A CANDIDATE BRIGHTEST PROTOCLUSTER GALAXY AT $z = 3.03$

JEFF COOKE,1,2,3 ELIZABETH J. BARTON,1,3 JAMES S. BULLOCK,1 KYLE R. STEWART,1 AND ARTHUR M. WOLFE3,4

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ABSTRACT

We report the discovery of a bright ($m_R = 22.2$) Lyman break galaxy at $z = 3.03$ that appears to be a massive system in a late stage of merging. Deep imaging reveals multiple peaks in the flux profile with angular separations of $\sim 0.8''$ ($\sim 20 h^{-1}$ kpc, comoving). In addition, high signal-to-noise ratio rest-frame UV spectroscopy shows evidence for at least three individual components based on stellar photospheric and ISM absorption lines. We find a 1D velocity dispersion of $\sigma \sim 450$ km s$^{-1}$ for the three strongest components. Both the dynamics and high luminosity as well as our analysis of an LCDM numerical simulation suggest that this is a system with halo mass $M \sim 10^{13} M_\odot$. We find in the simulation that all halos of this mass at $z = 3$ contain massive subhalos that agree with the observed component properties. These halos typically evolve into $M \sim 10^{14} - 10^{14.5} M_\odot$ halos in groups and clusters by $z = 0$. This discovery provides a rare opportunity to study the properties and components of a $z \sim 3$ system that is likely to be the progenitor of a brightest cluster galaxy.

Subject headings: galaxies: clusters: general — galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: interactions

Online material: color figures

1. INTRODUCTION

Massive galaxies and galaxy clusters at high redshift provide strong constraints on cosmological models and galaxy formation scenarios. The Lyman break galaxies (LBGs) are a star-forming population of high-redshift galaxies selected by their rest-frame FUV colors (Steidel et al. 1996, 1998). The clustering of LBGs at $z \sim 3$ has been interpreted as evidence that they reside in massive halos ($\sim 10^{12} M_\odot$; Adelberger et al. 2005) and, as a result, are believed to evolve into present-day massive elliptical galaxies. Although $\sim 5000$ color-selected $z > 2$ LBGs have spectroscopic confirmations (e.g., Steidel et al. 2003, 2004; Cooke et al. 2005 [hereafter C05]; J. Cooke et al. 2008, in preparation), only two systems selected by their radio emission have been spectroscopically identified as potential brightest protocluster galaxies to date (Zirm et al. 2005; Miley et al. 2006).

We report the discovery of a bright, $m_R = 22.2$, rest-frame FUV color-selected LBG (PC 1643+4631A-2377; hereafter LG2377) at $z = 3.03$ that appears to be in a late stage of merging. Ground-based imaging and spectroscopy finds no evidence for AGN activity or gravitational lensing, making this the most luminous $z \geq 3$ LBG discovered to date. The deep images and high signal-to-noise ratio (S/N) spectroscopy show evidence for multiple massive components indicative of a merging system. We show that the component velocity dispersion and integrated FUV luminosity suggest that LG2377 resides in a very massive halo ($\sim 10^{13} M_\odot$) and is likely to evolve into a present-day massive brightest cluster galaxy (§ 3.2). As a result, LG2377 provides a rare opportunity to study the dynamics and properties of a massive LBG halo in an early and active stage of formation.

All bright ($R \leq 23$) $z \gtrsim 3$ LBGs discovered to date are magnified by gravitational lensing (but see Shapley et al. 2003, § 6.2). Because all of these show Ly$\alpha$ in absorption, they are representative of the spectral properties observed in $\sim 25$–50% of the LBG population (Shapley et al. 2003). As shown below, LG2377 displays strong Ly$\alpha$ in emission in two of its components and, because of its brightness, is the only known system of its kind. The luminosity of LG2377 enables high-S/N study of its individual components and may thereby provide a means to help constrain the observed range of LBG spectral properties. In § 2 we briefly describe the imaging and spectroscopic observations. We highlight our initial analysis of the data in § 3 and present a discussion in § 4. We use AB (Fukugita et al. 1996) magnitudes, assume an $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $h = 0.7$ cosmology, and use comoving units throughout, unless otherwise noted.

2. OBSERVATIONS

2.1. Imaging

The deep images of the QSO PC 1643+4631A field were obtained on 2001 April 18 using the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) mounted on the Keck I telescope as part of a multifield survey for LBGs associated with damped Ly$\alpha$ systems at $z \sim 3$ (C05). Specifically, the field containing LG2377 was imaged in the $u'BRV_{\text{KAO}}I$ filters with seeing of $0.7'' - 0.9''$ FWHM and a depth of $u' = 28.8$ and $BVR'I \geq 28.1$ (1 $\sigma$). We selected LG2377 as an $R = 22.2$, $z \sim 3$ LBG candidate at R.A. 16h44m48.3s, decl. +46d27m08.2s (J2000.0) toward one edge of the imaged field with isophotal magnitudes $u' = 26.5 \pm 0.46$, $B = 24.3 \pm 0.10$, $V = 22.6 \pm 0.03$, $R = 22.2 \pm 0.06$, and $I = 22.3 \pm 0.07$.

LBGs at $z \sim 3$ typically appear as near-point sources with half-light radii of $\lesssim 0.3''$ (e.g., Giavalisco et al. 1996; Gardner et al. 2000; Ferguson et al. 2004) that correspond to $\lesssim 2 h^{-1}$ kpc (physical). As illustrated in the contour plot shown in

1 The Center for Cosmology and the Department of Physics and Astronomy, University of California, Irvine, CA 92697.
2 Gary McCue Postdoctoral Fellow.
3 Visiting Astronomer, W. M. Keck Telescope. The Keck Observatory is a joint facility of the University of California, the California Institute of Technology, and NASA and was made possible by the generous financial support of the W. M. Keck Foundation.
4 Center for Astrophysics and Space Sciences and the Department of Physics, University of California, San Diego, La Jolla, CA 92093-0424.
5 The $R_s$ is the H. Spinrad high-throughout night-sky $R$ filter made kindly available at the W. M. Keck Observatory. See Stern et al. (1999) for transformation equations. All $R_s$ magnitudes presented here have been transformed into the Johnson $R$ bandpass.
Figure 1. LBG-2377 spans ~2" × 3" in the ground-based images. The morphology of LBG-2377 may be either a single extended system exhibiting multiple vigorous star-forming regions or a system of several separate near-point sources. The flux ratio of the peaks of the three strongest identified components is approximately 10 : 5 : 1 with separations of ~0.6"–1.0" (~20–30 h⁻¹ kpc, comoving). Inspection of the deep images shows that there are no significant lensing-source candidates within ~10". A potential candidate 20" from LBG-2377 (R.A. 16°44′46.5″, decl. +46°27′04.1″) does have an effective photometric redshift for lensing (z_eff = 0.41 ± 0.2), but would need a halo mass of M ≳ 7 × 10¹⁴ M☉ to provide a significant (≥2–3 ×) magnification boost (Q. Minor 2007, private communication). Moreover, such a geometry would result in a large distortion of the LBG-2377 image. We see no evidence for this in the deep ground-based images.

2.2. Spectroscopy

LBG-2377 was confirmed to be a z = 3.03 galaxy from discovery low-resolution multioject spectroscopy on 2004 February 18 (C05). The data were taken using the 300 line mm⁻¹ grism on LRIS with a spectral resolution of ~10 Å FWHM. We acquired follow-up higher resolution, higher S/N long-slit spectroscopic observations with LRIS on 2007 May 21 using the 600 line mm⁻¹ grism blazed at 4000 Å and larger format CCDs on the blue arm and the 1200 line mm⁻¹ grating blazed at 7500 Å on the red arm. The observations were acquired prior to the release of the atmospheric dispersion corrector on LRIS and consisted of five 1800 s (and one 600 s) exposures that followed the parallactic angle. Therefore, each exposure sampled a slightly different region of LBG-2377. The five 1800 s exposures were combined to form a composite spectrum (Fig. 2) and resulted in a S/N of 10–15 and a resolution of ~2–3 Å.

The spectrum of LBG-2377 is dominated by O and B star continua, displays Lyα in emission, and exhibits a relatively flat continuum from rest-frame 1300–1700 Å. These features are consistent with the general properties of the z ~ 3 LBG population exhibiting Lyα in emission (Shapley et al. 2003; C05). Although the Lyα feature appears as a single emission line in the low-resolution discovery spectrum, the composite higher resolution high-S/N spectroscopy reveals two strong peaks (with potentially two weak peaks more evident in the individual spectra). The rest-frame FUV shows a complex series of interstellar atomic lines exhibiting gas absorption over velocities ≳2000 km s⁻¹ and evidence for at least three, and up to five, components. Over 20 FUV ISM absorption lines were used to identify and study individual components. Details of these observations and an in-depth analysis of these and future IR data will appear in a forthcoming paper.

3. ANALYSIS

3.1. Components

The Lyα emission and ISM absorption lines of z ~ 3 LBGs show observed velocity offsets of ~+500 and ~−150 km s⁻¹, respectively, from their systemic redshifts (e.g., Pettini et al. 2002; Steidel et al. 2003; C05). The accepted interpretation is that these offsets are caused by the presence of an expanding galactic-scale shell of gas and dust driven by supernovae and stellar winds. Lyα photons are largely absorbed in the approaching shell but are resonantly scattered off the receding portion and survive. In this scenario, the two prominent Lyα peaks observed in the spectrum of LBG-2377 would trace two distinct expanding galactic-scale shells with a velocity difference of ~550 km s⁻¹.

To estimate the systemic redshift of the individual components of LBG-2377, we performed a best fit to ≥5 stellar photospheric lines⁶ and made the assumption that the corresponding ISM and high-resolution, high-S/N spectroscopy reveals two strong peaks (with potentially two weak peaks more evident in the individual spectra). The rest-frame FUV shows a complex series of interstellar atomic lines exhibiting gas absorption over velocities ≳2000 km s⁻¹ and evidence for at least three, and up to five, components. Over 20 FUV ISM absorption lines were used to identify and study individual components. Details of these observations and an in-depth analysis of these and future IR data will appear in a forthcoming paper.

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⁶ For consistency with future analyses and because our observations are of similar quality, we use the stellar photospheric values listed in Table 1 of Pettini et al. (2000). The lines used in this estimate were Si iv λλ1294.54, 1296.73, 1417.24; C iv λλ1304.8, 1296.33, 1296.33, 1427.85; C ii λλ1323.93, N ii λ1324.32; O iv λ1343.35; and S v λ1501.76.
Lyα lines have velocity offsets from their systemic redshifts typical of the z ∼ 3 LBG spectroscopic sample. Details of the tentative components are listed in Table 1. We find a 1D velocity dispersion of σ ∼ 450 km s⁻¹ for the three components exhibiting the strongest Lyα emission and/ or ISM absorption features (components A, C, and D in Table 1). Although the photospheric lines are weak and therefore have low S/N, we find the resulting 1D velocity dispersion corresponds to a halo maximum circular velocity of km s⁻¹ (Klypin et al. 1999). Note that this substructure mass is typical of that expected for LBG hosts at z ∼ 3 (⟨M_{LBG}⟩ ∼ 10^{11.5} M_⊙; Adelberger et al. 2005). If we look at simulated halos that are significantly smaller than our estimate, we find that only two out of 16 objects with V_{max} > 450 km s⁻¹ in the simulation have no M > 10^{11.2} M_⊙ subhalos. We conclude that it would be very unlikely for an object like LBG-2377 to exist without multiple massive components.

3.2. Theoretical Expectations

The high luminosity, velocity dispersion, and complex structure of LBG-2377 suggest that this system may be a brightest cluster galaxy in formation. Here we investigate this possibility in the context of ΛCDM. We estimate the dark matter halo mass of LBG-2377 using both its measured kinematics and luminosity. Encouragingly, both estimates suggest a group-scale mass ∼ 10¹³ M_⊙. If we assume an NFW halo, our measured σ ∼ 450 km s⁻¹ 1D velocity dispersion corresponds to a halo maximum circular velocity of V_{max} ∼ 1.5 σ ∼ 700 km s⁻¹ (Klypin et al. 1999). At z ∼ 3 this implies M_{min} ∼ 3 × 10^{12} M_⊙ (e.g., Bullock et al. 2001).

Alternatively, if we assume a simple monotonic relationship between galaxy luminosity and dark matter halo V_{max} (e.g., Berrier et al. 2006) and use the z ∼ 3 LBG luminosity function (Steidel et al. 1999; Sawicki & Thompson 2006), the number density of objects similar to LBG-2377 (M_{LBG} ∼ 3.3, uncorrected) is ∼ 3 × 10⁻⁷ Mpc⁻³. This number density corresponds to halos with V_{max} ∼ 750 km s⁻¹ at z = 3 (Berrier et al. 2006; Lemson et al. 2006). While the relationship between halo mass and UV luminosity at z ∼ 3 is unlikely to be precisely monotonic (although Conroy et al. 2006 were able to reproduce LBG clustering statistics in this manner), it is reassuring that this simple approximation also suggests that LBG-2377 sits within a massive V_{max} ∼ 700 km s⁻¹ halo.

Halos that are this massive at z = 3 almost certainly contain substructure. We illustrate this explicitly by examining the high-resolution 80 h⁻³ Mpc⁻³ ΛCDM N-body simulation described in Stewart et al. (2008). There are three halos in this box with V_{max} > 600 km s⁻¹ at z = 3 (specifically, V_{max} = 620, 645, and 740 km s⁻¹). These objects have between five and eight tentative components are listed in Table 1. We find a 1D velocity dispersion of km s for the three components exhibiting a halo maximum circular velocity of km s⁻¹ (Klypin et al. 1999). Note that this substructure mass is typical of that expected for LBG hosts at z ∼ 3 (⟨M_{LBG}⟩ ∼ 10^{11.5} M_⊙; Adelberger et al. 2005). If we look at simulated halos that are significantly smaller than our estimate, we find that only two out of 16 objects with V_{max} > 450 km s⁻¹ in the simulation have no M > 10^{11.2} M_⊙ subhalos. We conclude that it would be very unlikely for an object like LBG-2377 to exist without multiple massive components.

By following the merger trees of our three V_{max} ≥ 600 km s⁻¹ halos, we find that they evolve from M = 10^{11.3}–10^{13.7} M_⊙ halos at z = 3 to cluster-mass systems with M = 10^{14.4}–10^{15.5} M_⊙ at z = 0. These are among the 12 most massive halos in the box at z = 0 and contain ∼ 10–50 subhalos larger than 10^{11.2} M_⊙. This analysis suggests that LBG-2377 will evolve into the dominant galaxy within a large group or cluster by z = 0.

3.3. Lyα Emission

The double peak nature of the Lyα feature in LBG-2377 was only detected with higher resolution and S/N. However, multiple Lyα peaks are not unique to LBG-2377. In the LBG spectroscopic survey of C05, we find that ∼ 3% of the z ∼ 3 LBGs display both double Lyα emission peaks in their low-resolution spectra and resolved double flux peaks in their deep image profiles. We can only assume that this fraction increases with higher resolution or S/N. One example of this effect may be found in the sample of Shapley et al. (2006). Three of the nine deep high-S/N LBG spectra with Lyα in emission have double peaks. Two of the remaining six have redshifts within Δz = 0.01 and a separation of ∼ 2″. This is consistent with a double-peak system at a larger angular separation. Interestingly, upon inspection of the average internal velocity differences between the Lyα emission and ISM absorption
features ($\Delta z = z_{\text{em}} - z_{\text{abs}}$), the single-peak systems are reported to have $\Delta z \sim 550$ km s$^{-1}$, whereas the double-peak systems have $\Delta z \sim 1200$ km s$^{-1}$. One plausible interpretation of this discrepancy is the result of the velocity separations, and consequent spectral blending, of two individual massive interacting systems. Confirming separate components in LBGs showing only Ly$\alpha$ emission is more difficult. However, there are indications of separate components in the intermediate-resolution, high-$S/N$ spectrum of the lensed LBG MS 1512-cB58 (Pettini et al. 2002). The prediction implied is that with higher $S/N$ and/or resolution, systems would have separations of $\sim 5$ Mpc. An event of three or more unbound systems with $M \sim 10^{12} M_\odot$, $\sim 10^4$ h$^{-1}$ Mpc$^{-3}$ has a vanishingly low probability, even if the systems were given reasonable peculiar velocities. The most likely scenario is interpretation 4 because it is consistent with the extended nature and multiple peaks seen in the images, the superposed spectra of multiple identified components, the observed velocity dispersion, and the expectations from the simulation. In addition, this interpretation provides a natural driver for the observed star formation and bright integrated luminosity. Furthermore, the double Ly$\alpha$ emission peak of LBG-2377 is also seen in other LBGs which exhibit two distinct components in deep images and Ly$\alpha$ emission-line velocity differences consistent with close galaxy pairs.

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2, LBG-2377 would be in less conflict with simulations yet the above assumptions for stellar and ISM lines must hold. In this case, LBG-2377 is a single system undergoing an unusually strong star formation episode that displays complex ISM absorption lines and Ly$\alpha$ emission lines with a velocity difference of $\sim 550$ km s$^{-1}$. In addition, this star formation must be occurring in multiple regions with an angular separation of $\geq 25$ kpc. If the velocity offsets are interpreted as redshifts, as in interpretation 3, the systems would have separations of $\geq 5$ Mpc.