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 $z \approx 3.1$ with observed frame equivalent widths $>150\Lambda$ and inferred emission line fluxes $>2.5 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ from deep narrow-band and broadband MUSYC images of the Extended Chandra Deep Field South. Covering 992 arcmin$^2$, this is the largest “blank field” surveyed for LAEs at $z \approx 3$, allowing an improved estimate of the space density of this population of $3 \pm 1 \times 10^5 h_{70}^2$ Mpc$^{-3}$. Spectroscopic follow-up of 23 candidates yielded 18 redshifts, all at $z \approx 3.1$. 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 $R \sim 27$ and very blue continuum colors, $(V - z) \approx 0$. Over 80% of the LAEs have the right UV colors to be selected as Lyman break galaxies, but only 10% also have $R < 25.5$. Stacking the $UBVRIzJK$ fluxes reveals that LAEs have stellar masses $\sim 5 \times 10^9 M_\odot$ and minimal dust extinction, $A_V \lesssim 0.1$. Inferred star formation rates are $\sim 6 h_{70}^2 M_\odot yr^{-1}$, yielding a cosmic star formation rate density of $2 \times 10^{-3} h_{70}^2 M_\odot yr^{-1}$ Mpc$^{-3}$. None of our LAE candidates show evidence for rest-frame line equivalent widths EW$_{\alpha} > 240\AA$ which might imply a non-standard IMF. One candidate is detected by Chandra, implying an AGN fraction of $\pm 2\%$ 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.

Subject headings: galaxies; high-redshift

1. INTRODUCTION

Because Lyman $\alpha$ 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 & McMahon1996). However, the differing behavior of Lyman $\alpha$ and continuum photons encountering dust and neutral gas makes it possible for older galaxies to exhibit Lyman $\alpha$ emission when morphology and kinematics favor the escape of these photons (e.g. Haiman & Spaans1999). 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 $R \lesssim 25.5$. Previous studies of LAEs at $z \approx 3$ 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 $z \approx 3.1$ and $z \approx 3.4$, 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 $z \approx 3.7$ (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 $z \approx 3.1$ (Venemans et al. 2005), 18 at $z = 4.5$ (LALA, Dawson et al. 2004) 27 at $z \approx 5.7$ (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 $z \approx 3$ is a major goal of the Multiwavelength Survey by Yale-Chile (MUSYC, Gawiser et al. 2006 http://www.astro.yale.edu/MUSYC). The Ex-
pointed Chandra Deep Field South (ECDF-S) has been
targeted with deep narrow-band imaging and multi-object
spectroscopy, complemented by deep broad-band UBVRIZJ
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 \(\Lambda\)CDM cosmology consistent with
WMAP results (Bennett et al. 2003) with \(\Omega_m = 0.3, \Omega_\Lambda = 0.7\)
and \(H_0 = 70h_70 \text{ km s}^{-1} \text{ Mpc}^{-1}\). All magnitudes are given in
the AB95 system (Fukugita et al. 1996).

2. OBSERVATIONS

Our narrow-band imaging of the ECDF-S was ob-
tained 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. 2002; Hildebrandt et al.
2005; Arnouts et al. 2001; Wolf et al. 2004). Our \(\prime\) 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′ × 31.5′ = 992 arcmin\(^2\)
centered on the Chandra Deep Field South and were pro-
cessed through the MUSYC photometric pipeline to gener-
ate APCORR (corrected aperture) fluxes and uncertainties as
described in Gawiser et al. (2006). Table I gives our source
detection depths.

| NB5000 | U | B | V | R | I | \(\prime\) | J | K |
|--------|---|---|---|---|---|------|---|---|
| 25.5   | 26.0| 26.9| 26.4| 26.4| 26.4| 24.6| 23.6| 22.7| 22.0|

Multi-object spectroscopy of 23 LAE candidates was per-
formed 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 4000−9000Å 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 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 wave-
lengths, 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 \(f_{BV}^\text{corr} = (f_B^\text{corr} + f_V^\text{corr})/2\) 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 \(EW_{\alpha} \simeq 150Å\). 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 \((BV - NB5000) \sim 0\), 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, \(\sigma_{BV-NB}\), 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 re-
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 spectro-
scopic 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 ob-
served spectroscopically, yielding 18 confirmations where the
Lyman \(\alpha\) 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 ex-
hibit clear emission lines in H\(\beta\), [O III]4959,5007 and H\(\alpha\).
Five of the LAE candidate spectra fail to show emission lines.

4. RESULTS

Figure 1 shows the distribution of candidate and con-
irmed LAE R-band continuum magnitudes versus the “spectro-
copic” 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 identi-
fying objects from the bulk of the high-redshift galaxy lu-
minosity function. Figure 2 shows \(UVR_{corr}R\) 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 Ly-
man \(\alpha\) 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.

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. 4. Bruzual & Charlot (2003) population synthesis models were used, with constant star formation rate, a Salpeter (1955) initial mass function from 0.1$M_\odot$ to 100$M_\odot$, 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 $\lesssim t_s \lesssim 2$ Gyr. The best-fit parameters shown in Fig. 4 correspond to minimal dust extinction, significant star formation rates ($5 \lesssim \text{SFR} \lesssim 23 h_{70}^{-2} M_\odot \text{yr}^{-1}$ 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, $A_V \sim 1$, $\sim 2 \times 10^{10} M_\odot$ Lyman break galaxy population (Shapley et al. 2001) or the $\sim 2$ Gyr old, $A_V \sim 2.5$, $\sim 10^{11} M_\odot$ Distant Red Galaxy population (Förster Schreiber et al. 2004). The star formation rates of the confirmed LAEs inferred from their Lyman $\alpha$ luminosities average $5 h_{70}^{-1} M_\odot \text{yr}^{-1}$ and from their rest-frame UV continuum luminosity densities average $9 h_{70}^{-2} M_\odot \text{yr}^{-1}$ (see also Sawicki et al. 2004). The consistency of these values with the best-fit SFR from SED modelling implies minimal dust extinction.

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 catalog of Virani et al. (2005) and Lehmer et al. (2005), 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 $200 h_{70}^{-2} M_\odot \text{yr}^{-1}$, 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 $\alpha$ or continuum emission.

5. DISCUSSION

Our survey covers $31.5' \times 31.5' \times (\Delta z = 0.04)$ or $59 \times 59 \times 38 h_{70}^{-1} \text{Mpc}^3$, yielding an LAE number density of $3 \pm 1 \times 10^{-4} h_{70}^{-1} \text{Mpc}^{-3}$, equivalent to 4000 $\pm 1600$ 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 $6 h_{70}^{-2} M_\odot \text{yr}^{-1}$, we find a cosmic star formation rate density of $2 \times 10^{-7} h_{70}^{-2} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$. This is significantly less than the LBG SFR den-

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**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.

**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=$7h_{70}^{-2} M_\odot \text{yr}^{-1}$ and $M_* = 1.1 \times 10^{10} h_{70}^{-2} M_\odot$.
sity (Steidel et al. 1999), but it underestimates the total LAE contribution due to our requirements of high equivalent width and relatively bright NB5000 flux designed to select a pure sample amenable to spectroscopic confirmation. A detailed calculation of the LAE luminosity function at \( z \approx 3.1 \), 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 \( \alpha \) 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 \( \alpha \) 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 \( z \approx 2.4 \) are typically red, \( (B-I) \approx 1.8 \). This differs from the median value of \( \langle V_{\text{corr}}-z \rangle \approx 0.1 \) for our spectroscopically confirmed LAEs and the median color \( \langle V-I \rangle \approx 0.1 \) 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 \( \text{EW}_{\text{rest}} > 240\AA \), 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 \( \alpha \) 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 \( 2\sigma \) upper limits on the continuum flux were used, only 10\% of their \( z = 4.5 \) sample had such high EWs, and \( \approx 20\% \) of the confirmed objects have \( \text{EW}_{\text{rest}} > 240\AA \) (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.

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