OVERTURNING THE CASE FOR GRAVITATIONAL POWERING IN THE PROTOTYPICAL COOLING LY\(\alpha\) NEBULA

MOIRE K. M. PRESCOTT\(^1\), IVELINA MOMCHEVA\(^2\), GABRIEL B. BRAMMER\(^3\), JOHAN P. U. FYNBO\(^1\), AND PALLE MØLLER\(^4\)

\(^1\) Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark; mkmprescott@dark-cosmology.dk
\(^2\) Department of Astronomy, Yale University, New Haven, CT 06511, USA
\(^3\) Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
\(^4\) European Southern Observatory, Karl-Schwarzschildstrasse 2, D-85748 Garching bei München, Germany

Received 2014 September 11; accepted 2015 January 20; published 2015 March 18

ABSTRACT

The Nilsson et al. Ly\(\alpha\) nebula has often been cited as the most plausible example of an Ly\(\alpha\) nebula powered by gravitational cooling. In this paper, we bring together new data from the Hubble Space Telescope and the Herschel Space Observatory as well as comparisons to recent theoretical simulations in order to revisit the questions of the local environment and most likely power source for the Ly\(\alpha\) nebula. In contrast to previous results, we find that this Ly\(\alpha\) nebula is associated with six nearby galaxies and an obscured AGN that is offset by \(\sim 4^\prime\) \(\approx 30\) kpc from the Ly\(\alpha\) peak. The local region is overdense relative to the field, by a factor of \(\sim 10\), and at low surface brightness levels the Ly\(\alpha\) emission appears to encircle the position of the obscured AGN, highly suggestive of a physical association. At the same time, we confirm that there is no compact continuum source located within \(\sim 2^\prime-3^\prime\) \(\approx 15–23\) kpc of the Ly\(\alpha\) peak. Since the latest cold accretion simulations predict that the brightest Ly\(\alpha\) emission will be coincident with a central growing galaxy, we conclude that this is actually a strong argument against, rather than for, the idea that the nebula is gravitationally powered. While we may be seeing gas within cosmic filaments, this gas is primarily being lit up, not by gravitational energy, but due to illumination from a nearby buried AGN.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift

1. INTRODUCTION

There has been a long-standing debate about the power source responsible for radio-quiet Ly\(\alpha\) nebulae (or “Ly\(\alpha\) blobs”). Unlike extended Ly\(\alpha\) halos observed around many radio galaxies and quasars, radio-quiet Ly\(\alpha\) nebulae do not always have an obvious single source of ionizing photons in their midst. Various explanations have been proposed: for example, shock-heating in galactic superwinds (Taniguchi & Shioya 2000; Taniguchi et al. 2001; Mori et al. 2004), photoionization from nearby galaxies and active galactic nuclei (AGNs; e.g., Cantalupo et al. 2005; Geach et al. 2009; Kollmeier et al. 2010; Prescott et al. 2012b; Overzier et al. 2013), and resonant scattering of centrally produced Ly\(\alpha\) photons (e.g., Möller and Warren 1998; Laursen & Sommer-Larsen 2007; Hayes et al. 2011; Steidel et al. 2011; Zheng et al. 2011). One final explanation is that Ly\(\alpha\) nebulae are powered by gravitational cooling radiation within cold accretion streams. This possibility has received substantial theoretical attention over the past few years, motivated in large part by evidence from numerical simulations that a cold mode of accretion could play an important if not dominant role in fueling galaxy formation (e.g., Keres et al. 2005; Dekel et al. 2009).

Against this backdrop, Nilsson et al. (2006) reported the discovery of a Ly\(\alpha\) nebula at \(z \approx 3.157\) in the GOODS-S field. Intriguingly, the deep GOODS imaging showed no associated continuum detections in any band, from the X-rays to the infrared. The photometric redshifts available at the time indicated that none of the nearby galaxies were likely to be at the redshift of the nebula nor would they be able to provide sufficient energy to power the nebula even if they were. Based on the lack of any obvious source of ionizing photons and on the similarity between the observed Ly\(\alpha\) surface brightness profile and early predictions from cold accretion models, the authors suggested that this system could be powered by cooling radiation. Since then, discussions of the range of power sources observed for Ly\(\alpha\) nebulae typically include a reference to this system as the clearest observational example of a “cooling” Ly\(\alpha\) nebula (e.g., Smith et al. 2008; Adams et al. 2009; Dijkstra 2009; Laursen et al. 2009; Rasmussen et al. 2009; Goerdt et al. 2010; Weijmans et al. 2010; Yang et al. 2010; Colbert et al. 2011; Erb et al. 2011; Cen & Zheng 2013; Laursen et al. 2013; Tamura et al. 2013; Yajima et al. 2013).

However, a number of things have changed substantially since the initial discovery of this Ly\(\alpha\) nebula. On the observational side, grism spectroscopy, deeper X-ray catalogs, and additional imaging—spanning the restframe optical to far-infrared—have become available in the GOODS-S field thanks to the Early Release Science program (Windhorst et al. 2011), the 2 Ms and 4 Ms Chandra Deep Field-South (CDF-S) Surveys (Luo et al. 2008; Xue et al. 2011), GOODS-Herschel\(^5\) (Elbaz et al. 2011), and HerMES (Levenson et al. 2010; Oliver et al. 2012), allowing for significant improvements to both photometric and spectroscopic redshift measurements in the region. In addition, some observational studies of other Ly\(\alpha\) nebulae have shown that the Ly\(\alpha\) emission can actually be offset substantially (\(\sim 10s\) of kpc) from associated galaxies and obscured AGNs at the same redshift (Prescott et al. 2009, 2012a, 2012b, 2013; Yang et al. 2014). On the theoretical side, simulations of “cooling” Ly\(\alpha\) nebulae have been carried out with greater and greater sophistication over the past few years (e.g., Faucher-Giguère et al. 2010; Goerdt et al. 2010; Rosdahl

\(^5\) Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
& Blaizot 2012). In light of the new observational data and more advanced numerical simulations, the time is ripe to return to this system and take another look at its local environment and most likely power source.

In this paper, we revisit the following questions: (1) does the Lyα nebula have any associated galaxies, and (2) is it likely powered by cold accretion? We describe the data sets used in this work in Section 2, and we study the neighborhood of the Lyα nebula in Section 3. In Section 4 we discuss the most likely powering mechanism responsible for the Lyα nebula, taking into account updated predictions from numerical simulations. Section 5 highlights some implications of this work for the larger class of Lyα nebulae, and we conclude in Section 6. We assume the standard ΛCDM cosmology ($Ω_m = 0.3$, $Ω_λ = 0.7$, $h = 0.7$); the angular scale at $z = 3.156$ is $7.58$ kpc/″. All magnitudes are in the AB system (Oke 1974).

2. DATA

This paper builds on the large number of existing data sets and catalogs with coverage of the GOODS-S field.

2.1. Lyα Narrowband Imaging and Spectroscopy

The original Lyα imaging was obtained as part of a survey for Lyα-emitting galaxies using FORS1 on the VLT 8.2 m telescope Antu and a standard narrowband filter ($λ = 5055$ Å; FWHM = 59 Å, corresponding to Lyα at $z = 3.126–3.174$). The nebula emission was confirmed to be Lyα at $z = 3.157$ via follow-up spectroscopy from VLT/FORS1, which showed a single emission line with the classic asymmetric profile expected for high redshift Lyα emission and no detections of the other strong lines that would have been expected from a low redshift interloper. Details on the Lyα imaging and follow-up spectroscopy are given in the original survey papers (Nilsson et al. 2006, 2007).

2.2. HST Imaging and Grism Spectroscopy

The Lyα nebula is located within the GOODS-S/ERS field. The area was originally observed as part of the GOODS South program in the ACS BVRiz filters (Dickinson et al. 2004; Giavalisco et al. 2004). The same region was more recently targeted as part of the WFC3/ERS observations in Cycle 17 following the installation of WFC3 during Servicing Mission 4 (GO/DD: 11359, 11360; PI: R. O’Connell; Windhorst et al. 2011). Images were acquired in the F098M, F125W and F160W filters, using two orbits in each filter. Additional shallower imaging in the F140W filter was done to provide a direct-image reference for a single pointing of ERS G141 grism observations (discussed below). The F140W observations partially overlap with the footprint of the 3D-HST program (GO: 12177; PI: van Dokkum) which also provides F140W images over a larger area. The GOODS-S/ERS field has been observed by an array of additional ground- and space-based facilities. In this work, we make use of WFC3-IR F125W, F140W, and F160W imaging and the WFC3-detected photometric catalog of the GOODS-S field compiled by Skelton et al. (2014). The WFC3 imaging represents a significant improvement over the ground-based J- and H-band data available previously, as it provides high resolution imaging coverage near the critical 4000 Å break, and enabling much more robust photometric redshift estimates; see Skelton et al. (2014) for further information. We make use of the photometric redshift catalog from Skelton et al. (2014), which is based on the code EAzY (Brammer et al. 2008), and morphological measurements for galaxies in the region taken from the CANDELS morphological catalog (van der Wel et al. 2012).

The Lyα nebula is serendipitously located in the one and only grism pointing observed as part of the ERS program (GO/DD: 11359, 11360; PI: R. O’Connell; Windhorst et al. 2011). The observations were done in both the G102 and G141 grisms, spanning 0.8–1.2 and 1.1–1.7 μm, respectively. The two grisms provide resolutions of $R \sim 210$ and 130. The pointing was observed for two orbits with each grism. In this work we use only the G141 grism observations, which covers the [O II] λ3727 emission line out to $z \approx 3.2$, as none of the objects relevant to this work have significant detections in the G102 spectra. The grism data were reduced by the 3D-HST team in a manner similar to that described in Brammer et al. (2012). Further details on the extraction and redshift-fitting methods will be presented in I. Momcheva et al. (2015, in preparation).

2.3. Mid- and Far-infrared Data

The original paper presented Spitzer IRAC and MIPS imaging of the field (Nilsson et al. 2006, their Figure 2). At longer wavelengths, Herschel PACS and SPIRE coverage of the field now exists from GOODS-Herschel and HerMES (Elbaz et al. 2011; Oliver et al. 2012). In addition, improvements have been made in extracting accurate IRAC/MIPS photometry properly accounting for source blending and the complex PSF of these instruments, and there has been extensive work on the best way to use IRAC/MIPS colors to distinguish AGNs from star-forming galaxies (Lacy et al. 2004; Stern et al. 2005; Lacy et al. 2007; Donley et al. 2008, 2012).

In this work, the mid- and far-infrared photometry are taken from the GOODS-Herschel catalog, which includes measurements from the GOODS-Spitzer Legacy Survey (Spitzer/IRAC+MIPS; P.I. Mark Dickinson) and the GOODS-Herschel Survey (Herschel/PACS; Elbaz et al. 2011), accessed via HeDaM. Source positions in the GOODS-Herschel catalog were determined first by using a weighted average of the 3.6 and 4.5 micron images, and then empirical PSFs at these source locations were fit to the mid- and far-infrared maps in order to determine the flux for each object and account for source blending. Further details are given in the GOODS-Herschel release documentation.

The field has been observed in the far-infrared with Herschel/ SPIRE as part of HerMES (Levenson et al. 2010; Roseboom et al. 2010, 2012; Oliver et al. 2012). In this work, we make use of Herschel/ SPIRE photometric measurements from the MIPS 24 μm matched catalog developed by the HerMES Team (HerMES Team 2014, private communication).

2.4. Chandra X-ray Coverage

Since the original paper, the Chandra X-ray coverage of GOODS-S has improved substantially from the original Chandra Deep Field-South 1 Ms survey, first by a factor of two and then by a factor of four in total exposure time. The resulting Chandra Deep Field-South 2 Ms and 4 Ms survey catalogs (Luo et al. 2008; Xue et al. 2011) provide a sample of 740 X-ray detected sources down to limiting on-axis fluxes of $\approx 3.2 \times 10^{-17}$, $9.1 \times 10^{-18}$, and $5.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for the

---

6. [http://hedam.lam.fr](http://hedam.lam.fr)

7. [http://hedam.lam.fr/GOODS-Herschel/goodss-data.php](http://hedam.lam.fr/GOODS-Herschel/goodss-data.php)
1. Photometric Redshifts

Figure 1 shows a stack of the WFC3-IR/F125W, F140W, and F160W imaging in the vicinity of the Lyα nebula, shown as contours, while Figure 2 shows the individual bands. Using the 3D-HST/CANDELS photometric redshift catalog (Skelton et al. 2014), we select sources that lie within a 10″ radius of the Lyα nebula. Figure 3 shows the distribution of photometric redshifts in this region, both as a histogram and as a sum of the individual galaxy P(z) distributions. The photometric redshift distribution shows two main peaks: one at $z \approx 1$ and one around $z \approx 3.1$, i.e., roughly the redshift of the nebula. Formally, 6 sources within this local region ($R < 10''$) have photometric redshifts within $\Delta z \pm 0.15$ of the nebula redshift; the positions and photometric redshifts of these “photometric redshift members” are given in Table 1. We plot the selected photometric redshift members on the HST imaging (Figure 2, right-hand panel). Of these 6 sources, photometric redshift estimates for two (Source 3 and 8) were given in the original paper; the new photometric redshifts for these sources are consistent with the previous estimates, given the quoted error bars. The photometric redshifts of the remaining sources were previously unknown.

We note that while photometric redshifts will clearly be less accurate and more susceptible to biases, especially at fainter magnitudes, relative to spectroscopic redshifts, a recent study of a suite of photometric redshift codes found that individual codes based on EAZY (Brammer et al. 2008) do reasonably well in terms of their reported errors (i.e., corresponding to the width of the reported P(z) peak), underestimating by about 5–15% (Dahlen et al. 2013). The scatter ($\sigma_0 = \sigma_{\text{rms}}(\Delta z/(1 + z))$) between the spectroscopic redshift and the median photometric redshift was found to increase from $\sigma_0 = 0.04$ at $m_H < 24$ mag to 0.09 at $m_H \sim 26$ mag, while the outlier fraction increased from about 10% to 20%. Thus by using a redshift window of $\Delta z \pm 0.15$, we can be reasonably confident that we are primarily selecting galaxies at the redshift of the nebula even at these fainter magnitudes.

To test the significance of the observed photometric redshift peak coincident with the nebula, we redid the analysis for 10,000 random apertures drawn from the entire GOODS-S field. We find that at $z \sim 3$, it is not common to find a peak in the photometric redshift distribution that is as strong as what is seen at the position of the Lyα nebula: formally there is a 2.0% chance of randomly selecting a region with comparable area under the summed P(z) distribution, or a 0.4% chance of randomly selecting a region with at least 6 galaxies with best fit photometric redshifts within $\Delta z \pm 0.15$ of the nebula redshift.

Interestingly, the very faint source visible in the F160W image that is located closest to the peak of the Lyα emission turns out to be one of the $z \approx 1$ sources (labeled as Galaxy “F” in Figure 1). The measured SED and P(z) derived by EAZY for this source show that it is well-described by the EAZY fit at $z = 0.91$ with a stellar mass of $\approx 1.2 \times 10^8 M_\odot$, and that it is inconsistent with either an AGN or starburst template at the nebula redshift (Figures 4–5). Thus, we confirm that there does not appear to be any associated continuum source within $\sim 2$–3″ $\approx 15–23$ kpc of the peak of the Lyα emission.

We note that gravitational lensing from the foreground sources at $z \approx 1$ should only have a minimal effect on the nebula. If we take all galaxies in the local vicinity that have

---

Notes:

8 We note that the surface brightness levels for the contours plotted in Nilsson et al. (2006) appear to have been stated incorrectly in the caption of their Figure 1.
3.1.3. Source 6—The IRAC/MIPS Source

We take a second look at Source 6, the mid-infrared source first identified in the Spitzer IRAC and MIPS data. We plot the full SED including the original GOODS-S imaging and Spitzer data, as well as the new HST/WFC3-IR imaging and measurements from Herschel/PACS and SPIRE (Figure 7). The source shows diffuse emission in the WFC3-IR imaging, but it is below the detection limit in the combined WFC3 detection image used in Skelton et al. (2014); therefore, we measure the photometry in these bands using a 2\arcmin radius [O\textsc{iii}] detection (Figure 6). This corresponds to a measured grism redshift of $z_{\text{grism}} = 3.153^{+0.019}_{-0.004}$ (Table 1), consistent with the photometric redshift ($z_{\text{phot}} = 3.206^{+0.065}_{-0.058}$) and with the nebula redshift measured from the Ly\alpha emission line ($cz_{\text{Ly} \alpha} = 3.157$). Neither the extended nebula itself nor any of the other galaxy members, which are all much fainter in $H$-band than Source 3, show a line detection in either the G102 or G141 grism spectroscopy.

3.1.2. Grism Redshifts

We next searched the grism redshift catalog for sources with grism redshifts consistent with the nebula. We find that one of the 6 photometric redshift neighbors (Source 3) shows a weak [O\textsc{ii}] emission, and the magnitudes of the other galaxy members, which are all much fainter in $H$-band than Source 3, show a line detection in either the G102 or G141 grism spectroscopy.

The summed $P(z)$ distribution is shown (gray shading) along with a histogram showing the best fit photometric redshifts (blue hashed histogram). The redshift of the Ly\alpha nebula is indicated with the red dashed line.

Photometric redshifts within $\pm 0.15$ of $z = 1$, the total stellar mass derived from the SED fitting is $\approx 3 \times 10^{10} M_\odot$, with the brighter (and presumably more massive) $z \approx 1$ sources being located about $5\arcsec$ to the northwest of the nebula (Figure 2, middle panel). If the corresponding total mass of the foreground structure is of order $3 \times 10^{11} M_\odot$, the expected Einstein radius would be $\approx 0.2\arcsec$, insignificant compared to the full extent of the Ly\alpha emission, and the magnification at the position of the Ly\alpha peak would only be about 3\%. If we consider only the source located closest to the center (Galaxy “F,” with a stellar mass of $1.2 \times 10^8 M_\odot$), the extended Einstein radius would be $\approx 0.05\arcsec$. Thus, neither the large scale morphology nor the surface brightness of the nebula is significantly affected by gravitational lensing from the $z \approx 1$ sources.

**Figure 2.** Region around the Ly\alpha nebula in the individual WFC3-IR/F125W, F140W, and F160W images. In all panels the Ly\alpha nebula is shown with black contours at Ly\alpha surface brightness levels of $[5.3, 7.0, 8.9] \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ after smoothing by $0.8 \times 0.8$. The IRAC centroid of Source 6 from the GOODS-Herschel catalog is indicated with a blue cross, and the yellow contours in each panel highlight diffuse emission in the corresponding WFC3-IR image that is detected within $R < 15\arcsec$ of Source 6. Left: the WFC3 F125W image. The F125W surface brightness contours at the position of Source 6 (yellow lines) correspond to SB$_{F125W} = [0.4, 0.6, 0.8] \times 10^{-20}$ erg s$^{-1}$ cm$^{-2}$ \ang$^{-1}$ arcsec$^{-2}$. Middle: the WFC3 F140W image; foreground sources with photometric redshifts within $\pm 0.15$ of $z = 1$ are indicated (green circles). The F140W surface brightness contours at the position of Source 6 (yellow lines) correspond to SB$_{F140W} = [0.8, 1.0, 1.2] \times 10^{-20}$ erg s$^{-1}$ cm$^{-2}$ \ang$^{-1}$ arcsec$^{-2}$. Right: the WFC3 F160W image; sources with photometric redshifts within $\pm 0.15$ of the redshift of the Ly\alpha nebula are indicated (red circles). The source with a detection of [O\textsc{ii}] at $z = 3.153$ in the G141 grism data is shown with a larger red circle. The F160W surface brightness contours at the position of Source 6 (yellow lines) correspond to SB$_{F160W} = [0.8, 1.0, 1.2] \times 10^{-20}$ erg s$^{-1}$ cm$^{-2}$ \ang$^{-1}$ arcsec$^{-2}$.

**Figure 3.** Photometric redshift distribution for sources within $R < 10\arcsec$ of the Ly\alpha nebula. The summed $P(z)$ distribution is shown (gray shading) along with a histogram of the best fit photometric redshifts (blue hashed histogram). The redshift of the Ly\alpha nebula is indicated with the red dashed line.

**Figure 4.** Photometric redshift distribution for Galaxy “F,” the faint galaxy closest to the peak of the Ly\alpha emission. The $P(z)$ distribution is shown (gray shading) along with a histogram showing the best fit photometric redshift (blue hashed). The redshift of the Ly\alpha nebula is indicated with the red dashed line.
aperature at the position of Source 6, as determined from the IRAC 3.6 and 4.5 μm imaging. The IRAC/MIPS photometry and Herschel PACS upper limits are taken from the GOODS-Herschel catalog (Elbaz et al. 2011), and the Herschel SPIRE measurements are from HerMES (HerMES Team 2014, private communication). We note that Source 6 is not detected in either the WFC3/G102 or G141 grism data.

Using these updated measurements, we derive the following MIR colors (relevant for the Ivison et al. (2004) color–color selection): $S_{3.6}/S_{4.5} = 9.959 \pm 0.792$ and $S_{8.0}/S_{4.5} = 2.160 \pm 0.380$. While Nilsson et al. (2006) suggest Source 6 is an obscured starburst at an approximate redshift of $z \approx 5.5$ based on its MIR colors, the MIR color measurements taken from the GOODS-Herschel catalog place Source 6 elsewhere in the Ivison et al. (2004) color space, much higher in $S_{3.6}/S_{4.5}$ and therefore much closer to the Mrk231 (i.e., AGN) locus. It is possible that the original measurements did not adequately account for source blending and the complex MIPS PSF, yielding an incorrect 24 μm flux for this relatively faint MIR source that happens to lie near the Airy ring from a brighter neighboring galaxy.

Furthermore, AGN selection based on MIR colors has been explored in great detail since the time of the original paper (Stern et al. 2005; Lacy et al. 2004, 2007; Donley et al. 2008, 2012). The measured MIR colors relevant for these color–color diagnostics are: log $(S_{4.5}/S_{8.0}) = 0.335 \pm 0.070$ and log $(S_{5.8}/S_{8.0}) = 0.243 \pm 0.107$. These measurements place Source 6 solidly within the AGN color selection window of Lacy et al. (2004, 2007), and within the more recent IRAC power-law AGN selection box of Donley et al. (2012). From the mid-infrared colors, Source 6 is therefore very likely an obscured AGN and not a starburst galaxy. The Herschel detections are susceptible to source confusion but suggest that there may be an additional cool dust component, e.g., emission from the host galaxy.

It is true that Source 6 was not detected in the deep 1 Ms CDF-S X-ray imaging, as pointed out in the original paper. We find that the source is still not detected in the more recent 2 Ms and 4 Ms CDF-S catalogs (Luo et al. 2008; Xue et al. 2011). However, a study of power-law IRAC selected AGN candidates in the 2 Ms Chandra Deep Field-North (CDF-N) X-ray imaging showed 23% (35%) were not detected above 3σ (5σ) in any X-ray band (Donley et al. 2007), while stacking of the X-ray non-detected sources still showed evidence for hard emission consistent with AGNs rather than star formation powering (Donley et al. 2012). Thus, it appears that the lack of an X-ray detection from Source 6, even in deep Chandra data, cannot necessarily be used to rule out the presence of an intrinsically luminous AGN that is simply heavily obscured at X-ray wavelengths.

Based on the photometry derived from the original GOODS-S HST and Spitzer/IRAC data and the new ERS imaging, we use the photometric redshift code EAZY (Brammer et al. 2008) to estimate a photometric redshift for Source 6. Including the IRAC photometric points and the standard EAZY star-forming galaxy templates results in a redshift of $z \approx 3.2–5.6$, similar to what was found in the original paper. However, if Source 6 is an obscured AGN, as we have argued, the IRAC bands will be dominated by AGN emission, making a photometric redshift estimate based on only star-forming templates highly unreliable. The photometric redshift estimate will be skewed to higher redshifts ($z \gtrsim 4$) by the need to fit the bright

### Table 1: Likely Galaxy Members

| ID | 3D-HST/CANDELS Catalog ID | R.A. (hours) | Decl. (degrees) | $m_{F160W}$ | $z_{\text{phot}}$ | $z_{\text{grism}}$ | Notes |
|----|--------------------------|-------------|----------------|-------------|-----------------|---------------|-------|
| 3  | GOODS-S-41192            | 03:32:14.072 | −27:43:03.72 | 23.54       | 3.208$^{+0.068}_{-0.058}$ | 3.153$^{+0.019}_{-0.004}$ | ... |
| 8  | GOODS-S-41189            | 03:32:14.886 | −27:43:03.54 | 24.83       | 3.246$^{+0.101}_{-0.101}$ | ... | ... |
| 9  | GOODS-S-41027            | 03:32:14.070 | −27:43:05.27 | 26.06       | 3.179$^{+0.171}_{-0.171}$ | ... | ... |
| 10 | GOODS-S-41047            | 03:32:13.947 | −27:43:04.81 | 26.02       | 3.024$^{+0.283}_{-0.085}$ | ... | ... |
| 11 | GOODS-S-41395            | 03:32:14.550 | −27:42:59.34 | 25.36       | 3.036$^{+0.856}_{-0.085}$ | ... | ... |
| 12 | GOODS-S-41673            | 03:32:14.884 | −27:42:54.27 | 27.26       | 3.231$^{+0.415}_{-0.215}$ | ... | ... |

* The ID column is based on the numbering scheme used in Nilsson et al. (2006).
3.2. Spatial Distribution of the Associated Galaxies and the Larger Scale Lyα Emission

The spatial distribution of likely members relative to the Lyα nebula is shown in Figure 2. The Lyα nebula lies between 6 galaxies with photometric redshifts consistent with being at the nebula redshift, one of which has a grism redshift as well. In Figure 8, we show the full extent of the Lyα emission in the original Lyα imaging, within three spatial windows (10″ × 10″, 20″ × 20″, and 32″ × 32″). At lower surface brightnesses than shown in the discovery paper, it appears that there is a nearly complete bridge of Lyα emission between the peak of the nebula, one associated galaxy to the north, and three associated galaxies to the west (including Source 3, the source with a consistent grism redshift). At even lower surface brightnesses, the diffuse Lyα emission connects all but one of the member galaxies and traces out what appears to be two intersecting filaments, a partial ring, or an asymmetric biconical nebula roughly centered on the position of Source 6. These morphological results and the result that Source 6 is an obscured AGN plausibly at the redshift of the nebula (Section 3.1.3) are together highly suggestive that Source 6 is indeed directly associated with the presence of the Lyα nebula. Further observations, e.g., detecting CO emission lines at submillimeter wavelengths, will allow us to confirm the redshift of Source 6 and verify that we are seeing a Lyα nebula surrounding an obscured AGN.

3.3. The Local Environment

Thus far we have shown that there are in fact galaxies associated with the Lyα nebula. Here we assess whether the region is in fact overdense relative to the field. To be consistent with previous studies of the environments of Lyα nebulae at $z \approx 3$ (Prescott et al. 2012b), we start by plotting the number counts in the F606W band measured from within the $R < 10''$ region around the Lyα nebula and from random $R < 10''$ apertures drawn from the full GOODS-S field (Figure 9; top panel). From this naive approach, there is only mild evidence for an enhancement in the region of the nebula; the number counts are slightly higher than in the field at $m_{F606W} \approx 25$ but consistent to within the errors, i.e., the scatter measured from the random aperture test. In addition, we have also seen from the photometric redshift analysis that there is an overdensity of $z \approx 1$ sources overlapping this region, which will necessarily boost the raw number counts. Next we look at the number density of sources with photometric redshifts within $\Delta z \pm 0.15$ of the redshift of the nebula ($z = 3.157$). In the bottom panel of Figure 9 we plot the corresponding densities for the region of the nebula and for random apertures drawn from the full GOODS-S field. The region of the nebula shows a factor of $\gtrsim 10$ overdensity at $m_{F606W} \approx 25$ relative to the field galaxy population at the same photometric redshift, even when accounting for the scatter measured from randomly placed apertures. Thus, not only are there galaxies associated with the Lyα nebula, it is in fact sitting in a galaxy-overdense region of the universe.

3.4. Properties of the Associated Galaxies

Having shown that Source 6 is an obscured AGN likely associated with the nebula, we briefly turn our attention to the properties of the other galaxies in this overdense region, and whether they are distinctive in any way relative to the field.
The position of Source 6 is indicated with a blue cross. LAEs from Nilsson et al. (2014) and best-fit photometric redshifts within Δz ± 0.15 of the redshift of the Lyα nebula are highlighted with red points, and Source 3, the source with a weak [O iii] detection at z = 3.153 in the G141 grism data, is shown with a larger red circle. The position of Source 6 is indicated with a blue cross. LAEs from Nilsson et al. (2007) are shown as green stars.

Figure 8. Spatial extent of the Lyα emission overlapped on the F160W imaging. In all panels the Lyα nebula, as shown in previous figures, is outlined with white contours (corresponding to a surface brightness level of 5.3 × 10^{-19} erg s^{-1} cm^{-2} arcsec^{-2}), while additional Lyα surface brightness contours are shown in grayscale at [1.3, 1.9, 3.2, 4.4, 6.3] × 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2} after smoothing by 0.4 × 0.9. Sources with photometric redshifts within Δz ± 0.15 of the redshift of the Lyα nebula are highlighted with red points, and Source 3, the source with a weak [O iii] detection at z = 3.153 in the G141 grism data, is shown with a larger red circle. The position of Source 6 is indicated with a blue cross. LAEs from Nilsson et al. (2007) are shown as green stars.

Figure 9. Top: number counts in the F606W band measured from the region around the Lyα nebula (R < 10″; blue diamonds) and from within random R < 10″ apertures across the entire GOOD-S-S field (with the mean and standard deviation shown as the black line and gray region, respectively). The F606W band was chosen to be consistent with previous studies of the environments of Lyα nebulae at z ≈ 3 (Prescott et al. 2012b). Bottom: sources with photometric redshifts within Δz ± 0.15 of the Lyα nebula redshift measured from the region around the Lyα nebula (R < 10″; red diamonds) and from within random R < 10″ apertures across the entireGOODS-S field (with the mean and standard deviation shown as the black line and gray region, respectively).

population. In Figure 10 we show the measured photometry and best-fit SEDs of the 6 galaxies that are likely associated with the Lyα nebula. We note that none of these member galaxies is detected in the MIPS imaging (Whitaker et al. 2014). Figure 11 shows the approximate luminosity function (LF) for the system, assuming that all 6 galaxies are at z ≈ 3,157, as well as the ages, stellar masses, star formation rates (SFRs), specific SFRs, and Av estimates from stellar population synthesis model fitting using FAST (Kriek et al. 2009), as reported in the 3D-HSTICANDELS catalog (Skelton et al. 2014). The galaxies are typically low luminosity, around ~0.2 L*, with only one (Source 3) around L*, assuming that M* ≈ −20.8 AB mag at this redshift (Reddy et al. 2008). The total UV luminosity of the member galaxies is ≈23.9 mag (AB) in the F606W band, or ≈2.3 L*, suggesting this may be a small group in formation. The member galaxies have typical ages of around 10⁸ yr, stellar masses of 10⁹ M⊙, SFRs of <10 M⊙ yr⁻¹, specific SFRs of 10⁻⁹ yr⁻¹, and extinctions of Av ≈ 0.2–0.8 mag. In Figure 11, we show the effective radii (R_e) and Sérsic parameter (n) measurements from parametric fits to the F160W imaging for the galaxies in the neighborhood of the nebula (van der Wel et al. 2012). The member galaxies are typically 1–3 kpc in radius, with Sérsic parameters clustered more around n ≈ 1, the value for an exponential disk, than around n ≈ 4, the value for a De Vaucouleurs profile. Two-sample Kolmogorov–Smirnov (KS) tests on all parameters did not reveal any statistical differences between the member galaxies and the field population at the same redshift (P_KS = 0.17, P_0.977 = 0.37, P_0.997 = 0.12, P_0.54 = 0.34, P_0.12 = 0.92, P_0.5 = 0.57, P_0.17 = 0.54, P_0.977 = 0.53). This may be due to the small sample size, or it could reflect that we are witnessing an early stage in the formation of a group-mass system when the individual member galaxies are separated by large physical distances and environmental effects have yet to become important.

4. POWERING THE Lyα NEBULA

4.1. The Energetics: Revisited

Nilsson et al. (2006) estimated that even if Source 3, the brightest neighbor galaxy, was at the nebula redshift, it was unlikely to be able to power the Lyα emission unless highly collimated in the direction of the nebula. Extrapolating the HST B- and V-band measurements of all the member galaxies, and accounting for the angle subtended by the nebula in each case, we find that galaxies can account for at most ≈14% of the Lyα emission, even under the optimistic assumption of an escape fraction of unity. Thus, the only source associated with the nebula that could plausibly contribute enough ionizing photons is the obscured AGN, i.e., Source 6.

The Spitzer SED of Source 6 (Figure 7) is consistent with a power-law spectrum of: L_{\nu} ≈ 1.7 \times 10^{30} (\nu / 10^{14})^{-1.75} \text{ erg s}^{-1} \text{ Hz}^{-1}, this corresponds to a total infrared luminosity of around 1.5 \times 10^{45} \text{ erg s}^{-1}, estimated by scaling the template of Mrk 231 to match the 8 μm flux, which is approaching the realm of ultra-luminous infrared galaxies (ULIRGs;
10^{12} L_\odot \approx 4 \times 10^{45}$ erg s$^{-1}$). Making the crude assumption that the MIR power-law can be extrapolated into the restframe UV, we estimate the ionizing photon flux of Source 6 to be \(\sim 3.5 \times 10^{53}\) photons s$^{-1}$ between restframe 200 and 912 Å. Producing the observed \(\alpha\) emissivity of the nebula (1.09 \pm 0.07 \times 10^{53}\) erg s$^{-1}$) requires a total of \(\sim 1.0 \times 10^{54}\) photons s$^{-1}$, assuming that two-thirds of recombinations result in a photon. Naively, it would appear that Source 6 can only account for about 35% of the \(\alpha\) emission, even when ignoring geometrical dilution. However, this extrapolation is very uncertain; for example, a somewhat shallower power-law index of \(-1.5\) is sufficient to match the required ionizing photon flux. If we instead take the total infrared emissivity (i.e., 3–1000 \(\mu\)m) to be measure of the intrinsic UV/optical emission (i.e., 1000 Å–1 \(\mu\)m) that is being reprocessed by dust, we estimate that the intrinsic ionizing photon flux from Source 6 is around \(\sim 10^{55}\) photons s$^{-1}$, more than sufficient to power the nebula. Given the uncertainties about the geometry of the system, the opening angle of the AGN, the obscuration of the source, and the true SED shortward of the Lyman limit, it seems plausible that Source 6 could simply be highly obscured along our line-of-sight but less obscured in the directions of the diffuse \(\alpha\) emission. Therefore, combined with the morphological evidence in Section 3.2, it appears likely that Source 6 is responsible for a significant fraction of the ionization in the Ly\(\alpha\) nebula.

While we have shown that there are several associated galaxies and an obscured AGN in this system that could contribute to the ionization of the nebula, we have also confirmed the previous result that there is no compact continuum source visible within the brightest part of the Ly\(\alpha\) nebula itself. The GOODS-S HST imaging provides an upper limit on the amount of star formation that could be going on within the nebula: the 3\(\sigma\) limit on the F606W flux (restframe \(\sim 1400\) Å) of \(4.66 \times 10^{-30}\) that was quoted in the original paper corresponds to a limit on the UV SFR of SFR (UV) = \(1.4 \times 10^{-28} L_\odot < 57 M_\odot\) yr$^{-1}$, assuming the standard conversion (Kennicutt 1998). High resolution millimeter/submillimeter imaging will be important for putting further constraints on the obscured star formation and molecular gas reservoir within the nebula.

4.2. Is the Ly\(\alpha\) Nebula Gravitationally Powered?

The argument up until now has been that a Ly\(\alpha\) nebula without any associated continuum counterparts is the best candidate for a system powered by gravitational cooling. In view of our improved observational understanding of the Nilsson et al. (2006) Ly\(\alpha\) nebula as well as updated theoretical simulations, it appears that this line of reasoning should actually be reversed, and that even this “best candidate” for a gravitationally powered Ly\(\alpha\) nebula is in fact powered by an AGN.

A number of authors have investigated whether gravitational cooling radiation within cold accretion streams can explain the observed properties of Ly\(\alpha\) nebulae, initially with analytic arguments (Haiman et al. 2000) and then using numerical simulations (Fardal et al. 2001; Furlanetto et al. 2005; Dijkstra et al. 2006; Yang et al. 2006; Dijkstra 2009; Faucher-Giguère et al. 2010; Goerdt et al. 2010; Rosdahl & Blaizot 2012). Due to the difficulty in appropriately simulating the self-shielding of the gas and the temperature of the IGM, the maximum predicted luminosities of “cooling” Ly\(\alpha\) nebulae from different numerical treatments have ranged from \(\sim 10^{42}\) erg s$^{-1}$, far below that of observed samples, to \(\sim 10^{44}\) erg s$^{-1}$, sufficient to explain even the brightest known systems. Thus it remains a matter of some debate whether gravitational cooling alone can in fact explain the large Ly\(\alpha\) luminosities of Ly\(\alpha\) nebulae.

At the same time, it is becoming clear that because gravitationally powered Ly\(\alpha\) emission originates from the extended cold streams that are fueling galaxy formation, star formation, and AGN activity, the simulations generically predict that there will be a growing galaxy at the center of any luminous “cooling” Ly\(\alpha\) nebula (e.g., Fardal et al. 2001; Furlanetto et al. 2005; Faucher-Giguère et al. 2010; Goerdt et al. 2010; Rosdahl & Blaizot 2012). Furthermore, these luminous Ly\(\alpha\) nebulae will necessarily be hosted by \(\gtrsim 10^{12}\) M_\odot halos (Rosdahl & Blaizot 2012). While it is possible that such halos go through an initial phase of gas cooling preceding any substantial star formation, this cooling-only phase would necessarily have occurred much earlier, when the halo was \(\sim 10^{15}– 10^{14}\) M_\odot and when the corresponding cooling Ly\(\alpha\) emission was several orders of magnitude fainter than observed Ly\(\alpha\) nebulae (Furlanetto et al. 2005). According to the most recent simulations, stellar continuum emission would therefore be expected at the position of the Ly\(\alpha\) peak, unless this galactic counterpart has been very effectively hidden (Rosdahl & Blaizot 2012). For this reason, we suspect that the correct argument is the opposite of what has often been assumed: namely, that the lack of any associated continuum sources in the Ly\(\alpha\) nebula makes it less likely that this system is predominantly powered by gravitational cooling. It is difficult to understand how the central growing galaxy, presumably the most massive member in the region located at a node within the cosmic web, has been so effectively hidden at the center of the Ly\(\alpha\) nebula. If it is simply highly obscured and therefore not visible in the restframe optical, then it should be the brightest source visible in the system at longer wavelengths. Higher resolution millimeter/submillimeter observations will be important for shedding further light on this issue, but the evidence thus far from the Spitzer data is that the bulk of the obscured emission in this system is concentrated at the position of Source 6, an obscured AGN that is offset by \(\sim 4\)" \(\approx 30\) kpc from the brightest part of the Ly\(\alpha\) nebula and that is instead located in an apparent “hole” in the fainter, larger scale Ly\(\alpha\) emission. Thus,
while it is still possible that the Lyα emission is tracing gas within cosmic filaments, the results of this paper argue strongly that it is being powered primarily by illumination from the obscured AGN in the region instead of by gravitational cooling.

We suspect that this Lyα nebula is not an isolated case. The key observational characteristics of this system—the small sizes, disk-like morphologies, and low luminosities of the member galaxies, the evidence for an overdense neighborhood, and the presence of a highly obscured AGN offset by 10 s of kpc from the Lyα peak that can provide some if not all of the requisite ionizing photons—are highly reminiscent of the properties LABd05, a more luminous Lyα nebula at $z \approx 2.7$ (Prescott et al. 2012b). It seems likely that these systems are intrinsically similar to cases such as Weidinger et al. (2004, 2005), a quasar at $z \approx 3$ with an extended, asymmetric biconical Lyα halo that is being viewed through one side of the ionization cone of the (unobscured) quasar. In the Nilsson et al. (2006) Lyα nebula, we are likely observing a similar phenomenon, an AGN powering an extended Lyα nebula, but with a line of sight passing outside the ionization cone. This picture is broadly consistent with the much higher obscuration of the AGN and the two lobe structure seen at low surface brightness levels in the Lyα emission. Our conclusions are consistent with the argument of Overzier et al. (2013) that AGNs must be the dominant power source for the majority (if not all) of the most luminous Lyα nebulae. The Nilsson

---

**Figure 11.** Luminosity function and physical properties derived from SED fitting (Skelton et al. 2014) for galaxies associated with the Lyα nebula (filled histograms) vs. all galaxies in the field within $\Delta z \pm 0.15$ (open histograms, scaled down for clarity). Top left: $F_{606W}$-band luminosity function (AB mag). Top right: log of the stellar age in years. Middle left: log of the stellar mass in solar masses. Middle right: log of the SFR in solar masses per year. Bottom left: log of the specific SFR in inverse years. Bottom right: attenuation $A_V$ (AB mag).
Figure 12. Effective radius ($R_e$) and Sérsic $n$ estimates derived from GALFIT parametric fits to the F160W data (van der Wel et al. 2012), for member galaxies ($\Delta z \pm 0.15, R < 10''$; filled histogram), and for all galaxies in the GOODS-S field within $\Delta z \pm 0.15$ of the nebula redshift (open histogram, scaled down for clarity). The size of the PSF (top panel) and the Sérsic $n$ values for exponential and De Vaucouleurs profiles (bottom panel) are indicated with dotted lines.

et al. (2006) Lyα nebula is somewhat lower luminosity than the systems studied by Overzier et al. (2013), suggesting that even at lower luminosities where less powerful mechanisms (gravitational cooling, winds, star formation) could in principle play a larger role, AGNs continue to be a dominant power source for Lyα nebulae.

5. IMPLICATIONS

On a more general level, while gravitational cooling radiation, as a fundamental physical process, must contribute to the total Lyα emission observed from Lyα nebulae, our experience with this Lyα nebula leads us to conclude that it will always be more difficult to prove that a given nebula is primarily gravitationally powered. Since bright Lyα emission from gravitationally cooling correlates strongly with actively growing galaxies (and AGNs), a lack of obvious power sources is not sufficient evidence, and the morphology and shape of the surface brightness profile could simply reflect the fact that the gas is being brought in by a cold accretion stream without necessarily proving the nebula is lit up by gravitational cooling. Determining what fraction of a given Lyα nebula is powered by gravity as opposed to by embedded sources requires more detailed studies of, e.g., the polarization of the Lyα emission to constrain the contribution of scattered light, as well as comparisons between emission line diagnostic measurements within the diffuse gas and improved theoretical predictions for the expected metal line emission from cold accretion streams.

Instead, we suspect that extended Lyα emission displaced from all associated continuum sources is actually less likely to be powered by cooling radiation and more likely to be a signature of cosmic gas illuminated by an offset AGN (leading to either Lyα fluorescence or Lyα resonant scattering), an AGN that may be highly obscured to the line-of-sight or recently extinguished. It is not particularly hard to hide an AGN with obscuration and geometry (i.e., if it is offset from the nebula and obscured to our line-of-sight but unobscured toward the nebula), or if it is in the process of ramping down in its output, leaving a seemingly abandoned light echo of Lyα emission at larger distances (and light travel times) from the AGN position (e.g., similar to Hanny’s Voorwerp, an [O III] nebula at lower redshift; Schawinski et al. 2010). In systems where we can identify an AGN as the dominant power source in this way, we have an opportunity to use the spatially extended line emission as a laboratory for studying AGN variability over $10^5$–$10^6$ year timescales as well as the physical conditions within the underlying cosmic web, lit up in emission while in the process of fueling and being impacted by ongoing local galaxy formation.

6. CONCLUSIONS

In light of new observations and more sophisticated numerical simulations, we have taken a second look at the local environment and most likely power source for the Nilsson et al. (2006) Lyα nebula. We find that the nebula is associated with 6 nearby galaxies and an obscured AGN located $\sim 4'' 
\sim 30$ kpc away. The Lyα emission is seen to extend further than previously realized, nearly encircling the position of the obscured AGN, and the local region shows evidence for being overdense relative to the field. At the same time, results from the latest generation of cold accretion simulations show that the brightest Lyα emission powered by gravitational cooling will be centered on a growing galaxy, which should be detectable as a counterpart in the continuum. Thus, while we confirm the previous finding that there is no associated continuum source located within the nebula itself, we conclude that this is actually a strong argument against, rather than for, the nebula being powered by gravitational energy. The Lyα emission at low surface brightness levels appears to trace out a complicated filamentary structure, perhaps consistent with gas within cold accretion streams, but this gas is most plausibly being lit up due to illumination from a nearby obscured AGN rather than due to gravitational powering. Follow-up observations of such emission line nebulae offer an exciting window into both AGN physics and the kinematics and physical conditions of the cosmic web surrounding regions of active galaxy formation.

We are grateful to Kim Nilsson for assistance with the original Lyα data, to Rosalind Skelton for guidance on using the 3D-HST/CANDELS photometric catalog, to Julie Wardlow and the HerMES team for providing early access to the HerMES catalogs, and to Lise Christensen, Kristian Finlator, Sebastian Hönig, Pieter van Dokkum, Natascha Förster Schreiber, and the anonymous referee for helpful discussions and comments. M.K.M.P. was supported by a Dark Cosmology Centre Fellowship. J.P.U.F. acknowledges support from the ERC-StG grant EGGS-278202. The Dark Cosmology Centre is funded by The Danish National Research Foundation. This
work is based on observations taken by the WFC3 Early Release Science program (GO 11359 and 11360) and the 3D-HST Treasury Program (GO 12177 and 12328) with the NASA/ESA HST, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. The GOODS-Herschel data was accessed through the Herschel Database in Marseille (HeDaM—http://hedam.lam.fr) operated by CeSAM and hosted by the Laboratoire d’Astrophysique de Marseille. This research has made use of data from HerMES project (http://hermes.sussex.ac.uk/). HerMES is a Herschel Key Programme utilizing Guaranteed Time from the SPIRE instrument team, ESAC scientists and a mission scientist.

REFERENCES

Adams, J. J., Hill, G. J., & MacQueen, P. J. 2009,ApJ, 694, 314
Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008,ApJ, 686, 1503
Brammer, G. B., van Dokkum, P. G., Franx, M., et al. 2012,ApJS, 200, 13
Cantalupo, S., Porciani, C., Lilly, S. J., & Miniati, F. 2005,ApJ, 628, 61
Cen, R., & Zheng, Z. 2013,ApJ, 775, 112
Colbert, J. W., Scarlata, C., Teplitz, H., et al. 2011,ApJ, 728, 59
Dahlen, T., Mobasher, B., Faber, S., et al. 2009,ApJ, 775, 93
Dekel, A., Birnboim, G., Engel, G., et al. 2009, Natur, 457, 451
Dickinson, M., Stern, D., Giavalisco, M., et al. 2004,ApJL, 600, L99
Dijkstra, M. 2009,ApJ, 690, 82
Dijkstra, M., Haiman, Z., & Spaans, M. 2006, ApJ, 649, 14
Donley, J. L., Rieke, G. H., Pérez-González, P. G., & Barro, G. 2008,ApJ, 687, 111
Donley, J. L., Rieke, G. H., Pérez-González, P. G., Rigby, J. R., & AlonsoHerrero, A. 2007,ApJ, 660, 167
Donley, J., Koeckemoer, A., Brusa, M., et al. 2012,ApJ, 748, 142
Elbaz, D., Dickinson, M., Hwang, H., et al. 2011,AA&A, 533, A119
Erb, D. K., Bogosavljević, M., & Steidel, C. C. 2011,ApJL, 740, L31
Fardal, M. A., Katz, N., Gardner, J. P., et al. 2001,ApJ, 562, 605
Faucher-Giguère, C.-A., Kereš, D., Dijkstra, M., Hernquist, L., & Zaldarriaga, M. 2010,ApJ, 725, 633
Furlanetto, S. R., Schaye, J., Springel, V., & Hernquist, L. 2005,ApJ, 622, 7
Geach, J., Alexander, D., Lehmer, B., et al. 2009,ApJ, 700, 1
Giavalisco, M., Ferguson, H., Koekemoer, A., et al. 2004,ApJL, 600, L93
Goerdt, T., Dijkstra, M., Hernquist, L., & Zaldarriaga, M. 2010,ApJ, 725, 633

REFERENCES

Adams, J. J., Hill, G. J., & MacQueen, P. J. 2009,ApJ, 694, 314
Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008,ApJ, 686, 1503
Brammer, G. B., van Dokkum, P. G., Franx, M., et al. 2012,ApJS, 200, 13
Cantalupo, S., Porciani, C., Lilly, S. J., & Miniati, F. 2005,ApJ, 628, 61
Cen, R., & Zheng, Z. 2013,ApJ, 775, 112
Colbert, J. W., Scarlata, C., Teplitz, H., et al. 2011,ApJ, 728, 59
Dahlen, T., Mobasher, B., Faber, S., et al. 2009,ApJ, 775, 93
Dekel, A., Birnboim, G., Engel, G., et al. 2009, Natur, 457, 451
Dickinson, M., Stern, D., Giavalisco, M., et al. 2004,ApJL, 600, L99
Dijkstra, M. 2009,ApJ, 690, 82
Dijkstra, M., Haiman, Z., & Spaans, M. 2006, ApJ, 649, 14
Donley, J. L., Rieke, G. H., Pérez-González, P. G., & Barro, G. 2008,ApJ, 687, 111
Donley, J. L., Rieke, G. H., Pérez-González, P. G., Rigby, J. R., & AlonsoHerrero, A. 2007,ApJ, 660, 167
Donley, J., Koeckemoer, A., Brusa, M., et al. 2012,ApJ, 748, 142
Elbaz, D., Dickinson, M., Hwang, H., et al. 2011,AA&A, 533, A119
Erb, D. K., Bogosavljević, M., & Steidel, C. C. 2011,ApJL, 740, L31
Fardal, M. A., Katz, N., Gardner, J. P., et al. 2001,ApJ, 562, 605
Faucher-Giguère, C.-A., Kereš, D., Dijkstra, M., Hernquist, L., & Zaldarriaga, M. 2010,ApJ, 725, 633
Furlanetto, S. R., Schaye, J., Springel, V., & Hernquist, L. 2005,ApJ, 622, 7
Geach, J., Alexander, D., Lehmer, B., et al. 2009,ApJ, 700, 1
Giavalisco, M., Ferguson, H., Koekemoer, A., et al. 2004,ApJL, 600, L93
Goerdt, T., Dijkstra, M., Hernquist, L., & Zaldarriaga, M. 2010,ApJ, 725, 633
