure is available in the online journal.)

3″ aperture magnitudes were first transformed to \( V \) band, via the relation \( V = g - 0.59(g - r) - 0.01 \) (Jester et al. 2005), and then used to determine the zero point of the Subaru image using the \( V \)-band magnitude offsets for matching stars and galaxies in the images. The co-added \( V \)-band image was astrometrically registered through matches to SDSS objects, again using the IRAF ccmap task.

Figure 3 shows the co-added FOCAS image. Not only is the counter-image A4 now very clear but we can now see that the central lensing galaxy (B) is clearly accompanied by two smaller galaxies (C and D). Our photometry analysis of this image is described below in Section 4.1.

After the imaging data were obtained, a single 600 s long-slit FOCAS spectrum was also taken, with the slit oriented to cover both knots A2 and A3 in the arc. The 300B grating and L600 filter were used, providing a dispersion of 1.34 Å per pixel, spectral coverage of 3700–6000 Å, and a resolution \( R \sim 400 \) with a 1′.0-wide slit. The \textit{Hubble Space Telescope} (HST) spectrophotometric standard G191-B2B was also observed and used for flux calibration. The FOCAS spectroscopic data were reduced using standard routines from the IRAF twodspec package. The extracted one-dimensional spectra for the A2 and A3 knots are shown in Figure 4. The redshift of the arc was found to be \( z = 2.0010 \pm 0.0009 \) based on measurements of prominent absorption lines due to \( \text{C} \text{II}, \text{Si} \text{IV}, \text{C} \text{IV}, \text{Fe} \text{II}, \) and \( \text{Al} \text{II} \), typical features seen in the spectra of star-forming LBGs (Shapley et al. 2003), in particular of the \( z \sim 2 \) “BX/BM” variety as defined by the classification scheme of Steidel et al. (2004). Table 2 summarizes details about the observed lines. The high redshifts of the knots, combined with the clear arc morphology seen in the Subaru image, confirm that this is indeed a gravitationally lensed system.

3.2. APO Imaging and Spectroscopy

Additional follow-up imaging data in the SDSS \( griz \) bands were obtained on the APO 3.5 m telescope using the SPIcam CCD imager, which has a scale of 0′.28 per pixel and a field of view of 4′.8 × 4′.8. The data were obtained under photometric conditions, and the seeing ranged from 0′.9 to 1′.2. The total exposure time in each filter was 900 s, divided into three dithered exposures (with 15″ offsets) of 300 s each in order to reject cosmic rays and bad pixels. Additional details are given in the observation log in Table 1.

The resulting \( griz \) images were reduced and co-added using the same procedure described above for the Subaru data. The SPIcam \( z \)-band data showed significant fringing and therefore an additional reduction step was necessary to subtract off a master fringe frame. The final co-added images were again
astrometrically registered by matching to SDSS objects. The photometric zero points for the co-added images were derived using unsaturated bright stars in the SPIcam images. Specifically, we used Galfit (Peng et al. 2002, also see below) to fit Moffat profiles to these stars, and compared the resulting total magnitudes to the corresponding SDSS model magnitudes. Note that we did not apply any color terms in our calibration of SPIcam to SDSS griz magnitudes, as verified by a comparison of SExtractor photometry of the SPIcam data versus the corresponding SDSS photometry for matching objects. Figure 5 shows a montage of the co-added griz SPIcam images, as well as a gri color composite. We describe our photometry analysis for these images in Section 4.3 below.

Additional follow-up long-slit spectroscopy of the arc was carried out with the Dual Imaging Spectrograph (DIS III) on the APO 3.5 m telescope. Two 600 s exposures were obtained, with a 1″5-wide slit covering knots A1 and A2, under ~ 1″5 seeing. The B400/R300 gratings were used, covering an effective spectral range of 3600–9600 Å, with a dispersion of 1.83 Å per pixel in the blue part of the spectrum and 2.31 Å per pixel in the red. The spatial scale is about 0″4 per pixel. HeNeAr lamp exposures were taken for wavelength calibration, and the spectrophotometric standard stars GD 50 and Feige 110 were observed for flux calibration. The spectra were reduced using the IRAF ccdred package and the doslit task. The two spectroscopic exposures of the arc were combined using the combine task, and the red and blue spectra were spliced together using the spliceSpec task from Gordon Richard’s distools external IRAF package. The reduced spectrum is shown in Figure 4. As with the Subaru spectra, a redshift was determined from the combined APO spectrum using absorption features typical of LBGs (see Table 2). The APO spectrum yields a redshift of \(z = 2.0001 \pm 0.0006\), consistent with that from the Subaru spectra.

4. MODELING THE SYSTEM

4.1. Subaru Photometry

We proceed next to derive a lensing model for the Clone system and to measure the photometric properties of the lensing galaxies and the lensed images. The first step is to model the lens components of the image so that their light can be subtracted off, leaving us with just the light of the lensed images that we can use to derive the lensing model, as described below in Section 4.2. To
model the lensing galaxies, we have used the GALFIT program (Peng et al. 2002). GALFIT can perform a simultaneous fit to multiple objects in a Flexible Image Transport System (FITS) image. It allows the user to fit a number of common galaxy profiles such as Sersic, de Vaucouleurs, and exponential disk. The inputs required are a FITS image of the system, a FITS file of the point-spread function (PSF), an optional mask which can be used to eliminate pixels from consideration in the fit, and a determination of the sky background. The initial object positions were determined using SExtractor. The modeling was done using the co-added $V$-band Subaru image as it has the highest resolution. The PSF was determined from stars in the image. We also included the arc and counter-image in the GALFIT model, but did not include the two faint galaxies that can be seen in the bottom right of Figure 3. The best description of the system is obtained using a Sersic profile for the main LRG, de Vaucouleurs profiles for the two small galaxies (C and D), and a combination of five exponential disks for the arc and one exponential disk for the counter-image. This gives a $\chi^2$/degrees of freedom (dof) of 1.13. In Table 3, we show the fitted parameters and in Figure 6 we show the model and the data-model residual image. From the residual image, we can see that the galaxies B, C, and D are well modeled, but that the exponential disk model for the arcs is not perfect. We then subtract off the models for just the lens objects B, C, and D from the image, leaving us with the light of the lensed arc and counter-image for the subsequent lens modeling.

### Table 2

| ID/Rest Wavelength | Subaru 8.2 m (A2+A3) | APO 3.5 m (A1+A2) |
|--------------------|----------------------|-------------------|
|                    | Observed Wavelength$^a$ | Redshift | Observed Wavelength$^a$ | Redshift |
| Ly$\alpha$ 1215.7 | ... | ... | 3650.0$^b$ | 2.0025 |
| Si$\pi$ 1260.4 | ... | ... | 3781.4 | 2.0002 |
| OI 1302.2, Si$\pi$ 1304.4 | ... | ... | 3904.6 | 1.9959 |
| C$\pi$ 1334.5 | 3999.1 | 1.9967 | 4002.6 | 1.9993 |
| Si$\text{iv}$ 1393.8 | 4180.3 | 1.9992 | 4181.8 | 2.0003 |
| Si$\text{iv}$ 1402.8 | 4210.4 | 2.0014 | 4209.1 | 2.0005 |
| Si$\pi$ 1526.7 | 4584.0 | 2.0026 | 4581.9 | 2.0012 |
| C$\text{iv}$ 1548.2,1550.8 | 4650.2 | 2.0011 | 4644.7 | 1.9975 |
| Fe$\pi$ 1608.4 | 4831.7 | 2.0040 | 4827.4 | 2.0014 |
| Al$\pi$ 1670.8 | 5015.6 | 2.0019 | 5015.2 | 2.0017 |

Mean redshift$^c$ 2.0010 ± 0.0009 2.0001 ± 0.0006

**Notes.**

$^a$ The observed wavelengths were converted from wavelengths in air to wavelengths in vacuum using Equation (3) of Morton (1991).

$^b$ Ly$\alpha$ is seen in absorption in the APO 3.5 m spectrum, with an observed equivalent width of $-15 \pm 1$ Å, or $-5 \pm 0.3$ Å in the rest frame.

$^c$ The error on the mean redshift is the standard deviation of the mean of the redshifts from the individual lines.

### 4.2. Lens Modeling

We have modeled the lens using the LENSVIEW program (Wayth & Webster 2006), a program for modeling resolved gravitational lenses. It is based on the LENSMEM algorithm (Wallington et al. 1996) and uses a maximum entropy constraint to find the best-fitting lens mass model and source brightness distribution. It supports a number of common mass models. The inputs to the program are a FITS image of the lensing system with the non-arc objects removed (Figure 7, left plot), a FITS file containing the PSF for the image, a FITS image of the pixel-by-pixel variance of the data, an empty FITS image with the dimensions of the desired source plane, and a FITS image containing a mask of the pixels over which the $\chi^2$ will be calculated (Figure 7, right plot). It also requires the ratio of the angular size of the pixels between the image and source planes. We have used a source plane of $10 \times 10$ pixels, with $0.052$ per pixel, i.e., four times finer than the image plane pixel scale.

Using LENSVIEW, we have modeled the system using a singular isothermal ellipsoid (SIE; Kormann et al. 1994) as the mass model. The best-fit model yields an Einstein radius of...
and 8 (left), we see that the model does look qualitatively quite
like the data. The best-fit
\[ \chi^2 \]

kpc at the LRG redshift of 0.422. The fitted axis ratio and
\[ \theta \]

Figure 7. Input image (left) and the pixel mask (right) used in the LENSVIEW lens model fits. LENSVIEW will use only the pixels inside the mask (the black region in the right panel) to calculate the \( \chi^2 \) between the input image and the model. The scale in the left panel is in units of observed counts per pixel per 15 s exposure for the Subaru V-band image. See Section 4.2 for details.

(A color version of this figure is available in the online journal.)

Table 3

| Object      | Model          | V Magnitude\(^a\) | Effective Radius \( r_e \) (arcsec) | Exponent | Axis Ratio | Position Angle (deg E of N) |
|-------------|----------------|-------------------|-------------------------------------|----------|------------|-----------------------------|
| B(LRG)      | Sersic         | 18.97 ± 0.05      | 3.67 ± 0.34                         | 4.68 ± 0.22 | 0.89 ± 0.01 | −68.2 ± 6.2                |
| C           | de Vaucouleurs | 22.54 ± 0.17      | 0.56 ± 0.16                         | 4         | 0.59 ± 0.15 | 47.3 ± 12.5               |
| D           | de Vaucouleurs | 22.84 ± 0.09      | 0.19 ± 0.1                          | 4         | 0.77 ± 0.2  | 42.7 ± 34.6               |

Scale length \( r_0 \) (arcsec)

| Arc (A3)    | Exponential    | 20.88 ± 0.01      | 0.52 ± 0.01                         | 0.24 ± 0.01 | 68.4 ± 0.5  | 39.4 ± 0.66                |
| Arc        | Exponential    | 21.72 ± 0.04      | 0.79 ± 0.04                         | 0.05 ± 0.01 | 39.4 ± 0.66 | 39.4 ± 0.66                |
| Arc (A2)   | Exponential    | 21.64 ± 0.07      | 0.47 ± 0.02                         | 0.15 ± 0.02 | 12.6 ± 1.2  | 12.6 ± 1.2                |
| Arc (A2)   | Exponential    | 21.82 ± 0.08      | 0.48 ± 0.03                         | 0.03 ± 0.0  | 6.5 ± 0.6   | 6.5 ± 0.6                 |
| Arc (A1)   | Exponential    | 20.91 ± 0.01      | 0.57 ± 0.01                         | 0.22 ± 0.01 | −28.0 ± 0.4 | 28.0 ± 0.4                |
| Counter-image (A4) | Exponential | 22.43 ± 0.03 | 0.23 ± 0.01                         | 0.28 ± 0.06 | 25.8 ± 3.2  | 25.8 ± 3.2                |

Notes.

\(^a\) The photometry errors given here are the formal errors reported by GALFIT. The magnitudes have been corrected for Milky Way extinction, using values from the SDSS DR5 database, which are in turn based on the dust maps of Schlegel et al. (1998). Specifically, the extinction correction in \( V \) is 0.070 mag and \( E(B - V) = 0.023 \).

\[ \theta_{\text{Ein}} = 3.82 \pm 0.03 \] kpc at the LRG redshift of 0.422. The fitted axis ratio and position angle are 0.751 ± 0.018 and −70.11 ± 0.39 (E of N), respectively. The best-fit model with the tangential critical curve is shown in Figure 8, left plot, and the predicted source with the corresponding tangential caustic is given in Figure 8, right plot. The best-fit lens center is offset by a small amount, (0′′.01 ± 0′′.02) E of N.

\[ \chi^2 \]

is shown in Figure 8, left plot, and the predicted source with the corresponding tangential caustic is given in Figure 8, right plot. The best-fit lens center is offset by a small amount, (0′′.01 ± 0′′.02) E of N, which is much less than 1 pixel (recall the scale is 0′′.208 per pixel) from the center of the LRG light distribution obtained from GALFIT. The total magnification of the system, obtained by dividing the total flux in the arcs by the total flux in the source, is 27 ± 1. Comparing Figures 7 (left) and 8 (left), we see that the model does look qualitatively quite like the data. The best-fit \( \chi^2 / \text{dof} \) is 2.18 (2102 for 968 dof), however, indicating formally a poor fit. This can be understood by looking at the pixel-by-pixel residuals scaled by the errors, (\( \text{counts}_{\text{data}} - \text{counts}_{\text{model}} / \sigma_{\text{data}} \)), shown in Figure 9. We see that there are large residuals coming from the A3 knot, which is brighter in the data than in the model by 23% within a 3′′ aperture. We have explored other mass models including SIE+external shear but find similar or worse agreement.

In strong lensing, it has been known for some years that the smooth mass models fit the image positions well but not always the flux ratios of the images. As LENSVIEW uses the full image information, it is not possible to use it to determine how well the image positions alone are determined. So we turn to gravlens/lensmodel (Keeton et al. 2001) which allows us to fit an SIE model using only the image positions. We use the A1–A4 image positions determined by running SExtractor on the Subaru image and given in Table 4 (same as used below in Section 4.3). We assign large errors to the flux ratios so that they do not contribute to the \( \chi^2 \). We obtain a very good fit to the image positions, with a \( \chi^2 / \text{dof} \) of 2.55 for 3 dof and values of the SIE parameters that agree with those from the LENSVIEW fit. As the image positions are well determined, the statistical errors quoted above for our lens model parameters are from the lensmodel fit rather than the LENSVIEW fit. The predicted flux for A3 in the lensmodel fit is smaller than the measured flux by a factor of 2. This is more discrepant than what we obtained from LENSVIEW above, in which the source light distribution is more realistically modeled as an extended source, as opposed to a point source as used in lensmodel. The A3 flux is also not better matched by adding external shear or by adding galaxies C and D as singular isothermal spheres. An interesting discussion of anomalous flux ratios in four-image lenses with a fold configuration, as is the case for our system, can be found in Keeton et al. (2005). They define the ratio \( R_{\text{fold}} = (F_+ - F_-)/(F_+ + F_-) \), where \( F_+ \) and \( F_- \) are the observed...
shown in red along with the 10 x 10 pixel source plane. On both plots, the spatial scale is indicated by the horizontal bar representing 1′′. The flux scales in the panels are in units of observed counts per image plane pixel (0′.208 per pixel) per 15 s exposure for the Subaru V-band image. Note the source plane pixels (0′.052 per pixel) in the right panel are 16 times smaller in area than the image plane pixels in the left panel.

(A color version of this figure is available in the online journal.)

Figure 8. Best-fit LENSVIEW model image (left). The tangential critical line is shown in red. The best-fit LENSVIEW model source (right). The tangential caustic is shown in red along with the 10 x 10 pixel source plane. On both plots, the spatial scale is indicated by the horizontal bar representing 1′′. The flux scales in the panels are in units of observed counts per image plane pixel (0′.208 per pixel) per 15 s exposure for the Subaru V-band image. Note the source plane pixels (0′.052 per pixel) in the right panel are 16 times smaller in area than the image plane pixels in the left panel.

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Figure 9. Normalized residual image, \((\text{counts}_{\text{data}} - \text{counts}_{\text{model}})/\sigma_{\text{data}}\) for the best-fit LENSVIEW model of the system.

(A color version of this figure is available in the online journal.)

Fluxes for a pair of images of opposite parity, as indicated by the subscripts. They model \(R_{\text{fold}}\) for different image pairs in four-image lenses. Deviations from the expected values are thought to indicate the presence of structure at scales smaller than the separation between the images. We measure \(R_{\text{fold}}\) = 0.173 for the image pair A3–A2. This value is not consistent with the range of values shown in Figure 5 of Keeton et al. (2005). Given this result and our poor \(\chi^2\) from LENSVIEW, we conclude that we may have substructure in the lens which is currently not being well modeled using a smooth SIE mass distribution.

From the SIE model, the velocity dispersion of the mass distribution doing the lensing is 440 ± 7 km s^{-1}, which would be quite large for an elliptical galaxy. The SDSS database does not provide a spectroscopic velocity dispersion for the LRG due to the low signal to noise of the SDSS spectrum. We obtained a similarly large value for the velocity dispersion of the 8 o’clock arc lensing mass, which is discussed in Allam et al. (2007). Combined with the large 3.82 Einstein radius and the presence of neighboring red galaxies like C, D, E (see Section 4.3), and others further away, this indicates that the lensing is due in part to the group environment around the central LRG (see, e.g., Oguri 2006). We have thus investigated two alternative mass models to attempt a better approximation of the group lensing contribution, specifically using SIE+external shear and a Navarro, Frenk, and White (NFW) profile (Navarro et al. 1997).

However, the LENSVIEW fits in both cases give about 10% worse \(\chi^2\) per dof than the simple SIE model, and in particular the SIE+external shear model gives only a small shear of 0.006 that is closely aligned with the position angle of the main SIE profile. Thus, using just a simple SIE fit, we are able to provide a reasonable model that reproduces the most salient features of the lensing system, namely, the positions and morphology of the lensed arc and counter-image.

Since both the redshift of the LRG and the source are known, we are able to determine the angular diameter distance to the source (\(D_s\)), to the lens (\(D_l\)), and between the source and lens (\(D_{sl}\)), to be 1209, 801, and 829 h^{-1} Mpc, respectively. Then, from the simple SIE model, we can determine the mass interior to \(R_{\text{Ein}}\) using \(M_{\text{Ein}} = (c^2/4G)(D_l/D_s) 	imes \theta_{\text{Ein}}^2 = 2.10 \pm 0.03 \times 10^{12} h^{-1} M_\odot\). As we are using the SIE convention of Kormann et al. (1994), to be more precise the enclosed mass is actually defined within an elliptical aperture with semimajor axis \(\theta_{\text{Ein}}\), and axis ratio and position angle as given above. For the same aperture, we also determine the lens light, by summing the fluxes from the best-fitting GALFIT models for the LRG and for galaxies C and D (see Sections 4.1 and 4.3); the results are given in Table 4. Note that due to the similarity of the Einstein radius of the lens mass model to the half-light (or effective) radius of the LRG, and likewise for the respective axis ratios and position angles (compare with Table 3), the flux within the lens light aperture is very close to half the total flux of the LRG (galaxies C and D contribute only a small amount). We then convert the apparent lens light to absolute fluxes, adopting k-corrections using an elliptical galaxy template (Coleman et al. 1980), and obtain mass-to-light ratios in the rest-frame gVriz bands of \(M/L = 27, 22, 19, 15, and 12 h M_\odot L_\odot^{-1}\), respectively (\(\Omega_M = 0.3, \Omega_\Lambda = 0.7\)). We note that these \(M/L\) values, out to a radius of 15 h^{-1} kpc, are ~5–10 times larger than those for the lensing LRGs, on the scale of a few kpc, from the SLACS sample (Treu et al. 2006; Koopmans et al. 2006). As shown Figure 7.8
of Kubik (2007), this trend of $M/L$ with radius is consistent with that determined for elliptical galaxies using independent dynamical and X-ray techniques (Bahcall et al. 1995).

### 4.3. APO Photometry

We turn now to the photometry analysis of the APO 3.5 m SPICam co-added imaging data in order to derive color information for the various lensing galaxies and lensed image components. Because the SPICam data were taken under only modest seeing conditions, we will rely on the galaxy profile parameters determined earlier from running GALFIT on the Subaru $V$-band image, rather than try to re-fit those parameters independently in each of the SPICam $gri z$ images. Specifically, we adopt all the best-fit $V$-band profile parameters for the LRG (= galaxy B), galaxies C and D, and counter-image A4, except that we will fit for the total magnitude of each of those four components. Moreover, we also re-fit for the position of the LRG, in order to account for small errors in the astrometric registration relative to the Subaru image; we find best-fit shifts of $\leq 0\prime.07$, which are small but nonetheless result in noticeable visual improvement in the residual image after subtracting off the LRG model. Note we do not attempt to fit models to the lensed arc images, as was done for the Subaru data. Instead, we mask out the image areas corresponding to the A1, A2, and A3 components before running GALFIT on the SPICam data. The masks are derived using SExtractor-generated “segmentation” images, which flag the pixels belonging to each detected object. We will later compute aperture magnitudes for the arc components, in a model-independent way as described below. For the PSF model needed by GALFIT, we use the best-fit Moffat profile derived by GALFIT for a bright unsaturated star in a given image. We find that our results are not sensitive to whether we use the Moffat profile or the actual data for the star itself as the PSF model. Note we also first use SExtractor to do sky subtraction on an image before feeding it to GALFIT. Our GALFIT photometry results for the SPICam co-added $gri z$ images are given in Table 4. As a comparison, we note that the GALFIT magnitudes for the LRG are brighter by $0.2$–$0.4$ mag compared to the MAG_AUTO values obtained from simpler SExtractor photometry. We plot the $gVriz$ total magnitudes of the LRG and of galaxies C and D in Figure 10, where we have also overlaid a template elliptical galaxy spectrum from Coleman et al. (1980), after redshifting to the LRG redshift $z = 0.422$ and converting the flux of the spectrum to AB magnitude units. The reasonable match of the spectral energy distributions (SEDs; described by the $gVriz$ magnitudes) of galaxies C and D to the template spectrum is consistent with the interpretation of those two galaxies as early-type galaxies at the same redshift as the LRG.

As noted above, for the lensed arc image components A1–A3, we measure simple aperture magnitudes. We do this instead of attempting profile fitting since we do not expect the lensed and distorted arc images to follow standard galaxy profiles, as can be seen in the residual image shown in Figure 6 (right panel) for the Subaru data. We measure 3″-diameter circular aperture magnitudes for each of the A1–A3 arc components, with centers determined from running SExtractor on the Subaru image. The aperture magnitudes are measured from the images after subtraction of the best-fit GALFIT galaxy models as described above. The Subaru $V$-band image is first convolved by a Gaussian to degrade the seeing to 1″0 to match the typical seeing in the SPICam data. Otherwise no aperture corrections are made to reconcile the small seeing differences among the $gri z$ data. We also ignore a small overlap in the apertures centered on the A1 and A2 components and do not attempt any deblending. In addition, we define a partial annular aperture, centered on the LRG, with inner radius 3″, outer radius 5″, and position angle ranging from $-140^\circ$ to $+5^\circ$ E of N. This (partial) annulus provides a simple aperture that captures the shape and flux of the lensed arc. Our aperture photometry results for lensed arc images are presented in Table 4. Using the $g$- and $r$-band magnitudes for the annulus aperture (with a lensing magnification of 24) and following Sawicki & Thompson (2006), we find that the Clone is approximately a $3L^*$ BX/BM galaxy ($L^*$ refers to rest-frame 1700 Å, or observed frame between $g$ and $r$).

### 5. SOURCE GALAXY STAR FORMATION RATE

To estimate the SFR of the Clone and facilitate comparison with previous rest-frame UV SFR estimates for cB58 and the 8 o’clock arc, we follow the procedure of Pettini et al. (2000). As in that paper, we use a simple constant SFR model (from the GALAXEV package; Bruzual & Charlot 2003), with age
Figure 10. $g_{	ext{Vriz}}$ AB magnitudes (points with error bars) of the LRG (left) and galaxies C and D (right) are compared to the rescaled spectrum of a template elliptical galaxy (CWW E) from Coleman et al. (1980). The CWW E template spectrum has been redshifted to the LRG redshift $z = 0.422$.

100 Myr, solar metallicity, and a Salpeter (1955) initial mass function (IMF) over the mass range $0.1$–$100 \, M_\odot$. We also assume the dust extinction prescription of Calzetti et al. (2000), with a (stellar continuum) color excess $E(B - V) = 0.25$, in order to obtain a good match to our observed $g_{	ext{Vriz}}$ magnitudes. We express our results in analogy with Equation (6) of Pettini et al. (2000), but using a flat cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 100 \, h \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, and obtain

$$\text{SFR} \approx 32 \times \left(\frac{24}{f_{\text{lens}}}\right) \times \left(\frac{f_{\text{dust}}}{11}\right) \times \left(\frac{7.8 \times 10^{27} \, \text{erg} \, \text{s}^{-1} \, \text{Hz}^{-1}}{F_{\nu, 1500}}\right) \times \left(\frac{2.5}{f_{\text{IMF}}}\right) \, h^{-1} \, M_\odot \, \text{yr}^{-1}, \tag{1}$$

where $f_{\text{lens}}$ is the lensing magnification corresponding to the flux inside the annulus aperture, $f_{\text{dust}}$ is the extinction at rest wavelength 1500 Å, $F_{\nu, 1500}$ is the flux at rest 1500 Å for a model forming stars at $1 \, M_\odot \, \text{yr}^{-1}$, and $f_{\text{IMF}}$ is a correction factor to the Salpeter IMF, as described by Pettini et al. (2000) and references therein.

We emphasize that there will be other models, with different ages, dust extinctions, and metallicities than adopted in our fiducial model, which can also provide good matches to our data, which cover just rest-frame UV wavelengths. To obtain better constraints will require use of data at observed-frame IR = rest-frame optical wavelengths (e.g., Ellingson et al. 1996). We also note that SFR estimates from the rest-frame UV can differ significantly from those obtained at redder wavelengths; see the discussion in Siana et al. (2008). With these caveats in mind, we can nonetheless still compare against the SFRs obtained under similar assumptions for other systems. In particular, our resulting SFR of $32 \, h^{-1} \, M_\odot \, \text{yr}^{-1}$ is about twice the value of $17 \, h^{-1} \, M_\odot \, \text{yr}^{-1}$ obtained by Pettini et al. (2000) for cB58 (after converting to our adopted cosmology), but it is much lower than the 160 $h^{-1} \, M_\odot \, \text{yr}^{-1}$ obtained by Allam et al. (2007) for the 8 o’clock arc. We can also compare our source galaxy with the sample of about 100 (unlensed) $z \sim 2$ star-forming galaxies of Erb et al. (2006a, 2006b), who derived SFRs using detailed SED fitting with Bruzual & Charlot (2003) models, including additional IR data in the fits. The bulk of the Erb et al. (2006a, 2006b) sample galaxies were best fit with constant-SFR models. Overall those galaxies have a mean SFR of $52 \, M_\odot \, \text{yr}^{-1}$ ($H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$), which becomes $26 \, h^{-1} \, M_\odot \, \text{yr}^{-1}$ after converting to our conventions. We see that our source galaxy has an SFR similar to the typical $z \sim 2$ star-forming galaxy from the Erb et al. (2006a, 2006b) sample.

6. CONCLUSIONS

We have reported on the discovery of the Clone system, consisting of a star-forming, BX/BM-type LBG in the SDSS at a redshift of $z = 2.001$, which is strongly lensed by a foreground LRG at a redshift of $z = 0.422$. The lensed galaxy is remarkably bright, and at $r = 19.8$ it is among the brightest known lensed source galaxies with $z \geq 2$.

A simple SIE lens model for the system yields an Einstein radius of $\theta_{\text{Ein}} = 3.82 \pm 0.03$ or $R_{\text{Ein}} = 14.8 \pm 0.1 \, h^{-1} \, \text{kpc}$ (at the lens redshift), a total lensing mass within the Einstein radius of $2.10 \pm 0.03 \times 10^{12} \, h^{-1} \, M_\odot$, and a magnification factor for the lensed LBG of $27 \pm 1$. Combining the lens model with our follow-up $g_{	ext{Vriz}}$ photometry, we have also estimated the (unlensed) SFR of the source galaxy to be $32 \, h^{-1} \, M_\odot \, \text{yr}^{-1}$, adopting a fiducial constant-SFR galaxy evolution model with an age of 100 Myr and $E(B - V) = 0.25$. Such an SFR is similar to that found for samples of similar, but unlensed, $z \sim 2$ BX/BM galaxies.

We are pursuing a number of further follow-up observations on this system, and we currently have optical and infrared data from HST Cycle 16, Spitzer Cycle 4, and Gemini North programs. Analysis of the higher-resolution HST images will help us investigate the issues of substructure and image flux anomalies that we have encountered in the lens modeling described here. Moreover, we will also use the SED information provided by the additional near-IR imaging and spectroscopy we are analyzing to better constrain the star formation history and dust content than we have been able to do here using just the optical data. These more detailed analyses will be the subjects of future papers that will exploit the rich follow-up data set that can be derived from this very bright high-redshift lensing system.

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9 We account for $H_0$, for a factor of 1.8 to convert the SFR normalization from the Chabrier (2003) IMF used by Erb et al. (2006a, 2006b) back to a Salpeter IMF, and finally for our use of the factor $f_{\text{IMF}} = 2.5$ from Pettini et al. (2000).
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