DISCOVERY OF A VERY BRIGHT STRONGLY LENSED GALAXY CANDIDATE AT $z \approx 7.6$\textsuperscript{1}

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ABSTRACT

Using Hubble Space Telescope (HST) and Spitzer IRAC imaging, we report the discovery of a very bright strongly lensed Lyman break galaxy (LBG) candidate at $z \approx 7.6$ in the field of the massive galaxy cluster Abell 1689 ($z = 0.18$). The galaxy candidate, which we refer to as A1689-zD1, shows a strong $z_{585} - J_{110}$ break of at least 2.2 mag and is completely undetected ($<1\sigma$) in HST Advanced Camera for Surveys (ACS) $g_{475}$, $r_{625}$, $i_{775}$, and $z_{585}$ data. These properties, combined with the very blue $J_{110} - H_{160}$ and $H_{160} - [4.5\mu m]$ colors, are exactly the properties of an $z \approx 7.6$ LBG, and can only be reasonably fit by a star-forming galaxy at $z = 7.6 \pm 0.4$ ($\chi^2 = 1.1$). Attempts to reproduce these properties with a model galaxy at $z < 4$ yield particularly poor fits ($\chi^2 > 25$). A1689-zD1 has an observed (lensed) magnitude of 24.7 AB ($8\sigma$) in the NICMOS $H_{160}$ band and is $\sim 1.3$ mag brighter than the brightest known $z_{585}$-dropout galaxy. When corrected for the cluster magnification of $\sim 9.3$ at $z \approx 7.6$, the candidate has an intrinsic magnitude of $H_{160} = 27.1$ AB, or about an $L_\star$ galaxy at $z \approx 7.6$. The source-plane deprojection shows that the star formation is occurring in compact knots of size $\lesssim 300$ pc. The best-fit stellar population synthesis models yield a median redshift of 7.6, stellar masses ($1.6 - 3.9 \times 10^9 M_\odot$), stellar ages 45–320 Myr, star formation rates $\lesssim 7.6 \times 10^{-5}$ yr$^{-1}$, and low reddenning with $A_V \lesssim 0.3$. These properties are generally similar to those of LBGs found at $z \approx 5 - 6$. The inferred stellar ages suggest a formation redshift of $z \approx 8 - 10$ ($t \lesssim 0.63$ Gyr). A1689-zD1 is the brightest observed, highly reliable $z > 7.0$ galaxy candidate found to date.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation — galaxies: high-redshift

1. INTRODUCTION

One of the most important frontiers of observational cosmology is the characterization of the earliest galaxies in the universe. The Hubble Space Telescope (HST) has been at the forefront of such high-redshift searches, which have recently provided significant insights to the mass assembly and buildup of the earliest galaxies ($z \geq 6, t < 0.95$ Gyr) and the contribution of star formation to cosmic reionization (Lehnert & Bremer 2003; Bunker et al. 2004; Yan & Windhorst 2004; Bouwens et al. 2006). Recent WMAP optical depth measurements indicate that reionization began between $z \approx 8 - 15$ (Spergel et al. 2007; Page et al. 2007), while measurements of Gunn-Peterson absorption troughs in SDSS quasars suggest reionization was complete by $z \approx 6$ (Fan et al. 2006). High-redshift galaxy searches are now probing the era of cosmic reionization (Hu et al. 2002; Kneib et al. 2004; Bouwens et al. 2004b, 2008; Egami et al. 2005; Mobasher et al. 2005; Stern et al. 2005; Richard et al. 2006; Iye et al. 2006; Bouwens & Illingworth 2006; Stark et al. 2007; but also see Chary et al. 2007 regarding the Mobasher et al. 2005 object) and are beginning to characterize the luminosity density and star formation history of this important epoch (Yan & Windhorst 2004; Bunker et al. 2004; Giavalisco et al. 2004; Yan et al. 2005; Stanway et al. 2005; Bouwens & Illingworth 2006; Bouwens et al. 2006). Early indications suggest that low-luminosity star-forming galaxies at high redshift ($z > 6$) likely play a significant role in reionizing the universe (Lehnert & Bremer 2003; Yan & Windhorst 2004; Bouwens et al. 2006), but this needs to be verified by studying fainter galaxies at higher redshifts; galaxies at $z \geq 7$ represent the current high-redshift frontier.

Strong gravitational lenses produced by massive galaxy clusters provide an opportunity to observe the high-redshift universe in unprecedented detail. The large magnifications provided by nature’s “cosmic telescopes” increase both the flux and size of background sources. These gains make it possible to detect faint high-redshift galaxies (Kneib et al. 1996, 2004; Pelló et al. 1999; Ellis et al. 2001; Hu et al. 2002; Egami et al. 2005; Frye et al. 2007) without requiring a huge investment of observing time, such as that dedicated to the Hubble Ultra Deep Field (Beckwith et al. 2006). The key to making the subsequent analyses viable is having detailed cluster magnification maps that constrain the “optics” of the “cosmic telescope.” Our team has been among the first to overcome this difficulty by using multiband HST/ACS data to perform detailed studies of massive rich galaxy clusters, including Abell 1689 (Broadhurst et al. 2005; Zekser et al. 2006; 2008).
D. A. Coe et al. (2008, in preparation) and CL0024+17 (Jee et al. 2007), to a precision useful for studying the properties of the background galaxy population.

In this paper we present the discovery of a bright strongly lensed Lyman break galaxy (LBG) candidate at $z = 7.6$ in the field of the massive cluster Abell 1689. We adopt a cosmology with $\Omega_m = 0.3$, $\Omega_k = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. This provides an angular scale of 5.0 kpc arcsec$^{-1}$ at $z = 7.6$. All magnitudes are given in the AB photometric system (Oke 1974).

2. OBSERVATIONS AND PHOTOMETRY

2.1. HST ACS and NICMOS Data

Abell 1689 is a well-studied and massive galaxy cluster at $z = 0.183$. With an unequaled Einstein radius of $\sim 50''$, it is the strongest gravitational lens known (Broadhurst et al. 2005). We observed the central $3.4'' \times 3.4''$ of Abell 1689 with a single pointing of the ACS Wide Field Camera (WFC) in 2002 June (see Fig. 1). The observations consisted of 20 orbits divided among four broadband filters: F475W ($g_{475}$; 9500 s), F625W ($r_{625}$; 9500 s), F775W ($i_{775}$; 11,800 s), and F850LP ($z_{850}$; 16,600 s). In 2005 May, we followed up our ACS observations with 18 orbits of Near Infrared Camera and Multi-Object Spectrometer (NICMOS)/NIC3 F110W ($J_{110}$) imaging to search for $z_{850}$-dropout candidates. The observations cover the central $2.5'' \times 2.5''$ high-magnification region of the cluster with a nine-pointing $3 \times 3$ mosaic (5376 s per NIC3 field).

The bright LBG candidate, which we refer to as A1689-zD1, was discovered by comparing the ACS/WFC $z_{850}$ and NICMOS/NIC3 $J_{110}$ data. The galaxy has an observed magnitude of 25.3 in the NICMOS $J_{110}$ band and a strong $z_{850} - J_{110}$ break of $\sim 2$ mag (see Table 1). With a magnification of $\mu \approx 9.3$, A1689-zD1 is strongly lensed by the foreground cluster and is $\sim 1.3$ mag brighter (as observed) than the brightest known $z_{850}$-dropout ($z \sim 7$) galaxy (Bouwens et al. 2008; Bouwens & Illingworth 2006). A1689-zD1 is completely undetected ($<1 \sigma$) in the ACS $g_{475}$, $r_{625}$, $i_{775}$, and $z_{850}$ data, as well as in the 20 orbit ACS rms-weighted “detection” image constructed by co-adding all of the ACS images (see Fig. 2). The $1 \sigma$ detection limits for this galaxy are 31.8, 31.2, 31.2, and 31.2 AB mag in the $g_{475}$, $r_{625}$, $i_{775}$, and $z_{850}$ bands, respectively.
are 28.3, 27.8, 27.8, and 27.5 in the $g_{775}$, $r_{625}$, $i_{775}$, and $z_{850}$ bands, respectively.

To verify that A1689-zD1 was not a low-redshift reddened interloper, we acquired a single-orbit NIC3 F160W ($H_{160}$) image of the source in 2007 June. Combining these data with the earlier NICMOS $J_{110}$ data, we measure $J_{110} - H_{160}$ colors of 0.6 ± 0.2. This is exactly what one would expect for an LBG at $z \sim 7.4-7.7$ (see, e.g., Fig. 1 in the Supplementary Information of Bouwens & Illingworth 2006), but much bluer than a reddened object at lower redshift. Note that the strong $z_{850} - J_{110}$ break and the blue color redward of the break are precisely the two criteria used to define high-redshift LBGs. Together this information provides compelling evidence that our source is a star-forming galaxy at $z \sim 7.4-7.7$.

A1689-zD1 is not detected in the individual $J_{110}$ and $H_{160}$ dither exposures ($\sim$640 s, 4 dithers per orbit), but there also does not appear to be any artifacts (e.g., cosmic rays) at the object position. Given the similar morphology in both the $J_{110}$ and $H_{160}$ images, which were taken about 2 years apart, and also that A1689-zD1 was located at different detector positions in the $J_{110}$ and $H_{160}$ images, we are confident that A1689-zD1 is not a spurious detection.

We present in Figure 3 the observed and intrinsic (lens-corrected) $H_{160}$ magnitudes of A1689-zD1 relative to other $z \sim 7-8$ galaxy candidates (Bouwens et al. 2008). While the observed (uncorrected) brightness of A1689-zD1 is $\sim$1.3 mag brighter than the brightest $z \sim 7-8$ candidate, its intrinsic (lens-corrected) magnitude is very similar to that of other $z_{850}$-dropout galaxies.

### 2.2. Spitzer IRAC Data

Further evidence supporting the interpretation of A1689-zD1 as a $z \sim 7.6$ LBG comes from archival Spitzer IRAC data (GO 20439, PI: Egami). In 2006, ultradeep IRAC imaging was obtained for Abell 1689 in the 3.6, 4.5, 5.8, and 8.0 μm bands (11.1 hr per band). Our LBG candidate is detected as a point source in the IRAC 3.6 and 4.5 μm bands.

The large size of the IRAC point-spread function (PSF; FWHM $\sim$2.2') poses a difficulty in that neighboring objects may significantly contaminate the photometry. In our case, we find that A1689-zD1 is blended with a nearby foreground object, which is separated by $\sim$1.5″. As seen in Figure 2, the foreground galaxy is rather blue, and we estimate its photometric redshift (Benítez 2000) is $\sim$2.2. To correct for the contamination of nearby objects, we convolved the NICMOS $H_{160}$ detections of A1689-zD1 and its neighbors with the IRAC PSF for a given band. The $H_{160}$-PSF-convolved objects were then simultaneously fitted to the IRAC data, allowing the relative flux scalings as free parameters. The fitted neighbors, which contributed $\sim$32% to the original flux, were then subtracted from the IRAC data, leaving the LBG source. We estimate that the neighbor subtraction induces an additional $\sim$0.2 mag of uncertainty to the IRAC photometry.

To minimize background noise and to further limit flux contamination from nearby objects, we performed the Spitzer IRAC photometry using a 2.5″ diameter aperture. Assuming a stellar profile to correct the fluxes for light falling outside the aperture, we applied aperture corrections of 0.56 and 0.60 mag to the [3.6 μm] and [4.5 μm] bands, respectively. We measure observed magnitudes of 24.2 and 23.9 in the [3.6 μm] and [4.5 μm] bands, respectively. The [5.8 μm] and [8.0 μm] upper limits are 23.9 (1 σ) and 23.4 (2 σ), respectively. The broadband photometry of A1689-zD1 is summarized in Table 1 and the HST/ACS, HST/NICMOS, and Spitzer IRAC cutout images are shown in Figure 2.

### 3. SOURCE MAGNIFICATION

It is valuable to calculate the intrinsic properties of A1689-zD1 by using strong-lensing models available for Abell 1689 (e.g., Broadhurst et al. 2005; Coe et al. 2008, in preparation). For an improved version of the Broadhurst et al. (2005) strong-lensing model and a redshift of $z \sim 7.6$ (see §4), we estimate a magnification $\mu$ of $\sim$9.3, which appears to be roughly consistent with other models in the literature (Halíkola et al. 2006; Limousin et al. 2007; Coe et al. 2008, in preparation). The improved Broadhurst lensing model is based on 42 sets of multiple images (12 more than Broadhurst et al. 2005), with several new counterimages close to the cluster center. Based on the mean slope of the radial mass profile, which is the most influential model parameter, we estimate that the 1 σ error on the magnification is at least 15%. The error is derived from the allowed range in radial slope parameters that are consistent with the data. However, comparison with other Abell 1689 models, e.g., Coe et al. 2008 (in preparation; $\mu = 7.3$ for A1689-zD1), suggests that a more realistic value...

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**Table 1**

**Photometry Summary**

| Measurement       | $g_{775}$ | $r_{625}$ | $i_{775}$ | $z_{850}$ | $J_{110}$ | $H_{160}$ | [3.6 μm] | [4.5 μm] | [5.8 μm] | [8.0 μm] |
|-------------------|-----------|-----------|-----------|-----------|-----------|-----------|----------|----------|----------|----------|
| A1689-zD1 observed magnitude | >28.3     | >27.8     | >27.8     | >27.5     | 25.3 (0.1) | 24.7 (0.1) | 24.2 (0.3) | 23.9 (0.3) | >23.9    | >23.4    |
| A1689-zD1 intrinsic magnitude | >30.7     | >30.2     | >30.2     | >29.9     | 27.7 (0.1) | 27.1 (0.1) | 26.6 (0.3) | 26.3 (0.3) | >26.3    | >25.8    |
| Companion magnitude | 27.4 (0.1)| 26.4 (0.1)| 26.1 (0.1)| 25.9 (0.1)| 25.0 (0.1)| 24.3 (0.1)| 25.0 (0.3) | 24.3 (0.3) | >23.9    | >23.4    |

**Notes:** Errors (1 σ) are given in parentheses. Intrinsic values were calculated assuming a cluster magnification of $\mu = 9.3$ (see §3). The [5.8 μm] and [8.0 μm] magnitudes are 1 and 2 σ upper limits, respectively. Because Abell 1689 lies in the plane of the ecliptic, the zodiacal light background is high and increases in the [5.8 μm] and [8.0 μm] bands, limiting our ability to detect the object in these two bands.

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**Figure 2**

Cutout images (P.A. = 115°) from the HST/ACS ($g_{775}$, $r_{625}$, $i_{775}$, and "Det"—"detection"), HST NICMOS ($J_{110}$ and $H_{160}$), and Spitzer IRAC (3.6, 4.5, 5.8, and 8.0 μm) data centered on A1689-zD1. The source is undetected (<1 σ) in the ACS data, including the 20 orbit combined "detection" image, and also not formally detected at 5.8 and 8.0 μm. The fluctuations that are present in the 5.8 and 8.0 μm images near the position of A1689-zD1 are consistent with being noise. The cutout images are 5″ × 5″, corresponding to 25 kpc on a side at $z = 7.6$. 
of the systematic uncertainty in our magnification value is \( \approx 25\% \). When corrected for the cluster magnification of 9.3, the intrinsic magnitudes of A1689-zD1 are 27.7, 27.1, 26.6, and 26.3 in the \( J_{110}, H_{160}, [3.6 \, \mu m] \), and \([4.5 \, \mu m]\) bands, respectively.

### 4. STELLAR POPULATION MODELS

To constrain the stellar populations of A1689-zD1, we fit the stellar population models of Bruzual & Charlot (2003) to the multiband photometry. We used a Salpeter (1955) initial mass function (IMF) with mass cutoffs of 0.1 and 100 \( M_\odot \) and explored models with both solar (\( Z = 0.02 \)) and subsolar (\( Z = 0.0004 = Z_{\odot}/50 \)) metallicities. The effect of dust reddening is included in the models using the Calzetti et al. (2000) obscuration law. We correct for Lyman series line-blanketing and photoelectric absorption following the prescription of Madau (1995). In the stellar population model fits, we constrain the stellar age to be less than the age of the universe at the fit redshift (e.g., 0.7 Gyr at \( z \approx 7.5 \)). We considered several star formation histories (SFH) including a simple (single-burst) stellar population (SSP), an exponentially declining star formation rate (SFR; \( \tau \) models) with \( e \)-folding times between 10 and 100 Myr, and constant SFR (CSF) models with SFRs up to 30 \( M_\odot \) yr\(^{-1}\).

The best-fit stellar population models are shown in Figure 4 and the parameters are given in Table 2. For both solar and subsolar metallicities, we find acceptable fits for the models. The best-fit redshifts are in the range from 7.4 < \( z < 7.7 \) with an 1 \( \sigma \) error of 0.3–0.4 and a median value of 7.6. A crosscheck of the redshift was also performed using the Bayesian photometric redshift (BPZ) code of Benítez (2000) and showed that A1689-zD1 is certainz > 7, with the probably concentrated at 7 < \( z < 8 \) and a spectral type between a Kinney et al. (1996) SB2 and SB3.

To examine the possibility that this source could be a highly reddened galaxy at low redshift, we refit the stellar population models by restricting the redshift to be \( z \leq 4 \). The best-fit \( \tau_{90} \) low-redshift solution is at a redshift of \( z = 1.6 \) with \( A_V = 1.0 \), but the fit is particularly poor (\( \chi^2 = 25 \)). As seen in Figure 5, the low-redshift models do not agree with the upper limits on the \( i_{775} \) and \( z_{850} \) fluxes and do not reproduce the strong \( z_{850} - J_{110} \) break, even with \( \geq 1.0 \) mag of extinction. In Figure 6 we plot the \( \chi^2 \) values of the best-fitting \( \tau_{90} \) solar-metallicity models as a function of redshift and reddening. We find that the low-redshift solutions (1.5 \( \leq z \leq 2.0 \)) all provide a much poorer fit to the data than the high-redshift (\( z > 6.5 \)) solutions. To further make the point, we looked at a single observational parameter, the \( z_{850} - J_{110} \) color. In Figure 7 we plot the \( z_{850} - J_{110} \) color as a function of redshift for a range of reddened (0 ≤ \( A_V \) ≤ 5) 100 Myr SSP solar metallicity models. The low-redshift models, even with extremely large values of the reddening, are unable to reproduce the strong \( z_{850} - J_{110} \) break of 2.2 mag observed for A1689-zD1.

For our preferred high-redshift solutions, we find stellar masses of (1.6–3.6) \( \times 10^8 \) \( M_\odot \) for the solar metallicity models and slightly higher masses of (2.1–3.9) \( \times 10^8 \) \( M_\odot \) for the subsolar metallicity models. In a similar fashion, the subsolar metallicity models generally produce slightly older ages (72–320 Myr) than the solar metallicity models (45–320 Myr). These stellar mass and age estimates are in the range of those previously estimated by Labbé et al. (2006) for a HUDF-selected \( z_{850}\)-dropout (\( z \approx 7 \)) sample. The derived instantaneous SFRs show modest star formation with rates up to 7.6 \( M_\odot \) yr\(^{-1}\). Most of the models require little reddening, with \( A_V \leq 0.3 \), which is in agreement with results for \( z \approx 6 \) LBGs (Yan et al. 2005; Dow-Hygeland et al. 2005; Eyles et al. 2007). While we assumed a Salpeter IMF, fitting models using a Chabrier (2003) IMF yields \( \approx 1.5 \) times lower stellar masses and roughly similar ages.

### 5. SOURCE-PLANE DEPROJECTION

#### 5.1. Morphology

The detailed Abell 1689 cluster deflection map (see §3) allows us to deproject the NICMOS \( J_{110} \) and \( H_{160} \) images of A1689-zD1 to the source plane at \( z \approx 7.6 \). The substantial magnification of the source provides us with a unique opportunity to examine the morphology of a \( z \approx 7.6 \) galaxy at very high resolution. The deprojected images of A1689-zD1 in the \( J_{110} \) and \( H_{160} \) bands are presented in Figure 8. The galaxy shows an extended morphology in both the image and source planes,

![Figure 3](image1.png)

**Figure 3.** Histogram of \( H_{160} \) magnitudes for \( z_{850}\)-dropout (\( z \approx 7–8 \)) galaxies (Bouwens et al. 2008). We denote both the observed (uncorrected) and intrinsic (lens-corrected) magnitudes of A1689-zD1. While the observed brightness of A1689-zD1 is \( \approx 1.3 \) mag brighter than the brightest \( z \approx 7–8 \) candidate, its intrinsic (lens-corrected) magnitude in very similar to that of other \( z_{850}\)-dropout galaxies.

![Figure 4](image2.png)

**Figure 4.** Best-fit stellar population models to the broadband photometry of a \( z \approx 7.6 \) candidate. Solar metallicity models are shown in the top panel, with the subsolar (\( Z = Z_{\odot}/50 \)) models in the bottom panel. The vertical bars denote the 1 \( \sigma \) flux uncertainties and the horizontal bars represent the width of the filter bandpass. The optical ACS nondetections are shown as 1 \( \sigma \) upper limits.

![Figure 5](image3.png)

**Figure 5.** Number of \( z_{850}\)-dropout galaxies as a function of \( H_{160} \) magnitude.
spanning ~0.4″ (2.0 kpc) in the source plane. The remarkable consistency of the morphology in both the $J_{110}$ and $H_{160}$ bands, as well as the >8σ detection in each band, provides strong evidence that the source is real and not a spurious detection.

In both images, A1689-zD1 appears to be comprised of at least two bright, marginally resolved knots connected by a lower luminosity region. The brighter knot is located to the southwest of the secondary knot and is separated from it by $\sim$ 1.0 kpc. Performing fits to the individual knots with GALFIT (Peng et al. 2002), we find that most of the luminosity of A1689-zD1 is emitted from the knots. The brighter (fainter) knot contributes ~4 (~2) of the total luminosity of A1689-zD1. The $J_{110} - H_{160}$ colors of the two knots are reasonably consistent, with values of 0.5 ± 0.2 and 0.8 ± 0.2 for the brighter and fainter knots, respectively. The knots are compact and have half-light radii ≤0.06″ (0.3 kpc) in the source plane.

The concentration of a significant fraction of the total flux in compact star-forming knots is consistent with findings for starburst galaxies over a wide range of redshifts (e.g., Meurer et al. 1995; Law et al. 2007; Smail et al. 2007; Overzier et al. 2007) and as shown quite dramatically in the $z = 4.92$ lensed galaxy pair in CL 1358+62 (Franx et al. 1997). The knots in A1689-zD1 are likely separate star-forming regions within the galaxy, but they could conceivably be interpreted as small star-forming galaxies merging at high redshift.

5.2. Half-Light Radius

We calculated the half-light radius of A1689-zD1 by defining the circular aperture containing half the total Kron flux (Kron 1980). For A1689-zD1, we measure a half-light radius of 0.48″, which translates to ~0.19″ (0.96 kpc) in the source plane at $z = 7.6$. The size translation was derived by comparing the size of the object along its major axis in both the image and source planes. As demonstrated by the PSF ellipses in Figure 8, the magnification of A1689-zD1 is greater along its minor axis than its major axis. This results in a source-to-image-plane size scaling along the galaxy major axis of 2.5, which is slightly smaller than the value one would obtain by assuming that the magnification is the same in all directions ($\sqrt{9.3} = 3.0$).

Although there is a fair amount of dispersion in the size of individual galaxies in high-redshift dropout samples, the mean...
size of galaxies at a given luminosity varies as \((1+z)^{-1.1\pm0.3}\) (Bouwens et al. 2006, see also Ferguson et al. 2004; Bouwens et al. 2004a). A1689-zD1 has a delensed \(H_{160}\) magnitude of 27.1, which corresponds to \(\sim0.3L_{\odot}\) (Steidel et al. 1999). Scaling the mean sizes (\(\sim1.3\) kpc) of \(\sim0.3L_{\odot}\) LBGs at \(z\sim3.8\) (Bouwens et al. 2004a), we would expect a mean half-light radius at \(z\sim7.6\) of 0.7 ± 0.1 kpc. While this is slightly smaller than the half-light radius of A1689-zD1, there is at least a ±20% dispersion in galaxy sizes about the mean size at any given redshift.

5.3. Counterimages

We also used the improved Broadhurst et al. (2005) Abell 1689 strong-lensing model (see §3) to look for potential counterimages of A1689-zD1. We reprojected the source image at \(z\sim7.6\) back to the image plane at \(z\sim0.18\) and found that the model does not predict any counterimages. For a simple isothermal sphere model with an Einstein radius of \(R_E\), one would expect that an object at radius \(r\) would have a counterimage on the opposite side of the cluster at a distance of \(2R_E - r\). However, because of the complexity of the Abell 1689 lensing model, not every background object is guaranteed to produce a counterimage.

6. ULTRAVIOLET (UV) LUMINOSITY FUNCTION (LF)

In theory our discovery of one very bright \(z_{850}\)-dropout in the \(\sim6\) arcmin\(^2\) \(J_{110}\)-band coverage around Abell 1689 should allow us to estimate the volume density of UV-bright galaxies at \(z\sim7\). To explore this further, we generated mock images based on the UV LF, sizes, and colors of LBGs at \(z\sim6\) found by Bouwens et al. (2006, 2007) and magnified them according to the Broadhurst et al. (2005) Abell 1689 deflection map. Unfortunately, from these no-evolution simulations we estimate that we would expect to find only \(\sim0.2\) galaxies over our search area. This suggests that there is very little that we could learn about the UV LF from our \(z_{850}\)-dropout survey around Abell 1689, and that, in fact, we may have been quite fortunate to find the bright candidate A1689-zD1. Even though the cluster magnification increases the typical depth by \(\sim2-3\) mag, the effective source-plane area that is surveyed decreases inversely proportional to the magnification factor. The
very small number of expected candidates follows from the tiny area (≤ 0.5 arcmin²) that the J_{110}-band coverage probes in the source plane at z ≥ 7.

If the effective slope of the LF was large enough (d(log_{10} N)/dz ≥ 0.4; Broadhurst et al. 1995), we would expect the greater depth to make up for the smaller search area. The only place the effective slope would be greater than ~0.4 is for luminosities above L^*, unless we assume that the LF at z ~ 7–8 is steeper than at z ~ 6 (i.e., α ≈ −1.74, as determined by Bouwens et al. 2007, which corresponds to d(log_{10} N)/dz ~ 0.5). Despite the small expected numbers, the present search around Abell 1689 should be more efficient at finding L^* galaxies at z ≥ 7 than a search without the lensing amplification. However, lensing may not provide as great an advantage in searches for galaxies fainter than L^*, given recent measurements of the faint-end slope [where d(log_{10} N)/dz ~ 0.3].

7. PREVIOUS z ≥ 6 LENSED LBG CANDIDATES

High-redshift z ≥ 6 galaxy candidates have been previously identified in searches around strong-lensing clusters (Hu et al. 2002; Kneib et al. 2004; Richard et al. 2006). For example, in the field of the lensing cluster Abell 2218, Kneib et al. (2004) found a very highly magnified (μ ~ 25) and triply imaged LBG candidate near the critical curve. They infer a redshift for the candidate of 6.6 < z < 7.1 from the broadband ACS and NICMOS photometry. However, because of the significant detection that their source shows in the z_{850} band and the modest z_{850} − J_{110} ~ 0.4 break, we are confident that this source is at a redshift lower than A1689-zD1 (where z_{850} − J_{110} > 2.2).

Using VLT ISAAC observations of Abell 1835 and AC114, Richard et al. (2006) identified 13 (first and second category) very bright LBG z ≥ 6 candidates (2.5 σ detections), some of which are ~1 mag brighter than A1689-zD1. We can evaluate the reliability of these sources by looking at the 5 candidates for which much deeper NICMOS H_{160}-band data exist. The deep NIC3 H_{160} observations (~0.7 arcmin²) of Abell 1835 and AC114 reach a 5 σ limiting magnitude of ~26.8 AB, which is ~2 mag deeper than their VLT ISSAC data. Unfortunately, the two first and second category candidates (highest confidence) and the five first, second, and third category candidates (slightly lower confidence) covered by the NICMOS fields show no detection (<2 σ) in the these data. This suggests that their sample of first, second, and third category z ≥ 6 candidates is largely spurious (Bouwens et al. 2008). Given its secure detection significance (8 σ), broadband colors, and strength of its z_{850} − J_{110} break, A1689-zD1 is the brightest LBG candidate that we can confidently place at a redshift z ≥ 7.

8. SUMMARY AND CONCLUSIONS

We report the discovery of a strongly lensed LBG candidate (A1689-zD1) at z ~ 7.6 in the field of the massive galaxy cluster Abell 1689. A1689-zD1 is ~1.3 mag brighter than the current brightest known z_{850}-dropout galaxy (Bouwens & Illingworth 2006; Bouwens et al. 2008). We find a strong z_{850} − J_{110} break of at least 2.2 mag and best-fit photometric redshift of z ~ 7.6. Employing a detailed cluster deflection model, we delensed the source to examine its intrinsic properties. We estimate a magnification of 9.3 at z ~ 7.6 at the position of A1689-zD1. The high detection significance (> 8 σ) of A1689-zD1 and the consistency of the morphology in both the J_{110} and H_{160} bands provide strong evidence that the source is real and not a spurious detection. The source plane deprojection shows that the star formation is occurring in compact knots of size ≤ 300 pc.

Using stellar population models to fit the rest-frame UV and optical fluxes, we derive best-fit values for stellar masses (1.6–3.9) × 10^{10} M_☉, stellar ages 45–320 Myr, and star formation rates <7.6 M_☉ yr^{-1}, properties generally similar to z ~ 5–6 LBGs. A1689-zD1, with a redshift of z ~ 7.6 and a formation redshift z ≥ 8.0 (t ≤ 0.63 Gyr), is the brightest observed, highly reliable z > 7 galaxy candidate found to date.

Given the unique brightness of A1689-zD1, we are actively working to confirm its redshift with near-IR spectroscopy. A spectrum of this bright galaxy would allow for the most detailed study of a z > 7 LBG to date and provide valuable insights into the properties of galaxies in the early universe.

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REFERENCES

Beckwith, S. V. W., et al. 2006, AJ, 132, 1729
Benitez, N. 2000, ApJ, 536, 571
Bouwens, R. J., Illingworth, G. D. 2006, Nature, 443, 189
Bouwens, R. J., Illingworth, G. D., Blakeslee, J. P., Broadhurst, T. J., & Franx, M. 2004a, ApJ, 611, L1
Bouwens, R. J., Illingworth, G. D., Blakeslee, J. P., & Franx, M. 2006, ApJ, 653, 53
Bouwens, R. J., Illingworth, G. D., Franx, M., & Ford, H. 2007, ApJ, 670, 928
Bouwens, R. J., et al. 2004b, ApJ, 616, L79
Broadhurst, T. J., Taylor, A. N., & Peacock, J. A. 1995, ApJ, 433, 49
Bouwens, R. J., et al. 2005, ApJ, 621, 53
Brusa, G., & Charlot, S. 2003, MNRAS, 344, 1000
Bunker, A. J., Stanway, E. R., Ellis, R. S., & McMahon, R. G. 2004, MNRAS, 355, 374
Calzetti, D., Armus, L., Bohlin, R. C., Kinney, A. L., Koornneef, J., & Storchi-Bergmann, T. 2000, ApJ, 533, 682
Chabrier, G. 2003, PASP, 115, 763
Chary, R.-R., Teplitz, H. I., Dickinson, M. E., Koo, D. C., Le Floc’h, E., Maihara, T., & Motohara, K. 2002, ApJ, 588, L5
Eyles, L. P., Bunker, A. J., Ellis, R. S., Lacy, M., Stanway, E. R., Stark, D. P., & Chiu, K. 2006, MNRAS, 374, 910
Fan, X., Carilli, C. L., & Keating, B. 2006, ARA&A, 44, 415
Ferguson, H. C., et al. 2004, ApJ, 600, L107
Forster Schreiber, N. M., et al. 2004, ApJ, 616, 40
Franx, M., Illingworth, G. D., Kelson, D. D., van Dokkum, P. G., & Tran, K.-V. 1997, ApJ, 486, L75
Frye, B. L., et al. 2007, ApJ, 665, 921
Giavalisco, M., et al. 2004, ApJ, 600, L103
Halkola, A., Seitz, S., & Pannella, M. 2006, MNRAS, 372, 1425
Hu, E. M., Cowie, L. L., McMahon, R. G., Capak, P., Iwamuro, F., Kneib, J.-P., Maihara, T., & Motohara, K. 2002, ApJ, 568, L75
Iye, M., et al. 2006, Nature, 443, 186
Jee, M. J., et al. 2007, ApJ, 661, 728
Kinney, A. L., Calzetti, D., Bohlin, R. C., McQuade, K., Storchi-Bergmann, T., & Schmitt, H. R. 1996, ApJ, 467, 38
Kneib, J.-P., Ellis, R. S., Santos, M. R., & Richard, J. 2004, ApJ, 607, 697
Kneib, J.-P., Ellis, R. S., Maini, I., Couch, W. J., & Sharples, R. M. 1996, ApJ, 471, 643
Kron, R. G. 1980, ApJS, 43, 305
Law, D. R., Steidel, C. C., Erb, D. K., Pettini, M., Reddy, N. A., Shapley, A. E., Adelberger, K. L., & Simenc, D. J. 2007, ApJ, 656, 1
Lehnert, M. D., & Bremer, M. 2003, ApJ, 593, 630
Limousin, M., et al. 2007, ApJ, 668, 643
Madau, P. 1995, ApJ, 441, 18
Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. R. 1995, AJ, 110, 2665
Mobasher, B., et al. 2005, ApJ, 635, 832
Oke, J. B. 1974, ApJS, 27, 21
Overzier, R. A., et al. 2007, preprint (arXiv: 0709.3304)
Page, L., et al. 2007, ApJS, 170, 335
Pelló, R., et al. 1999, A&A, 346, 359
Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, AJ, 124, 266
Richard, J., Pelló, R., Schaerer, D., Le Borgne, J.-F., & Kneib, J.-P. 2006, A&A, 456, 861
Salpeter, E. E. 1955, ApJ, 121, 161
Smail, I., et al. 2007, ApJ, 654, L33
Spergel, D. N., et al. 2007, ApJS, 170, 377
Stanway, E. R., McMahon, R. G., & Bunker, A. J. 2005, MNRAS, 359, 1184
Stark, D. P., Ellis, R. S., Richard, J., Kneib, J.-P., Smith, G. P., & Santos, M. R. 2007, ApJ, 663, 10
Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1
Steffen, Y., Yost, S. A., Eckart, M. E., Harrison, F. A., Helfand, D. J., Djorgovski, S. G., Malhotra, S., & Rhoads, J. E. 2005, ApJ, 619, 12
Yan, H., et al. 2005, ApJ, 634, 109
Yan, H., & Windhorst, R. A. 2004, ApJ, 600, L1
Zekser, K. C., et al. 2006, ApJ, 640, 639