THE 8 O’CLOCK ARC: A SERENDIPITOUS DISCOVERY OF A STRONGLY LENSED LYMAN BREAK GALAXY IN THE SDSS DR4 IMAGING DATA

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Received 2006 November 3; accepted 2007 May 7; published 2007 May 31

ABSTRACT

We report on the serendipitous discovery of the brightest Lyman break galaxy (LBG) currently known, a galaxy at $z = 2.73$ that is being strongly lensed by the $z = 0.38$ luminous red galaxy (LRG) SDSS J002240.91+143110.4. The arc of this gravitational lens system, which we have dubbed the “8 o’clock arc” due to its time of discovery, was initially identified in the imaging data of the Sloan Digital Sky Survey Data Release 4; followup observations on the Astrophysical Research Consortium (ARC) 3.5 m telescope at Apache Point Observatory confirmed the lensing nature of this system and led to the identification of the arc’s spectrum as that of an LBG. The arc has a spectrum and a redshift remarkably similar to those of the previous record-holder for brightest LBG (MS 1512−cB58, also known as cB58), but, with an estimated total magnitude of $(g, r, i) = (20.0, 19.2, 19.0)$ and surface brightness of $(μ_u, μ_r, μ_i) = (23.3, 22.5, 22.3)$ mag arcsec$^{-2}$, the 8 o’clock arc is thrice as bright. The 8 o’clock arc, which consists of three lensed images of the LBG, is 162° (9.6′) long and has a length-to-width ratio of 6 : 1. A fourth image of the LBG—a counterimage—can also be identified in the ARC 3.5 m g-band images. A simple lens model for the system assuming a singular isothermal ellipsoid yields an Einstein radius of $\theta_{E} = 3.32$ ± 0.16′, a total mass for the lensing LRG (within the 1 kpc enclosed by the Einstein radius) of $1.35 \times 10^{12} M_{\odot}$, and a magnification factor for the LBG of $12.3^{+15.0}_{-3.6}$. The LBG itself is intrinsically quite luminous (≈11$L_{\odot}$) and shows indications of massive recent star formation, perhaps as high as $160 h^{-1} M_{\odot}$ yr$^{-1}$.

Subject headings: galaxies: high-redshift — gravitational lensing

1. INTRODUCTION

Strongly lensed galaxies are particularly useful for studies of galaxy evolution due to the magnification of the galaxy flux: since surface brightness is conserved by lensing, the stretching of the galaxy shape increases the apparent brightness of the source galaxy. These apparently brighter objects are then prime candidates for detailed follow-up studies at a fraction of the telescope time that would be necessary for comparable but unlensed galaxies.

Due to their rarity, strongly lensed Lyman break galaxies (LBGs) are of particular interest. LBGs are galaxies in which the low-flux region of the spectrum bluedward of the Lyα hydrogen line at 1216 Å has been redshifted into the $U$ band; LBG samples thus provide a vital window into the galaxy populations of the high-redshift ($z > 2.7$) universe (e.g., Adelberger et al. 1998, 2003; Steidel et al. 1998; Giavalisco et al. 1998). LBGs, however, are generally rather faint, and detailed studies of these high-redshift galaxies profit from the additional magnification provided by strong lensing (Nesvadba et al. 2006).

Previously, only a few examples of strongly lensed LBGs have been discovered: MS 1512−cB58 at $z = 2.7$ (also known as cB58; Yee et al. 1996; Teplitz et al. 2000; Pettini et al. 2002; Baker et al. 2004), the 1E 0657−56 arc+core at $z = 3.2$ (Mehlert et al. 2001), the “Cosmic Eye” at $z = 3.07$ (Smail et al. 2007), and possibly FOR J0332−3557 at $z = 3.773$ (Cabanac et al. 2005). A search by Bentz et al. (2004) using the Sloan Digital Sky Survey (SDSS) Early Data Release (Stoughton et al. 2002) yielded six bright ($r \sim 20$) candidate LBGs with $z = 2.45–2.80$, but these were later found to be unlensed bright quasars (Ivison et al. 2005).

Here we report on the serendipitous discovery in the SDSS data of the brightest case of these rare objects, a strongly lensed $z = 2.73$ LBG, which we have nicknamed the “8 o’clock arc.” Throughout, 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. THE INITIAL DISCOVERY

The SDSS (York et al. 2000) is a digital imaging and spectroscopic survey that, over the course of 5 years, has mapped nearly one-quarter of the celestial sphere in five filter bands ($ugriz$; Fukugita et al. 1996) down to $r = 22.2$ and has obtained spectra for $\approx 10^7$ astronomical objects (Adelman-McCarthy et al. 2006).

To explore the effects of interactions on the properties of galaxies in different environments, Allam et al. (2004) extracted a catalog of interacting/merging galaxy pairs from the SDSS imaging data. During visual inspection of a new version of this catalog (S. S. Allam et al. 2007, in preparation) based on the SDSS imaging data of the brightest case of these rare objects, a strongly lensed $z = 2.73$ LBG, which we have nicknamed the “8 o’clock arc.” The SDSS targeted SDSS J002240.78+143110.4, which is a very blue and elongated object.

The SDSS targeted SDSS J002240.91+143110.4 (hereafter “the LRG”; for LRG selection, see Eisenstein et al. 2001) with a 3′ spectroscopic fiber. The LRG spectrum shows absorption features of an early-type galaxy at redshift of $z = 0.38$ with Ca H and K lines at 5463 and 5510 Å. The very blue and elongated SDSS J002240.78+143113.9 was not targeted for SDSS spectroscopy and hence has no SDSS spectrum. Allam recognized this system

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as a probable gravitational lens and, due to its time of discovery, dubbed it the "8 o’clock arc." The arc is a very blue high surface brightness object north of the LRG, subtending an angle of approximately 162° about the galaxy. The arc consists of three components: the blue A1, the reddish blue A2, and the blue A3. The full arc extends over 9.6" in length and has a length-to-width ratio of 6:1.

3. THE CONFIRMATION

In order to confirm the identification of the system as a gravitational lens, we carried out follow-up imaging and spectroscopy on the Astrophysical Research Consortium (ARC) 3.5 m at Apache Point Observatory on the night of 2006 August 24 (UT).

3.1. Imaging

The imaging was obtained under photometric conditions and with a seeing of 1.0”–1.2” (FWHM) during the first half of the night. The instrument used was the SPIcam CCD imager, which has a field of view of 4.78’ × 4.78’. Three exposures of 300 s each were obtained in each of the SDSS gri filters; a 15” dithering pattern about the LRG was employed.

The resulting images were processed using the IRAF ccdred package. The images were then co-added with the SWarp package (Bertin 2006, ver. 2.16; see Fig. 2), and object detection and measurement were made with SExtractor (Bertin & Arnouts 1996). We used a weighted co-addition, accounting for flux scaling between the images, and aperture photometry with an aperture of 3”. Photometric zero points were derived by matching objects detected in the co-added images with objects in the SDSS imaging data and comparing their SExtractor MAG_AUTO instrumental magnitudes with their SDSS model magnitudes. The gri magnitudes measured from these co-added images are listed in Table 1. An astrometric solution for the co-added images was measured relative to the SDSS overlapping bright stars in the field of view.

3.2. Spectroscopy

Slit spectroscopy was carried out with the DIS III (Dual Imaging Spectrograph) using the standard medium red/low blue grating setup during the second half of the night. Six exposures were obtained under moonless conditions for a total exposure time of 140 minutes. The seeing was 1”–1.2” (FWHM). A slit width of 1.5” was employed, and the slit was oriented to cover as much of the three components of the 8 o’clock arc as was possible. The standard medium red/low blue grating setup covers an effective spectral range of 3600–9600 Å at a linear resolution of 2.43 Å pixel⁻¹ in the blue part of the spectrum and 2.26 Å pixel⁻¹ in the red; the spatial scale is 0.4” pixel⁻¹. The Hubble Space Telescope spectrophotometric standard G191-B2B was observed for flux calibration.

The spectra were reduced using the IRAF ccdred package and the doslit task. The six individual spectroscopic exposures of the 8 o’clock arc were combined using the scombine task, and the red and blue spectra were spliced together using the spliceSpec task from G. Richard’s distools external IRAF package.

The redshift of the 8 o’clock arc was estimated to be $z = 2.73$ based on measurements of Ly$\alpha$ 1215.7, Si$\alpha$ 1260.4, O$\beta$ + Si$\alpha$ λ(1302.2 + 1304.4), C$\gamma$ λ1334.5, Si iv λ1393.8,

### Table 1

| Identification | R.A. (2000.0) | Decl. (2000.0) | $g'$ | $r'$ | $i'$ |
|---------------|--------------|---------------|-----|-----|-----|
| LRG           | 00 22 40.91  | 14 31 10.0    | 20.14| 18.62| 18.16|
| A1            | 00 22 40.79  | 14 31 13.8    | 21.18| 20.21| 20.13|
| A2            | 00 22 40.97  | 14 31 14.0    | 20.99| 20.40| 20.11|
| A3            | 00 22 41.15  | 14 31 12.6    | 21.27| 20.68| 20.21|
| A4            | 00 22 40.89  | 14 31 08.9    | ~22  | ...  | ...  |
| B1            | 00 22 41.44  | 14 31 06.8    | 23.67| 23.02| 22.40|
| Arc total mag | ...          | ...           | 19.95| 19.22| 18.96|
| Arc $\mu$ (mag arcsec⁻²) | ... | ... | 23.26| 22.54| 22.28|

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* The estimated magnitude error is ±0.1 mag. The magnitudes listed have not been corrected for instellar extinction, which is 0.22, 0.16, and 0.12 mag for $g$, $r$, and $i$, respectively (Schlegel et al. 1998).
Si iv λ1402.8, Si ii λ1526.7, C iv + C iv λ1549.5, and Al II λ1670.8, confirming that the arc is indeed a gravitational lens. Figure 3 shows the spectrum of the 8 o’clock arc and, for comparison, the SDSS-measured spectrum of the former “brightest known LBG” (cB58), and an LBG composite spectrum from Shapley et al. (2003). Both cB58 at z = 2.72 and the 8 o’clock arc at z = 2.73 show damped Lyα, along with the typical stellar and interstellar absorption lines found in LBGs, quite similar to those visible in the composite spectrum.

4. THE LENS MODEL

A simple singular isothermal ellipsoid (SIE) mass model proves a robust fit to this lens system. We measured the pixel positions of the three lensed images and the counterimage with SExtractor off the co-added SPIcam g-band image, as the counterimage (A4) is not resolved in either the r- or i-band co-added images. We then fitted these positions to an SIE model using the gravgens/lensmodel software of Keeton (2001). The best-fit SIE model (Fig. 4) yields an Einstein radius of θEin = 3.32′ ± 0.16′, which translates to Rein = 12.1 ± 0.6 h⁻¹ kpc. The χ² for this best-fit model is 2.2 for NDF = 7, where we assumed positional errors of ±0.1″. (We note that the brightest cluster galaxy of a nearby cluster [Koester et al. 2007] is only 260 kpc away from our LRG but in a direction [15° east, 69° south] that would reduce rather than enhance the lensing effect of the LRG’s ellipticity. Attempts to include that cluster in the lens model using a singular isothermal sphere [with σsis = 500, 750, or 1000 km s⁻¹] lead to significantly worse χ² values, and in fact an optimal model prefers zero mass for the cluster [C. Kochanek 2006, private communication].)

Since both the redshift of the LRG and the LBG are known, we were able to determine the angular diameter distance to the source (D_s), to the lens (D_L), and between the source and lens (D_o), to be 1141, 752, and 863 h⁻¹ Mpc, respectively. The total magnification was found to be a factor of 12.3 ± 3.6 (≈4 for each of the three arc images). From this simple SIE model, we can determine the mass interior to Rein using MEin = (c²/4G)(D_o/D_s)θ² Ein. We find that MEin = 1.35 × 10¹² h⁻¹ M☉. We determine the mass-to-light ratio M/L to be 17.5 h M☉/L☉ in the observer-frame g band, which corresponds to 13.8 h M☉/L☉ in the rest-frame B band, which is comparable with what is expected for a massive elliptical at z = 0.38 (see, e.g., Treu et al. 2005).

The velocity dispersion of the mass distribution doing the lensing was calculated to be σein = 390 ± 9.4 km s⁻¹, which is large but not unprecedented for an elliptical galaxy. (E.g., Crampton et al. [2002] modeled a velocity dispersion of 387 ± 5 km s⁻¹ for the strongly lensed elliptical galaxy CFRS 1077, and Bernardi et al. [2006] find ~50 galaxies with stellar velocity dispersions σ ≥ 350 km s⁻¹ from a SDSS sample of 39,320 elliptical galaxies.) Direct estimates of the LRG’s stellar velocity dispersion σ, based on its SDSS spectrum have proved of comparable magnitude but quite noisy and unreliable; in fact, the SDSS database does not report a σ for this LRG due to the spectrum’s low signal-to-noise ratio (~7). Estimates range from σ = 300–400 km s⁻¹, based on special runs of the SDSS pipeline σ code (M. Bernardi 2007, private communication) to 420 ± 70 km s⁻¹ from the SpecBS pipeline (D. Schlegel et al. 2007, in preparation). An estimate from a fundamental plane relation empirically derived from the SDSS database for z = 0.36–0.40 LRGs yields a smaller but likewise noisy value (σ = 260 ± 50 km s⁻¹). Even this smaller value of σ may be reconciled with the higher value of σ, due to the relatively large Einstein radius of this system (θbao ≈ 3′). According to Oguri (2006), systems with an Einstein radius of a few arcseconds should exhibit a significant contribution by the surrounding group-environment dark matter halo to the lens model velocity dispersion beyond that of the stellar component of the central elliptical. We will address this issue in more detail in a future paper once we acquire better spectroscopy of the LRG and deeper imaging to probe the LRG environment.

Finally, we note that the fitted ellipticity and position angle are 0.53 ± 0.06 and 12° ± 2°, respectively. These fitted values agree within 1σ with the observed values for these parameters for the LRG in the SDSS DR4 database (0.46° and 12°, respectively). (We note that using GALFIT [Peng et al. 2002] to fit a model to the lensing galaxy where we masked out the pixels in the lensed images yields an ellipticity of 0.37; however, using the subtracted image for the lens modeling does not alter the fitted parameters.)

5. THE LBG

The spectrum of the 8 o’clock arc (Fig. 3) shows that the lensed source galaxy is an LBG, albeit an uncommonly bright
one: lensed, it is 5.3 mag brighter ($r$ band) than an $L_{\ast} \ LBG$ (Adelberger & Steidel 2000). Even after accounting for a lensing magnification of $\approx12.3$ ($\S$ 4), the 8 o’clock arc is 2.6 mag ($\approx$ a factor of 11) more luminous than $L_{\ast}$, for LBGs. (We note that fits to lens models incorporating reasonable deviations [±20%] from the surface mass density slope of a standard SIE model yield magnifications well within the 1 σ error bars of our quoted value of 12.3+1.3−1.0.)

For comparison, cB58 is a typical $L_{\ast}$ LBG lensed by the large $z = 0.37$ foreground cluster MS 1512+36 (Yee et al. 1996). Furthermore, cB58 is magnified by a factor of $\approx30$ and has an apparent brightness only about one-third that of the 8 o’clock arc (Seitz et al. 1998). We also note that the relative simplicity of the environment surrounding the 8 o’clock arc’s lensing LRG permits a quite robust determination of the lensing amplification, whereas the lensing amplification for cB58 is rather sensitive to the assumed cluster mass distribution model.

We can also estimate the star formation rate of the 8 o’clock arc LBG using a scaling relation given in Pettini et al. (2000). The relation is given for cB58, but for the accuracy necessary here we can take cB58 and the 8 o’clock arc to be at the same redshift: SFR = $3 \times 37 (\frac{M_{\odot}}{M_{\odot, \text{cB58}}})(\frac{\text{f}_{\text{int}}}{\text{f}_{\text{int, cB58}}})(\frac{L_{\ast}}{L_{\ast, \text{cB58}}}) \ M_{\odot} \ yr^{-1}$, where the additional factor of 3 over the Pettini et al. relation (their eq. [6]) takes into account the fact the 8 o’clock arc’s total apparent brightness is $\approx3$ times that of cB58. For the 8 o’clock arc, $\text{f}_{\text{int}} = 12.3$, and we take the other parameters to be the same, leading to SFR = $270 \ M_{\odot} \ yr^{-1}$ ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.1$), or SFR = $160 \ h^{-1} \ M_{\odot} \ yr^{-1}$ ($\Omega_{\text{m}} = 0.3$, $\Omega_{\Lambda} = 0.7$). This should be taken as an estimate only, as the Pettini et al. relation is based on UV continuum luminosity and gives the highest of all the star formation rate estimates for cB58. Follow-up measurements of the 8 o’clock arc will provide more detailed rate estimates. Taking the estimate at face value, the 8 o’clock arc is in the top 20% of star formation rates given for LBGs in Shapley et al. (2001).

6. CONCLUSIONS

We have reported on the discovery of a strongly lensed LBG at a redshift of $z = 2.73$, the arc we have named the “8 o’clock arc.” At an apparent magnitude of $(g, r, i) = (19.95, 22.18, 18.96)$, it displaces cB58 as the brightest known LBG by over a magnitude. The arc consists of three lensed images of the LBG and subtends a length of 162” (9.6”) around the lensing galaxy, an early-type galaxy at $z = 0.38$. The length-to-width ratio of the arc is 6 : 1. A fourth (counter) image is also visible in the co-added ARC 3.5 m g-band image. A simple SIE lens model for the system yields an Einstein radius of $\theta_{\text{E}} = 3.32^\circ \pm 0.16^\circ$ ($R_{\text{E}} = 12.1 \pm 0.6 \ h^{-1} \text{ kpc}$), a total lensing mass within the Einstein radius of $1.35 \times 10^{15} \ h^{-1} M_{\odot}$, and a magnification factor for the LBG of $12.3^{+1.5}_{-1.3}$. Based on this model’s value for the magnification factor, it is clear that the LBG is not only apparently bright but also quite intrinsically luminous (about 11$L_{\ast}$). Furthermore, a simple scaling relation from Pettini et al. (2000) indicates that the LBG may be experiencing an episode of vigorous star formation, perhaps as high as $160 \ h^{-1} M_{\odot} \ yr^{-1}$. The remarkable apparent brightness of this object makes it an ideal object for further follow-up with more detailed observations.

We thank Chris Kochanek for useful discussions on the lensing model and Mariangela Bernardi for computing velocity dispersions from the LRG spectrum. S. S. A. acknowledges support from NSF NVO grant AST-0122449. These results are based on observations obtained with the Apache Point Observatory 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England.

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