THE PHYSICAL NATURE OF LYMAN ALPHA EMITTING GALAXIES AT $Z = 3.1$

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ABSTRACT

We selected 40 candidate Lyman Alpha Emitting galaxies (LAEs) at $z \simeq 3.1$ with observed frame equivalent widths $>$150Å and inferred emission line fluxes $> 2.5 \times 10^{-17}$ ergs cm^{-2} s^{-1} from deep narrow-band and broad-band MUSYC images of the Extended Chandra Deep Field South. Covering 992 arcmin^2, this is the largest "blank field" surveyed for LAEs at $z \sim 3$, allowing an improved estimate of the space density of this population of $3 \pm 1 \times 10^{-4} h_{70}^{3}$Mpc^{-3}. Spectroscopic follow-up of 23 candidates yielded 18 redshifts, all at $z \simeq 3.1$. Over 80% of the LAEs are dimmer in continuum magnitude than the typical Lyman break galaxy spectroscopic limit of $R = 25.5$ (AB), with a median continuum magnitude $R \simeq 27$ and very blue continuum colors, $(V - z) \simeq 0$. Over 80% of the LAEs have the right UVR colors to be selected as Lyman break galaxies, but only 10% also have $R \leq 25.5$. Stacking the $UBVRIzJK$ fluxes reveals that LAEs have stellar masses $\simeq 5 \times 10^{8} h_{70}^{-2}$ M$_\odot$ and minimal dust extinction, $A_V \lesssim 0.1$. Inferred star formation rates are $\simeq 6 h_{70}^{-2}$M$_\odot$yr^{-1}, yielding a cosmic star formation rate density of $2 \times 10^{-3} h_{70}$M$_\odot$yr^{-1}Mpc^{-3}. None of our LAE candidates show evidence for rest-frame emission line equivalent widths EW$_{rest}$>240Å which might imply a non-standard IMF. One candidate is detected by Chandra, implying an AGN fraction of 2 ± 2% for LAE candidate samples. In summary, LAEs at $z \sim 3$ have rapid star formation, low stellar mass, little dust obscuration and no evidence for a substantial AGN component.[1]

Subject headings: galaxies:high-redshift

1. INTRODUCTION

Because Lyman α emission is easily quenched by dust, the Lyman Alpha Emitting galaxies (LAEs) are often characterized as protogalaxies experiencing their first burst of star formation (Hu & McMahon 1996). However, the differing behavior of Lyman α and continuum photons encountering dust and neutral gas makes it possible for older galaxies to exhibit Lyman α emission when morphology and kinematics favor the escape of these photons (e.g. Haiman & Spaans 1999). Hence the LAEs could instead represent an older population with actively star-forming regions.

LAEs offer the chance to probe the bulk of the high-redshift galaxy luminosity function as the strong emission line allows spectroscopic confirmation of objects dimmer than the continuum limit $R \leq 25.5$. Previous studies of LAEs at $z \sim 3$ have concentrated on known overdensities (Steidel et al. 2000; Hayashino et al. 2004; Venemans et al. 2005) or searches for Lyman Alpha emission near known Damped Lyman Alpha absorption systems (Fynbo et al. 2003, see Wolfe et al. 2005 for a review). Blank fields, i.e. those not previously known to contain unusual objects or overdensities, have been studied at $z = 3.1$ and $z = 3.4$, covering 468 arcmin^2 (Ciardullo et al. 2002) and 70 arcmin^2 (Cowie & Hu 1998; Hu et al. 1998), respectively. Significant work has been done in recent years on large blank fields at higher redshifts to study the LAE luminosity function at $z = 3.7$ (Fujita et al. 2003), $z = 4.5$ (Hu et al. 1998), $z = 4.9$ (Ouchi et al. 2003; Shimasaku et al. 2003), $z = 5.7$ (Martin & Sawicki 2004;Malhotra & Rhoads 2004 and references therein) and $z = 6.5$ (Malhotra & Rhoads 2004). Spectroscopically confirmed samples are small, including 31 LAEs at $z = 3.1$ (Venemans et al. 2005), 18 at $z = 4.5$ (LALA, Dawson et al. 2004) 27 at $z = 5.7$ (Hu et al. 2004; Ouchi et al. 2005), and 9 at $z = 6.6$ (Taniguchi et al. 2005). The current investigation expands upon the blank-field survey of Ciardullo et al. (2002) by covering twice the area to a narrow-band detection limit one magnitude deeper.

The study of Lyman Alpha Emitting galaxies at $z \simeq 3.1$ is a major goal of the Multiwavelength Survey by Yale-Chile (MUSYC, Gawiser et al. 2006, `http://www.astro.yale.edu/MUSYC`). The Ex-

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[1]Based on observations obtained with the Magellan telescopes at Las Campanas Observatory and at Cerro Tololo Inter-American Observatory, a division of the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

tended Chandra Deep Field South (ECDF-S) has been targeted with deep narrow-band imaging and multi-object spectroscopy, complemented by deep broad-band $UBVRIzJK$ and public Chandra+ACIS-I imaging. These multiwavelength data make it possible to study the physical nature of LAEs and to distinguish star formation from AGN as the source of their emission. We assume a ΛCDM cosmology consistent with WMAP results (Bennett et al. 2003) with $\Omega_m = 0.3, \Omega_\Lambda = 0.7$ and $H_0 = 70h_{70}$ km s^{-1} Mpc^{-1}. All magnitudes are given in the AB95 system (Fukugita et al. 1996).

2. OBSERVATIONS

Our narrow-band imaging of the ECDF-S was obtained using the NB5000Å filter (50Å FWHM) with CTIO4m+MOSAIC-II on several nights from 2002 to 2004 for a total of 29 hours of exposure time. Our $UBVRI$ imaging results from combining public images taken with ESO2.2m+WFI by the ESO Deep Public Survey and COMBO-17 teams (Erben et al. 2005; Hildebrandt et al. 2005; Arnouts et al. 2001; Wolf et al. 2004). Our z' imaging was taken with CTIO4m+MOSAIC-II on January 15, 2005. Details of our optical images will be presented in E. Gawiser et al. (in prep.). Our JK images of ECDF-S were obtained with CTIO4m+ISPI on several nights during 2003-2004 and will be described in E.N. Taylor et al. (in prep.). The final images cover $31.5' \times 31.5'$ = 992 arcmin^2 centered on the Chandra Deep Field South and were processed through the MUSYC photometric pipeline to generate APCORR (corrected aperture) fluxes and uncertainties as described in Gawiser et al. (2006). Table 1 gives our source detection depths.

TABLE 1
5σ POINT SOURCE DETECTION LIMITS FOR MUSYC ECDF-S IMAGES IN AB MAGNITUDES.

NB5000	U	B	V	R	I	z′	J	K
25.5	26.0	26.9	26.4	26.4	24.6	23.6	22.7	22.0

Multi-object spectroscopy of 23 LAE candidates was performed with the IMACS instrument on the Magellan-Baade telescope on Oct. 26-27, 2003, Oct. 7-8, 2004, and Feb. 4-7, 2005. The 300 line/mm grism was used with 1.2″ slitlets to cover $4000-9000$Å at a resolution of 7.8Å . Details of our spectroscopy will be given in P. Lira et al. (in prep).

3. CANDIDATE SELECTION

The greatest challenge in selecting Lyman Alpha Emitting galaxies at $z \simeq 3.1$ is to minimize contamination from $z \simeq 0.34$ galaxies exhibiting emission lines in [O II]3727Å . These interlopers can be avoided by requiring a high equivalent width (>150Å in the observed frame) which eliminates all but the rarest [O II] emitters (Terlevich et al. 1991; Stern et al. 2000). Contamination from [O III]5007Å is minimal at these wavelengths, as the volume for extragalactic emitters is small, and Galactic planetary nebulae are very rare at such high Galactic latitude ($b = -54$).

Selecting LAEs requires an estimate of the continuum at the wavelength of the narrow-band filter, so we tested weighted sums of the B and V flux densities and found that $f_\nu^{BV} = (f_\nu^B + f_\nu^V)/2$ minimizes the scatter in predicting the NB5000 flux density of typical objects. The "narrow-band excess" in magnitudes, $BV - NB5000$, was then used to select the candidate LAEs with $(BV - NB5000) > 1.5$, corresponding to $\mathrm{EW}_{obs}^{Ly\alpha} > 150$Å . When the broad-band fluxes are small, significant errors in the equivalent width estimate may result, and a small fraction of the numerous objects without emission lines, i.e. with $(BV - NB5000) \simeq 0$, could enter the "narrow-band excess" sample. To avoid both types of interlopers, we calculated a formal uncertainty in the $BV - NB5000$ color in magnitudes, σ_{BV-NB}, and required candidate LAEs to have $(BV - NB5000) - \sigma_{BV-NB} > 1.5$ and $(BV - NB5000) - 3\sigma_{BV-NB} > 0$. The latter criterion is similar to the color excess requirement of Bunker et al. (1995), but our color uncertainties are object-specific and account for variation in image depth across the field (see Gawiser et al. 2006). To make spectroscopic confirmation feasible, we also required NB5000<25.0, implying an emission line flux $\geq 2.5 \times 10^{-17}$ ergs cm^{-2} s^{-1}. Visual inspection to eliminate false narrow-band detections caused by CCD defects or cosmic ray residuals resulted in 40 candidate LAEs. 23 of these candidates have been observed spectroscopically, yielding 18 confirmations where the Lyman α emission line was clearly detected in both the two-dimensional and extracted spectra and no other emission lines were visible across the full optical spectrum. We tested the procedure by observing lower-equivalent width objects and found several [O II]3727 emitters; all of these interlopers exhibit clear emission lines in Hβ, [O III]4959,5007 and Hα. Five of the LAE candidate spectra fail to show emission lines.

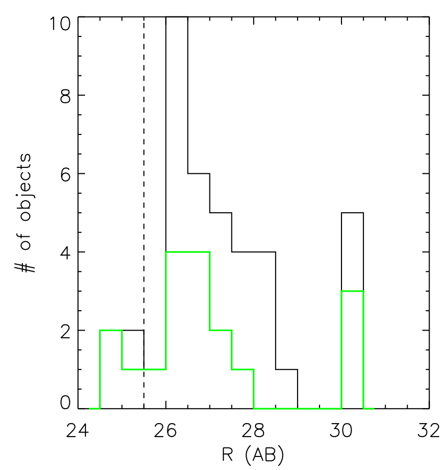

FIG. 1.— Histogram of R-band magnitudes for candidate LAEs (thin histogram) and the subset of confirmed LAEs (thick histogram), with typical spectroscopic limit of $R = 25.5$ marked with dashed vertical line. Objects with negative R fluxes were assigned $R = 30$.

4. RESULTS

Figure 1 shows the distribution of candidate and confirmed LAE R-band continuum magnitudes versus the "spectroscopic" Lyman break galaxy (LBG) limit of $R \leq 25.5$ (Steidel et al. 2003). Our study of LAEs is able to observe objects much dimmer than this, with a median magnitude $R \sim 27$. 36/40 candidates and 15/18 confirmed LAEs have $R > 25.5$, showing the efficacy of LAE selection in identifying objects from the bulk of the high-redshift galaxy luminosity function. Figure 2 shows $UV_{corr}R$ colors of our LAE candidates versus the LBG selection region determined by Gawiser et al. (2006), where V_{corr} refers to the V-band magnitude after subtracting the flux contributed by the Lyman α emission lines. Only 2 out of 18 confirmed LAEs fall within the $R \leq 25.5$ "spectroscopic" LBG sample, but

16 out of 18 fall within the color selection region. About half of our candidate LAEs would meet the $R < 27$ magnitude limit of the "photometric" LBG sample explored by Sawicki & Thompson (2005), and these objects should comprise 5% of their sample.

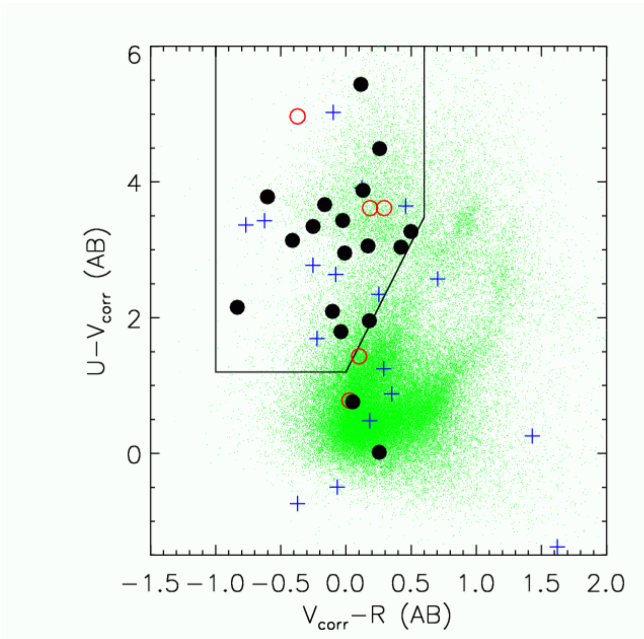

FIG. 2.— *UVR* color-color plot of confirmed LAEs (solid circles), candidate LAEs with spectroscopy but no confirmed redshift (open circles) and candidate LAEs without spectroscopy (plusses) versus distribution of the entire 84,410 object optical catalog (dots). The polygonal region in the upper left is the Lyman break galaxy selection region.

In order to investigate the full SED of the LAEs, which are too dim to obtain individual detections in our NIR photometry, we measured stacked fluxes for the confirmed sample and show the results of SED modelling in Fig. 3. Bruzual & Charlot (2003) population synthesis models were used, with constant star formation rate, a Salpeter (1955) initial mass function from 0.1M$_\odot$ to 100M$_\odot$, solar metallicity and Calzetti et al. (1997) dust reddening (e.g. Förster Schreiber et al. 2004; van Dokkum et al. 2004). Uncertainties in the stacked photometry were determined using bootstrap resampling and are close to the formal errors calculated from the reported APCORR flux uncertainties. Parameter uncertainties were computed via a Monte Carlo analysis where the stacked fluxes were varied within their uncertainties to yield a probability distribution of best-fit parameters. The age of the stellar population is weakly constrained and has been restricted to the physically reasonable range 10 Myr $\leq t_* \leq$ 2 Gyr. The best-fit parameters shown in Fig. 3 correspond to minimal dust extinction, significant star formation rates (5$\leq$SFR$\leq$23 h_{70}^{-2} M$_\odot$yr^{-1} at 95% confidence) and low stellar mass (the 95% confidence upper limit is $M_* = 8.5 \times 10^9 h_{70}^{-2}M_\odot$). The LAEs appear to have much less dust and stellar mass than the $\sim$ 500 Myr old, $A_V \simeq 1$, $\sim 2\times10^{10}$M$_\odot$ Lyman break galaxy population (Shapley et al. 2001) or the $\sim$ 2 Gyr old, $A_V \simeq 2.5$, $\sim 10^{11}$M$_\odot$ Distant Red Galaxy population (Förster Schreiber et al. 2004). The star formation rates of the confirmed LAEs inferred from their Lyman α luminosities average $5h_{70}^{-2}$ M$_\odot$yr^{-1} and from their rest-frame UV continuum luminosity densities average $9h_{70}^{-2}$ M$_\odot$yr^{-1}. The consistency of these values with the best-fit SFR from SED modelling implies minimal dust extinction.

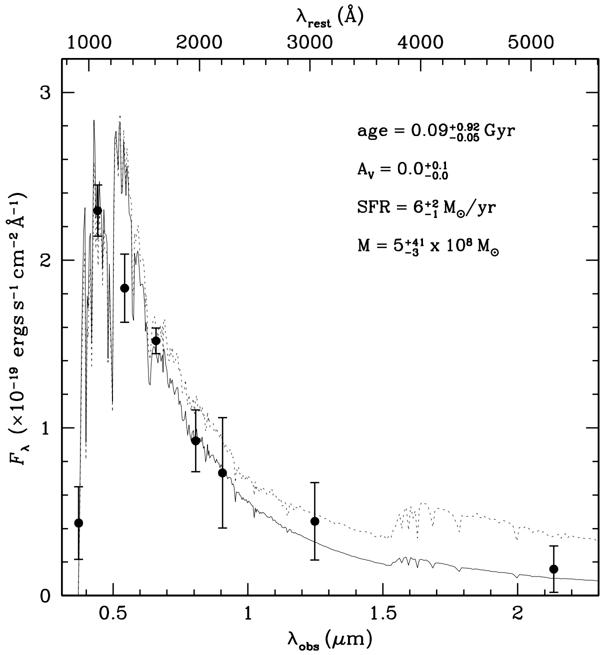

FIG. 3.— *UBVRIzJK* broad-band photometry (average flux density of stacked sample) of confirmed LAEs along with best-fit model from SED fitting (solid) with model parameters listed. The dotted curve shows a maximally old model with stellar population age fixed to 2 Gyr (the age of the universe at $z = 3.1$), $A_V = 0.1$, SFR=7h_{70}^{-2} M$_\odot$ yr^{-1} and $M_* = 1.1\times10^{10}h_{70}^{-2}$ M$_\odot$.

To check for AGN contamination of our LAE candidate sample, we have looked for Chandra detections of these objects. One LAE candidate has an X-ray detection in the catalogs of Virani et al. (2005) and Lehmer et al. (2005a), with a 0.5-8keV luminosity of 10^{44} erg s^{-1}. No other candidates showed individual detections, so we removed this object and performed a stacking analysis (e.g. Rubin et al. 2004; Lehmer et al. 2005b) which resulted in a non-detection of the entire population. Using the conversion between SFR and X-ray flux given by Ranalli et al. (2003), the upper limit on the average star formation rate per object is $200h_{70}^{-2}$ M$_\odot$ yr^{-1}, which is clearly consistent with the observed SFR. None of our LAE spectra show broad emission line widths ($>$ 1000 km s^{-1}) that would be inconsistent with the energetics of star formation. We therefore expect that very few LAE candidates contain luminous AGN which dominate their Lyman α or continuum emission.

5. DISCUSSION

Our survey covers $31.5' \times 31.5' \times (\Delta z = 0.04)$ or $59 \times 59 \times 38h_{70}^{-3}$Mpc^3, yielding an LAE number density of $3\pm1\times10^{-4}h_{70}^{3}$Mpc^{-3}, equivalent to 4000 ± 1600 deg^{-2} per unit redshift. The survey volume was computed using the filter bandpass FWHM=50Å, and the five candidates without confirmed redshifts were assumed to be LAEs. The error bars account for variations in the LAE abundance within our survey volume caused by large-scale structure assuming a bias of 2. The true uncertainties could be bigger given the large fluctuations in density observed for LAEs at $z = 4.9$ by Shimasaku et al. (2004). Combining the measured number density and using the best-fit star formation rate per object of $6h_{70}^{-2}$ M$_\odot$ yr^{-1}, we find a cosmic star formation rate density of $2\times10^{-3}h_{70}$ M$_\odot$ yr^{-1}Mpc^{-3}. This is significantly less than the LBG SFR density (Steidel et al. 1999), but it underestimates the total LAE contribution due to our requirements of high equivalent width and relatively bright *NB*5000 flux designed to select a pure sample amenable to spectroscopic confirmation. A detailed calculation of the LAE luminosity function at $z \simeq 3.1$, which can be integrated to give a fuller estimate of the SFR density, will be given in C. Gronwall et al. (in prep).

The number density, stellar masses, star formation rates, and median UV continuum fluxes found for LAEs are within a factor of three of those predicted by Le Delliou et al. (2005, 2006); the agreement is even better when our equivalent width threshold is accounted for. The only strong disagreement seen versus these models is their claimed escape fraction of 0.02 for Lyman α photons versus our lower limit of 0.2 (and best-fit of 0.8) implied by the comparison of star formation rates determined from the observed Lyman α luminosities and SED modelling. This discrepancy could be resolved by using a larger escape fraction and a standard IMF instead of the top-heavy IMF assumed in the models.

Our determination that $z = 3.1$ LAEs are predominantly blue contrasts with the results of Stiavelli et al. (2001) and Pascarelle et al. (1998) that LAEs in blank fields at $z \simeq 2.4$ are typically red, $(B-I) \simeq 1.8$. This differs from the median value of $(V_{corr}-z) \simeq 0.1$ for our spectroscopically confirmed LAEs and the median color $(V-I) \simeq 0.1$ measured by Venemans et al. (2005). The difference seems unlikely to be caused by evolution in the LAE population from $z = 3.1$ to $z = 2.4$ given the small increase in the age of the universe.

At $z = 4.5$, LALA (Malhotra & Rhoads 2002) reported that a majority of LAE candidates had $\mathrm{EW}_{rest} > 240$Å , providing evidence of a top-heavy IMF possibly caused by Population III stars, although equivalent widths this high could also result from highly anisotropic radiative transfer due to the differing effects of dust and gas on Lyman α and UV-continuum photons. This photometric measurement is sensitive to considerable scatter when the sample is selected in the narrow-band and the broad-band imaging is shallow, as broad-band non-detections can receive extremely large implied equivalent widths, and this is guaranteed to occur for any spurious narrow-band detections. Indeed, when 2σ upper limits on the continuum flux were used, only 10% of their $z = 4.5$ sample had such high EWs, and ~ 20% of the confirmed objects have $\mathrm{EW}_{rest} > 240$Å (Dawson et al. 2004). We do not find equivalent widths this high for any of our LAE candidates at $z = 3.1$. The difference might reveal evolution in the LAE population or could be the result of small number statistics.

We acknowledge the referee, Andrew Bunker, for helpful comments that improved this Letter. We thank James Rhoads and Masami Ouchi for valuable conversations. We are grateful for support from Fundación Andes, the FONDAP Centro de Astrofísica, and the Yale Astronomy Department. This material is based upon work supported by the National Science Foundation under Grant. Nos. AST-0201667,0137927,0071238, and 0302030 awarded to E.G., C.G., R.C. and J.F. respectively. This work was supported in part by NASA grant HST-GO-09525.13-A. Facilities:CTIO(MOSAIC II),LCO(IMACS)

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