EFFECTS OF DUST GEOMETRY IN Lyα GALAXIES AT \( z = 4.4 \)^1

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ABSTRACT

Equivalent widths (EWs) observed in high-redshift Lyα galaxies could be stronger than the EW intrinsic to the stellar population if dust is present residing in clumps in the interstellar medium (ISM). In this scenario, continuum photons could be extinguished, while the Lyα photons would be resonantly scattered by the clumps, eventually escaping the galaxy. We investigate this radiative transfer scenario with a new sample of six Lyα galaxy candidates in the GOODS CDF-S, selected at \( z = 4.4 \) with ground-based narrowband imaging obtained at CTIO. Grism spectra from the HST PEARS survey confirm that three objects are at \( z = 4.4 \), and that another object contains an active galactic nucleus (AGN). If we assume the other five (non-AGN) objects are at \( z = 4.4 \), they have rest-frame EWs from 47 to 190 Å. We present results of stellar population studies of these objects, constraining their rest-frame UV with HST and their rest-frame optical with Spitzer. Out of the four objects which we analyzed, three objects were best fit to contain stellar populations with ages on the order of 1 Myr and stellar masses from \( 3 \times 10^8 \) to \( 1 \times 10^9 \, M_\odot \), with dust in the amount of \( A_{1200} = 0.9–1.8 \) residing in a quasi-homogeneous distribution. However, one object (with a rest EW \( \sim 150 \, \text{Å} \)) was best fit by an 800 Myr, \( 6 \times 10^8 \, M_\odot \) stellar population with a smaller amount of dust (\( A_{1200} = 0.4 \)) attenuating the continuum only. In this object, the EW was enhanced \( \sim 50\% \) due to this dust. This suggests that large EW Lyα galaxies are a diverse population. Preferential extinction of the continuum in a clumpy ISM deserves further investigation as a possible cause of the overabundance of large-EW objects that have been seen in narrowband surveys in recent years.

Subject headings: galaxies: evolution — galaxies: fundamental parameters — galaxies: high-redshift — galaxies: ISM

Online material: color figures

1. INTRODUCTION

Over the last decade, numerous surveys have been conducted searching for galaxies with strong Lyα emission (Lyα galaxies) at high redshift (e.g., Rhoads et al. 2000, 2004; Rhoads & Malhotra 2001; Malhotra & Rhoads 2002, hereafter MR02; Cowie & Hu 1998; Hu et al. 1998, 2002, 2004; Kudritzki et al. 2000; Fynbo et al. 2001; Pentericci et al. 2000; Ouchi et al. 2001, 2003, 2004; Fujita et al. 2003; Shimasaku et al. 2003, 2006; Kodaira et al. 2003; Ajiki et al. 2004; Taniguchi et al. 2005; Venemans et al. 2002, 2004; Nilsson et al. 2007). Many of these studies have discovered Lyα galaxies with large rest-frame Lyα equivalent widths (EWs; Kudritzki et al. 2000; MR02; Dawson et al. 2004, 2007; Shimasaku et al. 2006). Since it was first suggested 40 years ago (Partridge & Peebles 1967) that Lyα emission would be an indicator of star formation in the first galaxies during formation, it has been thought that strong Lyα emission would be indicative of copious star formation. However, the ratio of high to low EWs found in many of these surveys is too high to be explained by a so-called normal stellar population with a Salpeter (1955) initial mass function (IMF) and a constant star formation rate (SFR). This normal stellar population has mass from 260 Å to 10^9 yr, settling toward 95 Å by 10^9 yr. Thus, something is causing the EWs in many of the observed Lyα galaxies to be higher than normal.

We examine three possible causes for the stronger than expected Lyα EWs seen in these high-redshift objects. Strong Lyα emission could be produced via star formation if the stellar photospheres were hotter than normal. This could happen in extremely low metallicity galaxies, or galaxies which have their stellar mass distributed via a top-heavy IMF, forming more high-mass stars than normal. More high-mass stars would result in more ionizing photons, which would thus create more Lyα photons when they interact with the local interstellar medium (ISM). Low-metallicity or top-heavy IMFs are possible in primitive galaxies, which are thought to contain young stars and little dust (Ellis et al. 2001; Venemans et al. 2005; Gawiser et al. 2006; Pirzkal et al. 2007; Finkelstein et al. 2007).

Active galactic nuclei (AGNs) can also produce large Lyα EWs. However, the lines in type I AGNs are much broader than the width of the narrowband filter, and none of the accompanying high ionization state emission lines have been detected in many Lyα galaxies (Dawson et al. 2004). While the lines in type II AGNs are narrower, a deep Chandra exposure in the LALA fields showed no significant X-ray flux, even when individual galaxies were stacked (Malhotra et al. 2003; Wang et al. 2004). Wang et al. determined that less than 4.8% of their sample could be possible AGNs. Thus, while one could never entirely rule out AGNs from their sample, if one uses well thought out selection criteria, one could be confident that there are at most a small number of AGN interlopers. In general, narrowband selection techniques usually result in a low AGN fraction.

While Lyα galaxies are historically thought to be primitive and dust free, there is a scenario involving dust which could cause an older stellar population to exhibit a strong Lyα EW. If the dust is primarily in cold, neutral clouds with a hot, ionized intercloud medium the Lyα EW would be enhanced because Lyα photons are resonantly scattered (Neufeld 1991; Hansen & Oh 2006).

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Assuming the clouds are thoroughly mixed with neutral hydrogen, Lyα would be preferentially absorbed by the hydrogen at the surface of these clouds, while continuum photons would be more likely to penetrate these clouds more deeply before they get absorbed by dust. The Lyα photons would likely be reemitted quickly, proceeding to effectively “bounce” around the ISM by being absorbed and reemitted right on the surface of these clouds. Thus, Lyα photons would have a much greater chance of escaping the galaxy than continuum photons, which would suffer a much greater chance of extinction. In this scenario a strong Lyα galaxy would emit more Lyα photons than continuum photons, which would suffer a much greater chance of extinction. Because the Lyα photons are not absorbed by dust, the Lyα EW could be observed in a galaxy with an older stellar population and a clumpy dusty interstellar medium. Our goal in this paper is to research the likelihood that this scenario is occurring in a sample of Lyα galaxies.

In this paper we assume a Benchmark Model cosmology, where $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 0.7$ (cf. Spergel et al. 2007). All magnitudes in this paper are listed in AB magnitudes (Oke & Gunn 1983). In §2 we discuss our data reduction and sample. In §3 we discuss our stellar population models. In §4 we detail our results, and they are discussed in §5. We present our conclusions in §6.

2. DATA HANDLING

2.1. Observations

In order to study Lyα galaxies at $z = 4.4$, we obtained a 2.75 hr exposure in the 6563 Å (Hα) narrowband filter (NB656) in 2006 October using the MOSAIC II CCD imager on the Blanco 4 m telescope at Cerro Tololo Inter-American Observatory (CTIO). MOSAIC II has eight chips over a $36' \times 36'$ field of view, with each pixel covering 0.27'' on the sky. In our previous study (Finkelstein et al. 2007), we obtained ground-based broadband data of regions with preexisting narrowband data. However, the broadband data were not nearly deep enough to constrain the dusty scenario.

We observed the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) Chandra Deep Field—South (CDF-S; R.A. = 03h31m45.s0, decl. = $-27^\circ 48' 31.5''$ [J2000.0]) to take advantage of the extremely deep HST Advanced Camera for Surveys (ACS; Ford et al. 1998) and Spitzer Infrared Array Camera (IRAC; Fazio et al. 2004) broadband data publicly available. In addition, the photometry and astrometry of these broadband data have been extremely well determined, further reducing errors in our results. The data consist of the following broadband filters: F435W (B), F606W (V), F775W (I'), F850LP (z'), 3.6 μm (channel 1), 4.5 μm (channel 2), 5.8 μm (channel 3), and 8.0 μm (channel 4).

2.2. Data Reduction

The CTIO data were reduced with IRAF5 (Tody 1986, 1993), using the MSCRED (Valdes & Tody 1998; Valdes 1998) reduction package, following the method set forth in Rhoads et al. (2000, 2004). First, we performed the standard image reduction steps of overscan subtraction, bias subtraction, and flat-fielding. Cross-talk was also removed between chip pairs sharing readout electronics. We derived a supersky flat from the science data, and used this to remove the residual large-scale imperfections in the sky. The world coordinate systems (WCS) of individual frames were adjusted by comparing the frames to the astrometry from the USNO-A2.0 catalog. Cosmic rays were rejected using the algorithm of Rhoads (2000), and satellite trails were manually flagged and excluded from the final stacked image. Weights for image stacking were determined using the ATTWEIGHT algorithm (Fischer & Kochanski 1994), with the task mscat used to make the final stack. See Rhoads et al. (2000) and Wang et al. (2005) for further details on data reduction.

2.3. Object Extraction

In order to select Lyα galaxies in our field, we used the GOODS CDF-S ACS version 1.0 catalogs, obtained from the GOODS Web site. Because the GOODS ACS data are much deeper and have a higher resolution than our narrowband data, we chose to extract sources from our narrowband data using point-spread function (PSF) fitting routines rather than aperture photometry. We were able to do this because typical high-z Lyα galaxies are not resolved from the ground (Pirzkal et al. 2007). We performed PSF fitting using the routines in the IRAF port of DAOPHOT (Stetson 1987).

We chose the positions to fit the PSF based on the positions of sources in the GOODS catalogs. The objects we were looking for were $z \approx 4.4$ Lyα galaxies, so they should be B-band dropouts with a narrowband excess. We used the B-dropout color criteria from Giavalisco et al. (2004) with the magnitudes from the GOODS catalogs in order to find out which objects were Lyman break galaxies (LBGs) at $z \sim 4.4$. The number counts of the $V$ magnitudes of all objects in the catalog turned over just brighter than 27th magnitude, so we chose to only fit the PSF to objects with $V \leq 27$ in order to avoid selecting objects beyond the completeness limit of the GOODS data set.

The input list to the PSF-fitting routine consisted of the x- and y-positions in the narrowband image corresponding to the right ascension and declination coordinates of the objects we wanted to fit from the GOODS catalog. To be sure the coordinates matched up correctly, we performed a transformation to correct for any WCS distortion between the WCS of the narrowband image and the GOODS catalog. The PSF-fitting routine was then given this corrected list of x- and y-coordinates, along with the PSF image computed from the narrowband image. The outputs were a file of the object magnitudes along with a subtraction image (an image showing the residuals left when the fitted PSFs were subtracted out). On inspecting this image, we found that, with the exception of extremely bright stars or extended objects, this method of PSF fitting extracted the objects very well.

In order to calculate the zero point of the Hα image, we plotted a color-magnitude diagram of Hα-V versus V. The Hα filter is contained entirely within the V filter, so that the mean colors of these objects should be zero. We fit the zero point using only unsaturated stars, and find a zero point of 27.55 mag for 1 count in the final image. The DAOPHOT photometry errors imply a 5 σ limiting magnitude of 24.90 for the narrowband image.

2.4. Lyα Galaxy Selection

We find $z \approx 4.4$ galaxy candidates by seeing which B-band dropouts exhibit a narrowband excess. Figure 1 shows the color-magnitude diagram for all of the objects we extracted, highlighting the B-band dropouts, along with the initial galaxy candidates. There were 11 initial candidates, and six of them we eventually determined to be true candidates after visual inspection showed that they were real, uncontaminated objects. The five objects which were rejected at this stage were either contaminated by a nearby star or were not visible above the noise in the NB656 image.

We performed a number of tests to check the validity of our six candidates. First, we looked for other B dropouts with similar V-band magnitudes to each of the six candidates, and then

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5 IRAF is distributed by the National Optical Astronomy Observatory (NOAO), which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
checked to see whether these somewhat randomly selected objects showed any narrowband excess, which none of them did. We then looked at the subtraction image. With a perfect PSF extraction, we should see nothing at the location of our candidates. Indeed, when inspecting these subtracted areas, nothing stands out from the noise. Finally, we took a mosaicked image of the GOODS V-band tiles and convolved it to the seeing of the ground-based Hα image (∼0.9″). We then subtracted this image from the Hα image, and checked to ensure that the six candidates showed a narrowband excess, which five out of the six did. The object that did not show an excess on visual inspection is near a bright star (object 5), and also has the smallest computed excess, which could explain why it does not stand out above the noise in the Hα-V image. Figure 2 shows stamps of each of the six candidates, along with the results of some of the methods listed above. Figure 3 shows stamps of each candidate in each of the Hα, B, V, i′, z′, 3.6 μm, and 4.5 μm bands. Table 1 details the EWs of each object, while Table 2 lists the magnitudes of each object for each filter we used.

2.5. Spectroscopic Confirmations

While we have assumed that our narrowband filter has selected Lyα galaxies at z ≈ 4.4, it could also pick up [O ii] emitters at z ∼ 0.3 and [O iii] emitters at z ∼ 0.75. Ideally, we would like to be able to see a Lyα line in a given spectrum to make a confirmation, but lacking that we can still confirm a redshift based off of a Lyman break. The Probing Evolution and Reionization Spectroscopically (PEARS; PI S. Malhotra) HST Treasury Program (10530) has obtained ACS grism spectroscopy of approximately a third of the solid angle of the CDF-S via 5 ACS pointings. Four of our candidates were observed in PEARS.

Based on the positions of observed emission lines and breaks in the observed spectra, we have been able to spectroscopically confirm objects 1, 2, and 6 to be at z ≈ 4.4. While object 4 is not in any of the PEARS fields, it is covered by GOODS-MUSIC (Grazian et al. 2006), and it was calculated to have a photometric redshift of 4.42. For completeness, we list the photometric redshifts for objects 1, 2, and 6, which are 4.24, 4.44, and 4.36, respectively.

In order to search for AGNs in our sample, we checked the GOODS CDF-S data set (Giacconi et al. 2001), which consists of a deep Chandra exposure in the GOODS CDF-S. One object was detected in the Chandra data (object 3), and we found in the literature that it is a known [C iv] λ1549 emitter at z = 3.19 (Szokoly et al. 2004; Xu et al. 2007). This object was not included in our analysis.

2.6. Broadband Photometry

For our analysis, we used the updated version of the GOODS CDF-S catalog (ver. 1.9; M. Giavalisco et al. 2008, in preparation), which has deeper observations in i′ and z′, resulting in lower error bars for those two bands. As an external check on the photometry errors in the GOODS catalog, we used the Hubble Ultra Deep Field (HUDF; Beckwith et al. 2006) catalog. The HUDF is much deeper than the version 1.9 data in the same regions, thus any errors would be dominated by the version 1.9 data. We matched the HUDF and version 1.9 catalogs, then plotted the magnitude difference between the two versus the version 1.9 data for each of the four bands (B, V, i′, and z′). We characterized this error as being 1 σ of the spread in the magnitude difference in a certain magnitude slice. This error was small (<0.1 mag in our magnitude regime), but in the cases where it was larger than the version 1.9 photometry error, we used this error in its place.

When comparing data from different telescopes to models, we needed to be sure that the magnitudes we were using from our narrowband, ACS, and IRAC data meant the same thing. In the narrowband, we obtained fluxes from PSF fitting, so then the magnitudes from these fluxes were total magnitudes. For the GOODS ACS data, we used the MAG_AUTO parameter, which is known to be 5% fainter than the total magnitude (Bertin 2006). Thus, we corrected the GOODS ACS data, adding on a factor of 5% to the flux to make them total magnitudes.

The GOODS Spitzer IRAC data do not yet have a public catalog, but a catalog has been created using the TFIT software package (Laidler et al. 2007). TFIT uses a priori knowledge of spatial positions and morphologies from a higher resolution image (in this case the GOODS ACS z′ image) to construct object templates and fit them to the lower resolution image. However, this used the ACS catalog’s MAG_ISO parameter as a guideline for the radius of the galaxy, so in order to find the total magnitude, we added to the IRAC magnitudes the difference between MAG_ISO and MAG_AUTO for our objects in the ACS z′ catalog. We then added an additional factor of 5% to correct the IRAC magnitudes to total magnitudes. We now had total magnitudes for our objects in nine bands, from B to 8.0 μm.

3. MODELING

3.1. Stellar Population Models

We have derived the physical properties of our candidate Lyα galaxies by comparing them to stellar population models, using the modeling software of Bruzual & Charlot (2003, hereafter BC03). Comparing to models allows one to choose a variety of physical parameters to see which matches the observations the best. We attempted to fit the following parameters for each galaxy: age, metallicity, SFR, mass, and dust content. We used a grid of 24 ages ranging from 1 Myr to 1.35 Gyr (the age of the universe at z = 4.4). We fit the objects to the full range of metallicity available with BC03, from 0.005 to 2.5 Z⊙. We modeled exponentially decaying SFRs with characteristic decay times (τ) of 10^6
Fig. 2.—Results from our tests to check the validity of our candidates. The first column shows a $10^\circ$ stamp of each candidate in the NB656 image. The second column shows each candidate in a narrowband excess ($\text{NB656} - V$) image. We see flux in five out of the six objects, visually confirming that they exhibit a narrowband excess. The one object that does not definitively show a narrowband excess is very near a bright star, which could affect this observation. Regardless, this object is thrown out of our analysis as the nearby star contaminates its Spitzer fluxes. The third column shows each candidate’s position in the subtraction ($\text{PSF} - \text{residual}$) image. The lack of any flux above the noise proves that the PSF extraction was satisfactory.
We also approximated an instantaneous burst/simple stellar population (SSP) by using an exponentially decaying SFR with $\tau = 10^7$ yr, and a constant SFR with $\tau = 4 \times 10^9$ yr. We included dust via the Calzetti dust extinction law (Calzetti et al. 1994), which is applicable to starburst galaxies, using the range $0 \leq A_{1200} \leq 2$. Galactic dust was included from the method of Schlegel et al. (1998) with a value of $E(B-V) = 0.009$ mag.

We include intergalactic medium (IGM) absorption via the prescription of Madau (1995).

The BC03 models do not tabulate any emission lines, but in order to model the dusty scenario we needed to include the Ly$\alpha$ emission line. We derived the Ly$\alpha$ line flux from the number of ionizing photons output for each model, assuming case B recombination (see Finkelstein et al. 2007 for details). Some of our

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**TABLE 1**

Ly$\alpha$ Galaxy Candidates

| Name       | $m_{AB}$ (NB656) | $m_{AB}$ (F606W) | Rest EW ($\lambda$) | Spectroscopic Confirmation |
|------------|------------------|------------------|---------------------|---------------------------|
| Object 1   | 24.03            | 26.49            | 189.7 ± 46.8        | ~4.4                      |
| Object 2   | 24.15            | 26.52            | 166.6 ± 42.9        | ~4.4                      |
| Object 3   | 23.50            | 24.84            | 52.8 ± 5.9$^a$      | AGN at $z = 3.19$         |
| Object 4   | 24.08            | 26.37            | 149.1 ± 36.4        | No spectra                |
| Object 5   | 24.48            | 25.89            | 46.9 ± 13.0         | No spectra                |
| Object 6   | 24.24            | 25.81            | 56.3 ± 11.0         | ~4.4                      |

$^a$ Object 3 is a known AGN at $z = 3.19$, and the line we detected in the narrowband filter is [C iv]; thus, the EW for object 3 is the [C iv] rest-frame EW for an object at $z = 3.19$. The calculated rest-frame EWs for the other objects assume a redshift equal to that of Ly$\alpha$ at the center of the H$\alpha$ filter, which is 4.399. Objects 1, 2, 3, and 6 had grism spectra from PEARs; thus, we were able to spectroscopically confirm objects 1, 2, and 6 to be at $z = 4.4$. Object 5 was not confirmed. Object 4 was confirmed to be at $z = 3.19$. Object 3 was confirmed to be an AGN at $z = 3.19$.
objects showed a stronger 3.6 μm flux than would have otherwise been expected. At z = 4.4, the Hα emission line would fall in this filter, so we also included an Hα emission line in the models (assuming case B recombination, the Hα line strength is 0.112 times the Lyα line strength; Kennicutt 1983).

In order to model the clumpy dust scenario, we needed to ensure that the Lyα line did not suffer dust attenuation. To do this, the continuum flux (and Hα flux) was multiplied by the Calzetti dust law before we added in the Lyα flux to the spectrum at the correct wavelength bin. In this case, the continuum suffers dust attenuation while the Lyα line does not. Lyα sits right at a step function in the Madau IGM treatment, so the amount of attenuation applied to Lyα depends strongly on the exact wavelength position of the Lyα line. The accepted interpretation is that the internal kinematics of a given galaxy will result in half of the Lyα flux coming out slightly blue of the rest wavelength, and half slightly red. This results in the characteristic asymmetric profile of the Lyα observed in many spectra, where the blue side is truncated. We approximate this interpretation by attenuating the Lyα line to be approximately half of its original (postdust where applicable) flux.

In order to go from the BC03 output flux to bandpass-averaged fluxes, we used the method outlined by Papovich et al. (2001). In short, we took the output from BC03, and converted it from L_{Lyα} into L_{Lyα}, and then from L_{Lyα} into F_{Lyα} units of ergs s^{-1} cm^{-2} Hz^{-1} using F_{Lyα} = (1+z)L_{Lyα}/(4πd^2) to do the conversion and redshift the spectrum. This flux was then multiplied by the transmission function for a given bandpass (including the filter transmission and the quantum efficiency of the detector), and integrated over all frequencies. The bandpass-averaged flux (F_{Lyα}) is this result normalized to the integral of the transmission function. AB magnitudes (Oke & Gunn 1983) for the models were then computed.

### 3.2. Dust Effects on the Lyα EW

The scenario we are probing observationally is whether or not dust could enhance the Lyα EW. Traditionally, it has been thought that Lyα galaxies could possibly be too primitive to have formed dust yet. However, some evidence does exist that would enable a galaxy to form dust quickly. Massive stars evolve on a very short timescale, so after a few Myr, a galaxy could begin to have some heavier elements in its ISM. Also, supernovae metallicity and CO emission have been seen in quasars at z ~ 6 (Pentericci et al. 2002; Bertoldi et al. 2003), and Lyα emission has been seen in submillimeter-selected galaxies (Chapman et al. 2004).

However, even if Lyα galaxies did have dust, it has been thought that it would vastly attenuate the Lyα flux (Meier & Terlevich 1981). Lyα photons have long scattering path-lengths, making them extremely vulnerable to dust attenuation, assuming a uniform distribution of dust. It is possible that dust could be geometrically distributed such that the Lyα photons are attenuated less than the continuum. The most likely of these scenarios involves an ISM with clumpy dust clouds thoroughly mixed with neutral hydrogen with an intercloud medium which is tenuous and ionized (Neufeld 1991; Hansen & Oh 2006). Evidence for the possible existence of this scenario also comes from Giavalisco et al. (1996), who find a lack of correlation between UV slope and Lyα EW, meaning that a UV slope indicative of dust does not necessarily mean a low Lyα EW. They conclude that the ISM in their sample of galaxies is highly inhomogeneous, and that the transport of Lyα photons is primarily governed by the geometry of the ISM rather than the amount of dust.

This is intriguing, because if Lyα galaxies had a dusty, inhomogeneous ISM then it is possible that the continuum photons were attenuated and the Lyα photons were not. Then the observed EW would be greater than the EW intrinsic to the underlying stellar population by a factor relating to the amount of dust present. To better understand this, we will follow the journey of a photon through an ISM, starting from the point when it is emitted from a massive star. This star will emit numerous ionizing photons, 2/3 of which will become Lyα photons assuming case B recombination. When a Lyα photon encounters a region of dust mixed with neutral hydrogen, it has a very high probability of being absorbed by the first hydrogen atom it encounters. It will then be reemitted in a random direction, with an equal probability of being sent back the way it came as being sent forward in its original direction of travel. If the ISM is uniformly distributed, the Lyα photon will only move a short distance before it is absorbed again, making it take a very long time for a given Lyα photon to escape the galaxy. If the ISM is composed of clouds in a nearly empty intercloud medium, then when a Lyα photon is emitted back out of the clump, it will travel a long distance before it encounters another clump, vastly increasing the probability that it will escape the galaxy. Even if it is reemitted in the direction further into the clump, it will still be scattered close to the surface, so it still has a chance to escape.

However, continuum photons in a homogeneously distributed ISM will be absorbed by dust as they travel through the ISM, but since their wavelengths are continuously distributed they will essentially not be affected by the presence of neutral hydrogen. The same holds true in a clumpy ISM. A continuum photon will be able to “bypass” the hydrogen in the clump until it encounters a dust grain, at which point it could either get scattered or absorbed. If the continuum photon is absorbed, it will eventually be reemitted, but its wavelength will have changed to the far-IR. The net effect of this is to lower the amount of continuum flux escaping the galaxy (as well as to redden the flux due to those

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**TABLE 2**

**Magnitudes of Lyα Galaxy Candidates**

| Name | IAU Format Name | m_{B} | m_{g} | m_{V} | m_{F} | m_{C11} | m_{C12} |
|------|-----------------|-------|-------|-------|-------|---------|---------|
| Object 1 | J033215.991−274235.57 | 24.03 ± 0.09 | 29.54 ± 1.33 | 26.49 ± 0.14 | 25.70 ± 0.10 | 25.95 ± 0.17 | 25.20 ± 0.14 | 25.64 ± 0.36 |
| Object 2 | J033239.771−275114.95 | 24.15 ± 0.11 | 98.95 ± 98.91 | 25.62 ± 0.14 | 25.52 ± 0.09 | 25.61 ± 0.10 | 25.24 ± 0.12 | 25.92 ± 0.36 |
| Object 3 | J033242.838−274702.53 | 23.50 ± 0.05 | 26.20 ± 0.08 | 24.84 ± 0.06 | 24.83 ± 0.08 | 24.87 ± 0.07 | 23.09 ± 0.01 | 23.02 ± 0.02 |
| Object 4 | J033258.380−275339.58 | 24.08 ± 0.11 | 30.40 ± 3.10 | 26.37 ± 0.13 | 25.54 ± 0.09 | 25.70 ± 0.11 | 24.89 ± 0.13 | 24.92 ± 0.21 |
| Object 5 | J033224.227−274124.48 | 24.45 ± 0.17 | 98.95 ± 98.91 | 25.89 ± 0.10 | 25.10 ± 0.09 | 24.84 ± 0.08 | 23.09 ± 0.02 | 24.23 ± 0.10 |
| Object 6 | J033248.244−275136.90 | 24.24 ± 0.12 | 98.95 ± 98.91 | 25.81 ± 0.09 | 24.96 ± 0.10 | 24.82 ± 0.07 | 24.16 ± 0.05 | 24.93 ± 0.16 |

* 3σ upper limits. Coordinates and magnitudes for each of our candidate Lyα galaxies. Each magnitude has been corrected to represent the total magnitude for the object.

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The probability of a Lyα photon being absorbed in a clump is \( \approx 2/\epsilon \), where \( \epsilon \) is the single scattering albedo (Hansen & Oh 2006). This is valid for \( \epsilon \ll 1 \), where \( \epsilon = 0 \) signifies complete reflectance.
photons which are scattered rather than absorbed). Thus, a clumpy ISM could result in a higher Lyα EW than the underlying stellar population.

It has been generally believed that Lyα galaxies are very young, primitive objects. If we find proof that an object shows dust enhancement of the Lyα EW, it could turn out that some fraction of Lyα galaxies known to exist could in fact be older, more evolved stellar populations, changing our view of where Lyα galaxies belong in the galactic zoo.

3.3. IGM Inhomogeneities

Although differences in the IGM can affect the models in the V band, we chose to include this band in our fits. The V band is complicated, as at \(z = 4.4\) it contains the entire Lyα forest region from the Lyman limit out to Lyα. To account for inhomogeneities in the IGM, we chose to include a flux variance for the model V-band flux (this results in a second parameter in the denominator for the V-band \(\chi^2\) term; see §4.1). To account for IGM absorption in our models, we have attenuated the cumulative flux which comes out of BC03 by a factor of \(\exp(-\tau_{IGM})\), such that the bandpass-averaged flux in the V band is given by

\[
\langle f_V \rangle = \int_{\lambda_1}^{\lambda_2} f_{BC03,V} \cdot \exp(-\tau_{IGM}) d\lambda,
\]

where \(f_{BC03,V}\) is the initial output of the models and \(\tau_{IGM}\) is the 1σ error in the IGM optical depth due to inhomogeneities among different lines of sight. We can then break this up into a sum over discrete intervals, and calculate the variance, which for a small \(\tau_{IGM}\) is

\[
\sigma^2_{\langle f_V \rangle} = \sum_{n=1}^{N} \frac{\int_{\lambda_1}^{\lambda_2} f_{BC03,V} (e^{-\tau_{IGM}})^2 \Delta \lambda^2}{\sum_{n=1}^{N} \frac{\int_{\lambda_1}^{\lambda_2} f_{BC03,V} \Delta \lambda^2}{N^2 (e^{-\tau_{IGM}})^2}},
\]

where \(N\) is the number of bins we chose to break the V band into. We approximate this as

\[
\sigma^2_{\langle f_V \rangle} \approx N \langle \tau_{IGM} \rangle^2 \frac{\int_{\lambda_1}^{\lambda_2} f_{BC03,V} \Delta \lambda^2}{N^2} (e^{-\tau_{IGM}})^2,
\]

where \(F^2_{BC03,V}\) is the total flux in the bandpass. The rms flux in the V band due to the IGM inhomogeneities is then

\[
\sigma = F_{BC03,V} e^{-\tau_{IGM}} N^{-\frac{1}{2}}.
\]

Thus, the fractional error in the model flux which needs to be added in is \(\delta \tau \times N^{-\frac{1}{2}}\). To make this physically correct, the bin size should be equal to a typical clustering length for Lyα forest clouds such that the Lyα forest optical depth variations in adjacent bins are essentially uncorrelated. Penton et al. (2000) calculated the two-point correlation function for Lyα forest clouds. They found that the correlation drops to zero at a separation of \(\sim 11\) Mpc. For \(z = 4.4\), the co-moving distance between the front and back of the V-band filter is 1205 Mpc; thus, we chose to use 110 bins. The uncertainty in the IGM absorption \(\delta \tau\) was found from Madau (1995). Extrapolating from his example of \(az \sim 3.5\) galaxy, we found an uncertainty in \(\exp(-\tau)\) of \(\sim 0.35\), which corresponds to \(\delta \tau \sim 1.05\). Plugging these values into the above equations, we find that we need to include an error of \(\sim 0.1\) mag for the V-band model fluxes to account for inhomogeneities in the IGM.

3.4. Equivalent Widths

Model Lyα equivalent widths were calculated using the ratio of the model flux in the Lyα wavelength bin to the average continuum value on either side of that bin \((\times \Delta \lambda)\). We compare our model EW distribution to previous studies (i.e., Charlot & Fall 1993; MR02). We also quantify the multiplicative effect adding clumpy dust to the models has on the Lyα EW.

Figure 4 shows the EWs of our models plotted versus stellar population age for \(Z = 0.02\) Z⊙ and three different star formation rates: SSP (single burst), \(\tau = 10^7\) (exponentially decaying), and a constant star formation rate. We first discuss the results from the left-hand vertical axis, which shows the EWs from dust-free models. All of the models start at some value \((\sim 400\, \text{Å})\) at \(10^8\) yr and then decay from there. The EWs from the SSP and \(\tau\) models fall all the way to zero at approximately 30 and 100 Myr, respectively. Models which are constantly forming stars asymptotically reach a constant value of EW at \(\sim 120\, \text{Å}\) due to the constant replenishment of massive stars. The upturn at later ages for the SSP and \(\tau\) models are due to either hot horizontal branch stars and/or planetary nebula nuclei, which will start to dominate the UV flux after \(\sim 10^8\) yr. While technically the Lyα EW will be high, the actual UV continuum flux is tiny compared to what it was at earlier ages, and thus objects in this stage will likely not appear in Lyα galaxy samples. We calculate that at 400 Myr (the age at which the UV-upturn causes the EW to surpass a single 50 Å) a mass in excess of \(10^{12}\, M_\odot\) would be required in order for a given stellar population to be detected in our narrowband image. This mass is extremely high even in local universe terms (e.g., Tremonti et al. 2004), and thus is not likely to exist at high redshift. In order to distinguish EW due to young stars from EW due to faint UV continuum flux, the solid lines in these plots change to dashed lines when the continuum (V band) flux falls to 10% of its value at \(10^8\) yr.

Charlot & Fall (1993) computed the Lyα EW from stellar population models using an earlier version of the Bruzual & Charlot (1993) software. Their models assumed solar metallicity and case B recombination. They computed the Lyα EW for multiple...
Our continuously star-forming models start at a maximum EW of 300 \( \mu m \), falling to zero by 10\(^8\) yr for an SFR, upper mass cut-off of 80 (120) \( M_\odot \). Our continuously star-forming models start at a maximum EW of 400 \( \mu m \) (\( \sim 200 \) \( \mu m \) at 5 Myr), much closer to the results of Charlot & Fall. For a constant SFR, Charlot & Fall find a maximum Ly\(\alpha\) EW of 150 (250) \( \mu m \), falling to a constant value of 90 (100) \( \mu m \) by 10\(^8\) yr for an upper mass cut-off of 80 (120) \( M_\odot \). Our continuously star-forming models start at a maximum EW of \( \sim 400 \) \( \mu m \) (\( \sim 220 \) \( \mu m \) at 5 Myr), falling to 120 \( \mu m \) by 10\(^8\) yr. Taking into account the differences between IMF slopes, metallicities, and upper mass cut-offs, we feel our constant SFR models are consistent with those of Charlot & Fall. In a more recent study, MR02 did a similar analysis using Starburst99 models (Leitherer et al. 1999). Their Salpeter IMF model has a constant SFR, upper mass cut-off of 120 \( M_\odot \), and \( Z = 0.05 \) Z\(_\odot\). The EW from this model had a maximum value of 300 \( \mu m \) at an age of 1 Myr, asymptoting to a value of 100 \( \mu m \) by 100 Myr, both of which are consistent with our models.

When clumpy dust comes into the models, things can change dramatically. As we discussed above, in our models the dust is not attenuating the Ly\(\alpha\) line, which results in the Ly\(\alpha\) EW being enhanced as the continuum is suppressed. Consequently, given an amount of dust extinction, the Ly\(\alpha\) EW will be enhanced by a multiplicative factor. For dust amounts of \( A_{1200} = 0.5, 1.0, 1.5, \) and 2.0 this factor is 1.64, 2.68, 4.40, and 7.21, respectively. The right-hand vertical axis in Figure 4 shows what the EWs from the models are with 2.0 mag of clumpy dust extinction. What this tells us is that for a given model, you can go out to a larger age while still keeping a high EW. For example, for a SSP with \( Z = 0.02 \) Z\(_\odot\), the EW drops below 200 \( \mu m \) by 3 Myr, while with 2.0 mag of clumpy dust, this does not happen until after 10 Myr, over a factor of 3 times longer, making it much more likely that this object would be observed with a high EW in a narrowband-selected survey. Table 3 shows the maximum possible age allowed for a stellar population with EW < 200 \( \mu m \) for a variety of models.

### TABLE 3

| SFR | No Dust (Myr) | \( A_{1200} = 2.0 \) (Myr) |
|-----|---------------|-----------------------------|
|     | \( Z = 0.02 \) Z\(_\odot\) | \( Z = Z_\odot\) | \( Z = 0.02 \) Z\(_\odot\) | \( Z = Z_\odot\) |
| SSP | 3 (182 \( \mu m \)) | 1 (193 \( \mu m \)) | 10–20 (222–34 \( \mu m \)) | 5–6 (424–181 \( \mu m \)) |
| \( \tau = 10^7 \) | 7 (184 \( \mu m \)) | 3 (186 \( \mu m \)) | 50–60 (291–167 \( \mu m \)) | 50–60 (300–193 \( \mu m \)) |
| Constant SFR | 8 (193 \( \mu m \)) | 3 (190 \( \mu m \)) | Never | Never |

Notes—Values in parenthesis are the equivalent widths at the reported ages. Since the grid of model ages is not continuous, in some cases there is a large amount of time around when the EW drops below 200 \( \mu m \) in the models. In these cases we report the ages and EWs on either side of 200 \( \mu m \). Depending on the SFR and metallicity, two magnitudes of clumpy dust extinction can keep the Ly\(\alpha\) EW above 200 \( \mu m \) up to 3–20 times longer than just young stars alone (indeed for a population which suffers no drop in star formation activity). Models with dust have \( q = 0 \).

IMF slopes, upper mass cut-offs, and star formation rates, with their youngest age being 5 Myr. For a SSP with a near-Salpeter IMF (\( x = 1.5, x_{\text{Salpeter}} = 1.35 \)), their maximum EW was calculated to be 210 (240) \( \mu m \) for an upper mass cut-off of 80 (120) \( M_\odot \), falling to zero at 40 Myr. The EWs from our SSP model have a maximum value of 400 \( \mu m \) (only \( \sim 100 \) \( \mu m \) at \( \tau = 5 \) Myr), falling to zero by \( \sim 20–30 \) Myr. However, their definition of SSP differs from ours. We defined ours as having a characteristic decay rate of 10\(^3\) yr, while their burst model had a timescale of 10\(^7\) yr. We can thus compare their results to our \( \tau \) model (which has \( \tau = 10^7 \) yr). This model has a maximum EW of 400 \( \mu m \) (\( \sim 200 \) \( \mu m \) at 5 Myr), much closer to the results of Charlot & Fall. For a constant SFR, Charlot & Fall find a maximum Ly\(\alpha\) EW of 150 (250) \( \mu m \), falling to a constant value of 90 (100) \( \mu m \) by 10\(^8\) yr for an upper mass cut-off of 80 (120) \( M_\odot \) (our upper mass cut-off was 100 \( M_\odot \)).

Out of our five Ly\(\alpha\) galaxy candidates, we only fit stellar population models to four of them. While we have no reason to suspect object 5 is not a real Ly\(\alpha\) emitter, its proximity to a very bright object makes its Spitzer fluxes inaccurate. Only with the ACS and narrowband data to go on, there are not enough available passbands to fit this object. Thus, the four objects which we fit were 1, 2, 4, and 6. We did have data in all nine bands listed above, not all were used in our fitting. Both the IRAC 5.8 and 8.0 \( \mu m \) were undetected in the four objects we fit, and thus were not used. Because the entire \( B \) band is blueward of the Lyman break, we can be highly confident that on any line of sight there will be no significant flux transmitted through the \( B \) band. If redshift were a free parameter in our models, then we would definitely use the \( B \) band, as the absence of flux would be a helpful redshift indicator. However, given that three of our four objects were spectroscopically confirmed (and the fourth has a photo-z) to be at \( z = 4.4 \), we did not feel it would be worthwhile to introduce redshift as a free parameter. Thus, we have left the \( B \) band out of the fitting.

As a final step, we introduced a parameter, \( q \), which we called the geometry parameter because its value simulates the effects of different dust geometries. Previously, when we applied dust to the models we added in the Ly\(\alpha\) flux after the dust was added; that way, the Ly\(\alpha\) flux was not attenuated. This had a very “cartoon” effect on the models, meaning that Ly\(\alpha\) was attenuated by either all of the dust or none of the dust. We still do things in the same order as before, only now we multiplied the Ly\(\alpha\) flux by \( e^{-q \times \tau} \), with \( q \) ranging from 0 to 10. A \( q \)-value of zero represents exactly...
what our original models had been doing, namely, not attenuating Ly$\alpha$ by dust. This models the dust geometry of clumpy clouds in an empty intercloud medium, i.e., Neufeld (1991) and Hansen & Oh (2006). A $q$-value of 10 attenuates Ly$\alpha$ 10 times more than the continuum. Thus, $q \geq 10$ models the effects of a uniform dust distribution, attenuating Ly$\alpha$ much more than the continuum due to the fact that it is resonantly scattered. Values between 0 and 10 model differing geometries, with the case of $q = 1$ modeling a geometry where Ly$\alpha$ and the continuum are attenuated at the same rate (possibly a scenario with dust in clouds but in which the intercloud medium is not entirely empty). Introducing this parameter vastly increased the quality of the best fits, but it did come at a cost. Since we had no additional data, we could not add another free parameter without taking away one. We decided to remove metallicity as a free parameter, as the effects of changing metallicity had the least effect on the models. We decided to fix a value of $Z = 0.02 Z_{\odot}$ for all models.

4.2. Object 1

Object 1 is best fit by a 5 Myr stellar population with a mass of $3.0 \times 10^{6} M_{\odot}$, a continuous star formation rate, and 1.1 mag of dust extinction ($A_{1200}$) which attenuates Ly$\alpha$ 50% more than the continuum ($q = 1.5$). The quality of this fit was high, with $\chi^{2} / C_{11} = 2.00$. This object is thus very young, but its red color (specifically, $z' - 3.6 \, \mu m$) indicates a significant amount of dust. However, an object this young, especially with a continuous SFR, already has a pretty high Ly$\alpha$ EW. Thus, even though it is best fit by a significant amount of dust, it does not require this dust to enhance its EW, as evidenced by its value of $q > 1$. This object fits the mold of a “typical” Ly$\alpha$ galaxy, as it is young and of low mass. This being said, its dust content is intriguing, as it indicates that this object is definitely not primitive.

4.3. Object 2

Object 2 is also best fit by a young, low-mass stellar population ($3 \, Myr; 3.2 \times 10^{6} M_{\odot}$); however, it has a fast-decaying SFR, with $\tau = 10^{6} \, yr$. It has less dust than object 1 ($A_{1200} = 0.9 \, mag$), but a larger value of $q$, with $q = 2$, indicating that Ly$\alpha$ is being extinguished at twice the value of the continuum. However, we can be somewhat skeptical about these results, as this object has the worst fit out of our sample, with $\chi^{2} / C_{11} = 5.269$. That being said, these results are not astonishing, as they indicate that this object is possibly very similar to object 1.

4.4. Object 4

Object 4 is the most intriguing object in our sample. It has the best fit of the whole sample, with $\chi^{2} / C_{11} = 1.326$, lending the most credulity to its results. It is best fit by an 800 Myr, $6.5 \times 10^{9} M_{\odot}$ stellar population with a continuous SFR. While the amount of dust extinction is lower than the other objects ($A_{1200} = 0.4 \, mag$), it has a value of $q = 0$, the only object with $q < 1.5$. While 0.4 mag of dust is not a lot, if it is not attenuating Ly$\alpha$, as $q = 0$ attests to, it will increase the EW by ~50%, making this object a candidate for dust enhancement of the Ly$\alpha$ EW. This object definitely does not fit the mold of a typical Ly$\alpha$ galaxy with its old age and larger mass. Although we only have one object like this in our small sample, its existence means that Ly$\alpha$ galaxies may not all be uniformly young.

4.5. Object 6

Similar to objects 1 and 2, object 6 is also best fit by a young (3 Myr) and low-mass ($9.9 \times 10^{5} M_{\odot}$) stellar population. It has an exponentially decaying SFR with $\tau = 10^{6} \, yr$ and 1.8 mag of dust attenuating Ly$\alpha$ 50% more than the continuum. The best-fit model ($\chi^{2} = 2.121$) has a low EW of ~61 Å, which is very comparable to the measured EW of the object, which was ~56 Å. Although this object has a young age, its fast-decaying SFR and large amount of dust which is attenuating Ly$\alpha$ are keeping the Ly$\alpha$ EW down. Figure 5 shows the best-fit models for each object, and Table 4 details the best-fit parameters.

4.6. Best-Fit Models Without Dust

As an exercise, we wanted to see what the best-fit models to these objects would be if we forced the amount of dust to be zero while keeping everything else the same. In doing this, the number of degrees of freedom became three, because both dust and $q$ were dropped as free parameters; thus, the reduced $\chi^{2}$ reported is $\chi^{2}/N$. Figure 6 shows the results of this analysis. With no dust, all of the objects were forced to have an older age to explain the red colors. In all cases, the best fit model with no dust had a significantly higher $\chi^{2}$ than the best-fit model allowing dust; thus, we can be reasonably sure that these objects have some dust, and that we have treated it correctly in the models.

4.7. Monte Carlo Analysis

To determine confidence regions for our model parameters, we ran $10^{4}$ Monte Carlo simulations. In each simulation, we add or subtract flux to each band for each object equal to a Gaussian random deviate multiplied by the object’s flux error in a given band. Each band had its own random number in each simulation, which was computed by the IDL function RANDOMN, which generates Gaussian-distributed random numbers. For each possible model (25,200 possible models; 5 SFRs, 24 ages, 21 dust optical depths, and 10 values of $q$), the $\chi^{2}$ was computed for each simulated object flux. The result was that for each object, we now had 10,000 best-fit models. In an ideal case, these models would be distributed around the best-fit parameters to the actual observations.

In order to see if this was true, we plotted contours showing the density of best-fit parameters for each object in three planes: dust versus age, dust versus $q$, and age versus $q$ (Fig. 7). The blue, green, and red contours show the 1σ (68%), 2σ (95%), and 3σ (99.5%) confidence levels, respectively. For object 1, it appears as if the age is well constrained to be very young, as the 1σ contour is fairly thin along the age axis. The same is true for $q$, constraining it to be between 1 and 3, ruling out dust enhancement of the Ly$\alpha$ EW for this object. The only parameter that may be degenerate is dust, as the 1σ contour is very long along the dust axis. However, in no case is any model best fit with zero dust, and the 1σ contour is roughly centered on the best-fit value of $A_{1200} = 1.1$.

Object 2 is very similar to object 1 in that its age is well constrained to be young, and its $q$-value is well constrained to be greater than 1. Similarly, the dust in object 2 is slightly degenerate, but it is well constrained to have some dust, with the best-fit value being the most likely value. The age of object 6 is also well constrained to be young, although there is a slight 1σ blip at $t = 100 \, Myr$. The $q$-value is even better constrained than in objects 1 or 2, being very centered on the best-fit value of 1.5. Dust attenuation
is still degenerate, although less so than in objects 1 or 2, with 1σ values ranging from 1.5 to 2.0 mag.

Object 4 is the only object in our sample which shows evidence of dust enhancement of the Lyα EW. The age is mostly constrained to be >100 Myr, with a large 1σ area centered around the best-fit model at 800 Myr, and a smaller 1σ area around 200 Myr (and an even smaller one at 30 Myr). A range of dust values are permitted, but generally lie in the range from 0.1 to 0.9 mag. The q-parameter is definitely constrained to be <1, with

### Table 4

| Name     | Age (Myr) | Mass (M⊙) | A1200 (mag) | SFR   | q      |
|----------|-----------|-----------|-------------|-------|--------|
| Object 1 | 2.000     | 5         | 3.00 × 10⁴  | Continuous | 1.50   |
| Object 2 | 5.269     | 3         | 3.15 × 10⁵  | τ = 10⁶  | 2.00   |
| Object 3 | 1.326     | 800       | 65.39 × 10⁷ | Continuous | 0.00   |
| Object 6 | 2.121     | 5         | 9.85 × 10⁴  | τ = 10⁴  | 1.50   |

**Notes.**—The best-fit parameters for each of our objects. These were found by minimizing the reduced χ² between each object and a grid of models.

5. DISCUSSION

5.1. Lyα Detection Fraction

Out of the whole GOODS CDF-S catalog, we found that there were 229 B-band dropouts. The dropout criteria selects galaxies with a Δz range of ~1.0. The width of our narrowband filter is 80 Å around a central wavelength of 6563 Å, corresponding to a
Δz range of 0.07 for Lyα. Thus, about 0.07 × 229 = 16 B dropouts lie in the redshift range where we could detect Lyα. Among these, only five show a narrowband excess. This corresponds to a Lyα detection fraction of 31%, comparable with previous studies (e.g., Shapley et al. 2003; 25%).

### 5.2. Hα Equivalent Widths

When comparing the best-fit models to the data points, it is obvious that the model Hα flux is dominating the model 3.6 μm flux, as is evident from the fact that the 3.6 μm data point is far above the model continuum level. The model rest-frame Hα EWs are 3800, 8500, 200, and 1700 Å for objects 1, 2, 4, and 6, respectively. At first glance, these seem large, but one needs to remember that with the exception of object 4, these objects have been found to be extremely young, low-mass, star-forming galaxies. Keeping that in mind, these values of Hα EW are quite reasonable.

In a survey of H ii regions in a nearby galaxy, Cedres et al. (2005) found that the Hα EW distribution peaked at ~1000 Å, with a few H ii regions with EWs as high as 10000 Å. In an analysis of a z = 6.56 Lyα galaxy, Chary et al. (2005) derived an Hα EW of 2000 Å, concluding that the Hα line dominated the 4.5 μm flux in their object. While computing the synthetic properties of starburst galaxies, Letherer & Heckman (1995) computed a Hα EW of ~3200 Å for a population with 0.1 Z⊙ and a constant star formation rate. Taking into account model differences (including a difference of 5 times in metallicity), we find our values of the Hα EW consistent with those previously found in the literature for star-forming galaxies.

The addition of Hα flux to the model spectra led to an interesting result. In a young star-forming galaxy both Lyα and Hα photons will be produced in large quantities, thus producing the large Lyα and Hα EWs seen in objects 1, 2, and 6. However, if the Lyα EW is only observed as being large due to dust enhancement, there is no reason why the Hα EW should be large (as Hα photons are not resonantly scattered). This is seen in our sample, as object 4 has a best-fit Hα EW of only 200 Å, much less than the other three objects. Thus, obtaining data about Hα lines in Lyα galaxies could be a very important diagnostic tool for deciphering the underlying stellar population, as the Lyα-Hα ratios should indicate whether dust enhancement is playing a role. This tool will be a prime candidate for study on future observatories such as the James Webb Space Telescope (JWST) or the Stratospheric Observatory for Infrared Astronomy (SOFIA).

### 5.3. Comparison to Other Work

It is useful to compare our results to those of other studies done using HST and Spitzer data together, as the IR data (which corresponds to the rest-frame optical at z = 4.4) better constrains the stellar masses as it is less attenuated by dust than the rest-frame UV. Two recent studies have been published studying Lyα-emitting
galaxies (LAEs) at $z \sim 5$ and 5.7 by Pirzkal et al. (2007) and Lai et al. (2007), respectively. Pirzkal et al. studies the stellar populations of nine LAEs in the HUDF detected on the basis of their \textsc{Ly}α emission lines in the Grism ACS Program for Extragalactic Science (GRAPES; Pirzkal et al. 2004; Xu et al. 2007; Rhoads et al. 2008) survey. Using stellar population models similar to ours, they found very young ages ($\sim 10^6$ yr) and low masses ($\sim$ few $\times 10^7 M_\odot$), with some dust in a good fraction of their objects. Lai et al. studied three narrowband-selected LAEs spectroscopically confirmed to lie at $z \sim 5.7$ in the GOODS HDF-N field. Also using BC03 models, with an instantaneous burst they found ages from 5 to 100 Myr (up to 700 Myr with a constant SFR), and

**Fig. 7.**—Contours showing the density of results of our Monte Carlo simulations. Each asterisk represents the best fit of one Monte Carlo run (most of the asterisks are really multiple points). The rest of the model grid which did not have a best fit are denoted by dots. The best-fit model from the actual object is denoted by a triangle. The four objects are in the four rows, and the columns represent three different planes: dust vs. age, dust vs. $q$, and age vs. $q$ (note that the range of the age axis is different for some of the objects). Sixty-seven percent of the best fits from the simulations fall in the black contour, and as such this is the 1σ contour. Likewise, the dark grey is the 2σ contour, and the light grey is the 3σ contour. The cross-hatched region represents the area of parameter space where we would not expect to detect an object due to dust extinction. Models falling in this region had their $V$- or NB656-band flux reduced to less than a third of that of the best-fit model. Studying these figures, we were satisfied that our best-fit models accurately represented the most likely best fit for each object. [See the electronic edition of the Journal for a color version of this figure.]
masses from $10^9$ to $10^{10} \, M_\odot$. Their objects were also best fit by dust, with $E(B-V) \sim 0.3$–0.4.

Three of our four objects have ages consistent with those from Pirzkal et al. (2007) and Lai et al. (2007), who find ages from ~1 to 100 Myr. Our fourth object has an age much larger than those found in these papers, at 800 Myr. Eight out of the nine Pirzkal et al. objects have $M < 10^9 \, M_\odot$, whereas the Lai et al. objects have masses 2 orders of magnitude higher. The masses of our objects reside in the middle, from $10^8$ to $10^9 \, M_\odot$. The likely reason that our masses are higher than those of Pirzkal et al. is because they reach fainter luminosities, detecting objects with emission lines as faint as $5 \times 10^{-18} \, \text{erg cm}^{-2} \, \text{s}^{-1}$. On the flip side, the larger masses from Lai et al. are likely due to their selection criteria. They found 12 LAEs in the GOODS-N field, but they only analyzed the three objects with significant 3.6 and 4.5 \, \mu m flux. They acknowledge that their masses are high, and that this may be due to selecting objects from the high-mass end of the mass distribution.

Another difference is how each study treated Ly$\alpha$ in their model fitting. Pirzkal et al. chose to exclude the ACS $i'$ band from their fitting, as at their redshifts the Ly$\alpha$ line would fall in this band, and they did not want to include the uncertainties that subtracting the line flux from the $i'$ flux would create. Lai et al. (2007) chose to treat Ly$\alpha$ by estimating the amount of flux Ly$\alpha$ contributed to the $i'$ flux, then adding this percentage as an $i'$-band error (~30%). As described in detail in earlier sections, we chose to add the Ly$\alpha$ emission to the models in order to investigate the effect dust had on the Ly$\alpha$ EW. While each of these methods has its merit, the method of Pirzkal et al. likely introduces the least amount of uncertainty by simply not including the broadband which contains the Ly$\alpha$ emission. They had the luxury that in addition to the ACS and IRAC data, they also had HST NICMOS and VLT ISAAC near-IR data, so cutting a band from the fitting did not force them to throw out a constraint.

One other interesting study is that done by Chary et al. (2005) by fitting stellar population models to a $z = 6.56$ Ly$\alpha$ galaxy with near-IR and IRAC data. As we mentioned above, they determined that their 4.5 \, \mu m flux was dominated by a H$\alpha$ line, implying vigorous star formation. Taking this line into account, they found a best-fit stellar population of 5 Myr, $8.4 \times 10^8 \, M_\odot$ with $A_T = 1.0$ mag. This is even dustier than our objects, showing that not only is dust common at $z = 4.4$, it may exist in Ly$\alpha$ galaxies up to $z \sim 6.5$.

By including Ly$\alpha$ in our models rather then attempting to subtract out its influence in the observed broadbands, we were able to investigate the effect dust geometry had on the Ly$\alpha$ EW. While the other two studies listed here did not do this analysis, they did include homogeneous dust in their models. They found that many/all of their objects were best fit by including at least a small amount of dust. This confirms our result that regardless of the effect of the dust geometry, one needs to include dust when analyzing LAEs, as it appears to be present in a majority of them. Failure to include dust in the models will result in a poorer fit, likely with an older or more massive stellar population than is really in place.

6. CONCLUSION

We have presented the results of our analysis of four narrowband-selected Ly$\alpha$ galaxies in the GOODS CDF-S. By observing in such a well-studied field, we were able to take advantage of the plethora of deep public broadband data (GOODS HST ACS, Spitzer IRAC, and MUSIC), as well as previous spectroscopic studies (PEARS) available in the region. Three out of our four objects were spectroscopically confirmed to lie at $z = 4.4$. The other object has a photometric redshift of 4.42.

Previously, it has been assumed that Ly$\alpha$ galaxies were young, low-mass galaxies with little to no dust. Even when dust has been found, it has been assumed to be homogeneously distributed, meaning that it would attenuate the Ly$\alpha$ flux much more than the continuum flux because Ly$\alpha$ photons are resonantly scattered. However, a scenario has been theoretically studied in which the geometry of a dusty ISM could actually enhance the Ly$\alpha$ EW rather than reduce it. This scenario consists of an ISM in which the dust resides in clouds, mixed in with neutral hydrogen, whereas the intercloud medium is hot and ionized. In this scenario, Ly$\alpha$ photons would effectively bounce off the surface of the clouds, finding it much easier to escape the galaxy than continuum photons. Thus, a galaxy could exhibit a much larger Ly$\alpha$ EW than that intrinsic to the underlying stellar population.

In order to investigate this, we have compared the fluxes of our objects to stellar population models. We have included Ly$\alpha$ emission in the models, as well as introducing a geometry parameter, $q$, which dictates how much Ly$\alpha$ is attenuated by a given dust amount. Three of our four objects were best fit by models with a very young age (~few Myr) and low stellar masses (~few $\times 10^8 \, M_\odot$), with a significant amount of dust ($A_{1200} = 0.9$–1.8) attenuating the Ly$\alpha$ flux more than the continuum ($q = 1.5$–2.0). However, one object, object 4, is best fit by a vastly different model. This object is best fit by a much older, more massive stellar population, with an age of 800 Myr and $M = 6.5 \times 10^9 \, M_\odot$. What is interesting about this object is that its EW is among the highest in our sample. Even with a constant SFR, an 800 Myr stellar population would not be able to produce a Ly$\alpha$ EW above 120 \, Å, while this object has an observed rest-frame EW of ~150 \, Å and a best-fit model EW of ~180 \, Å. Thus, something is causing the EW of this object to be enhanced, and the models tell us that it is due to dust. This object is best fit by $A_{1200} = 0.4$ mag of dust, and while this is less than any of the other objects, the geometry parameter is best fit to be $q = 0.0$. This means that the 0.4 mag of dust are attenuating the continuum, but not the Ly$\alpha$ flux, enhancing the EW by 50\%. Figure 7 shows a fair margin of parameter space is allowed for most objects at the 2–3 \, $\sigma$ level.

Comparing our results to those from other studies, we find that our age and mass results are consistent when data and selection differences are accounted for. However, no other observational studies have yet tried to model the effect dust could have on Ly$\alpha$ for differing geometries. While our sample size is small, analysis of a larger sample could indicate that there are really two classes of Ly$\alpha$ galaxies: a young, low-mass Ly$\alpha$ galaxy with an intrinsically high Ly$\alpha$ EW and an older, higher mass galaxy with a lower intrinsic EW which has been enhanced due to dust.

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