LYα EMISSION-LINE GALAXIES AT z = 3.1 IN THE EXTENDED CHANDRA DEEP FIELD–SOUTH

CARYL GRONWALL,1 ROBIN CIARULLO,1 THOMAS HICKEY,1 ERIC GAWISER,2,3 JOHN J. FELDMIEER,1,4 PIETER G. VAN DOKKUM,5 C. MEGAN URY,5 DAVID HERRERA,5 BRETT D. LEHMIER,1 LEOPOLDO INFANTE,6 ALVARO ORSI,6 DANILIO MARCHESENI,2 GUILLERMO A. BLANC,7 HAROLD FRANCKE,8 PAULINA LIRA,8 AND EZEQUIEL T. TREISTER9

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ABSTRACT

We describe the results of an extremely deep, 0.28 deg2 survey for z = 3.1 LYα emission-line galaxies in the Extended Chandra Deep Field–South. By using a narrowband 5000 Å filter and complementary broadband photometry from the MUSYC survey, we identify a statistically complete sample of 162 galaxies with monochromatic fluxes brighter than 1.5 × 10−17 ergs cm−2 s−1 and observer’s frame equivalent widths greater than 80 Å. We show that the equivalent width distribution of these objects follows an exponential with a rest-frame scale length of w0 = 76±11 Å. In addition, we show that in the emission line, the luminosity function of LYα galaxies has a faint-end power-law slope of α = −1.49+0.43 −0.33, a bright-end cutoff of log L* = 42.64±0.26 −0.15, and a space density above our detection thresholds of (1.46 ± 0.12) × 10−3 h5 h−3 galaxies Mpc−3. Finally, by comparing the emission-line and continuum properties of the LYα emitters, we show that while in the emission-line galaxies have a faint-end luminosity function, a bright-end cutoff, and a space density above our detection thresholds of (1.46 ± 0.12) × 10−3 h5 h−3 galaxies Mpc−3, we also show that the star formation rates derived from LYα are ~3 times lower than those inferred from the rest-frame UV continuum. We use this offset to deduce the existence of a small amount of internal extinction within the host galaxies. This extinction, coupled with the lack of extremely high equivalent width emitters, argues that these galaxies are not primordial Population III objects, although they are young and relatively chemically unevolved.

Subject headings: cosmology: observations — galaxies: formation — galaxies: high-redshift — galaxies: luminosity function, mass function

Online material: color figures, machine-readable tables

1. INTRODUCTION

The past decade has seen an explosion in our ability to detect and study z > 3 galaxies and probe the history of star formation in the universe (e.g., Madau et al. 1996). This has been mostly due to the development of the Lyman break technique, whereby high-redshift galaxies are identified via a flux discontinuity caused by Lyman limit absorption (see Steidel et al. 1996a, 1996b). By taking deep broadband images and searching for L, B, and F-band dropouts, astronomers have been able to explore large-scale structure (Steidel et al. 2000; Shimasaku et al. 2004), it is possible to efficiently probe the expansion history of the universe. In addition, by using LAEs as tracers of large-scale structure, it is therefore possible to probe much farther down the galaxy continuum luminosity function than with the Lyman break technique, and perhaps identify the most dust-free objects in the universe. Starting with the Keck observations of Cowie & Hu (1998) and Hu et al. (1998), narrowband searches for LYα emisison have been successfully conducted at a number of redshifts, including z ~ 2.4 (Stiavelli et al. 2001), z ~ 3.1 (Ciardullo et al. 2002; Hayashino et al. 2004; Venemans et al. 2005; Gawiser et al. 2006a), z ~ 3.7 (Fujita et al. 2003), z ~ 4.5 (Rhoads et al. 2000), z ~ 4.9 (Ouchi et al. 2003), z ~ 5.7 (Rhoads et al. 2003; Ajiki et al. 2003; Takpen et al. 2006), and z ~ 6.5 (Kodaia et al. 2005; Taniguchi et al. 2005). The discovery of these high-redshift LYα emitters (LAEs) has opened up a new frontier in astronomy. At z > 4, LAEs are as easy to detect as Lyman break galaxies (LBGs), and by z > 6 they are the only galaxies observable from the ground. By selecting galaxies via their LYα emission, it is therefore possible to probe much farther down the galaxy continuum luminosity function than with the Lyman break technique, and perhaps identify the most dust-free objects in the universe. In addition, by using LAEs as tracers of large-scale structure (Steidel et al. 2000; Shimasaku et al. 2004), it is possible to efficiently probe the expansion history of the universe with a minimum of cosmological assumptions (e.g., Blake & Glazebrook 2003; Seo & Eisenstein 2003; Koehler et al. 2007).

Here we describe the results of a deep survey for LYα emission-line galaxies in a 0.28 deg2 region centered on the Extended Chandra Deep Field–South (ECDF-S). This region has an extraordinary amount of complementary data, including high-resolution optical images from the Hubble Space Telescope.
via the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) and the Galaxy Evolution from Morphology and SEDs program (GEMS; Rix et al. 2004); deep ground-based $UBVRIz$ photometry from the Multiwavelength Survey by Yale-Chile (MUSYC; Gawiser et al. 2006b); mid- and far-IR observations from Spitzer, GOODS, and MUSYC; and deep X-ray data from Chandra (Giacconi et al. 2002; Alexander et al. 2003; Lehmer et al. 2005). In § 2 we describe our observations, which include over 28 hours’ worth of exposures through a narrowband filter on the CTIO 4 m telescope. We also review the techniques used to detect the emission-line galaxies, and discuss the difficulties associated with analyzing samples of LAEs discovered via fast-beam instruments. In § 3 we describe the continuum properties of our LAEs, including their rest-frame $m_{1050} - m_{1570}$ colors, and compare their space density to that of LBGs. In § 4 we examine the LAEs’ equivalent width distribution and show that our sample contains very few of the extremely high equivalent width objects found by Dawson et al. (2004) at $z = 4.5$. In § 5 we present the Ly$\alpha$ emission-line luminosity function and give values for its best-fit Schechter (1976) parameters and normalization. In § 6 we translate these Ly$\alpha$ fluxes into star formation rates and consider the properties of LAEs in the context of the star formation rate (SFR) history of the universe. We conclude by discussing the implications our observations have for surveys aimed at determining cosmic evolution.

For our analysis, we adopt a $\Lambda$CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ ($h_{70} = 1$), $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$. At $z = 3.1$, this implies a physical scale of 7.6 kpc arcsec$^{-1}$.

2. OBSERVATIONS AND REDUCTIONS

Narrowband observations of the ECDF-S were performed with the MOSAIC II CCD camera on the CTIO Blanco 4 m telescope. These data consisted of a series of 111 exposures taken over 16 nights through a 50 $\text{Å}$ wide full width at half-maximum (FWHM) $\lambda 5000$ filter (see Fig. 1). The total exposure time for these images was 28.17 hr; when the effects of dithering to cover for a dead CCD during some of the observations are included, the net exposure time becomes ~24 hr. The total area covered in our survey is 998 arcmin$^2$; after the regions around bright stars are excluded, this area shrinks to 993 arcmin$^2$. The overall seeing on the images is 1.0$''$. A log of our narrowband exposures appears in Table 1.

The procedures used to reduce the data, identify line emitters, and measure their brightnesses were identical to those detailed in Ciardullo et al. (2002) and Feldmeier et al. (2003). After debiasing, flat-fielding, and aligning the data, our narrowband frames were co-added to create a master image that was clipped of cosmic rays. This frame was then compared to a deep $B + V$ continuum image provided by the MUSYC survey (Gawiser et al. 2006b) in two different ways. First, the DAOFIND task within IRAF was run on the summed narrowband and continuum image using a series of three convolution kernels, ranging from one matching the image point-spread function (PSF) to one ~3 times larger. This created a source catalog of all objects in our field. These targets were then photometrically measured with DAOPHOT’s PHOT routine, and sources with on-band minus continuum colors less than $-1.03$ in the AB system were flagged as possible emission-line sources (see Fig. 2). At the same time, candidate LAEs were also identified by searching for positive residuals on a “difference” image made by subtracting a scaled continuum image from the narrowband image. In this case, the DAOFIND algorithm was set to flag all objects brighter than 4 times the local standard deviation of the background sky (see Fig. 3). As pointed out by Feldmeier et al. (2003), these two techniques complement each other, since each detects objects that the other does not. Specifically, $\leq 10\%$ of galaxies were missed by the color-magnitude method due to image blending and confusion, but found with the difference method. Conversely, objects at the frame limit that were lost amid the increased noise of the difference frame could still be identified via their on-band minus off-band colors.

Finally, because we intentionally biased our DAOFIND parameters to identify faint sources at the expense of false detections, each emission-line candidate was visually inspected on the narrowband, $B + V$ continuum, and difference frames, as well as on two frames made from subsamples of half the on-band exposures. This last step excluded many false detections at the frame

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**Table 1**

| UT Date       | Exposure (hr) | Seeing (arcsec) | Active CCDs |
|---------------|---------------|-----------------|-------------|
| 2002 Oct 6    | 2.0           | 1.4             | 8           |
| 2002 Oct 12   | 1.7           | 0.9             | 8           |
| 2003 Jan 4    | 2.0           | 1.0             | 8           |
| 2003 Jan 5    | 3.0           | 1.0             | 8           |
| 2003 Jan 6    | 3.0           | 1.1             | 8           |
| 2003 Nov 29   | 2.5           | 1.0             | 7           |
| 2003 Dec 1    | 1.7           | 0.9             | 7           |
| 2004 Jan 23   | 2.3           | 1.3             | 7           |
| 2004 Jan 24   | 2.0           | 0.9             | 7           |
| 2004 Jan 25   | 2.5           | 1.1             | 7           |
| 2004 Feb 16   | 1.1           | 1.0             | 7           |
| 2004 Feb 17   | 0.8           | 1.1             | 7           |
| 2004 Feb 18   | 1.3           | 1.0             | 7           |
| 2004 Feb 19   | 1.2           | 0.9             | 7           |
| 2004 Feb 20   | 0.9           | 1.0             | 7           |
for objects in our survey field. The abscissa gives the instrumental $i$-5000 magnitude, while the ordinate shows the difference between the sources’ narrowband and $B + V$ continuum AB magnitudes. Our narrowband completeness limit of $1.5 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ is represented by a vertical line; our equivalent width limit of 90 Å is shown via the horizontal line. The curve shows the expected 1$\sigma$ errors in the photometry. Candidate emission-line galaxies are denoted as blue circles; the green dots indicate LAE candidates found by our detection algorithms, but rejected upon visual inspection.

limit and left us with a sample of 259 candidate LAEs for analysis.

Once found, the equatorial positions of the candidate emission-line galaxies were derived with respect to the reference stars of the USNO-A2.0 astrometric catalog (Monet et al. 1998). The measured residuals of the plate solution were $\sim 0.2''$, a number slightly less than the 0.25$''$ external error associated with the catalog. Relative narrowband magnitudes for the objects were derived by first measuring the sources with respect to field stars using an aperture slightly greater than the frame PSF. Since most of the galaxies detected in this survey are, at best, marginally resolved on our 1$''$ images, this procedure was sufficiently accurate for our purposes. We then obtained standard AB magnitudes by trimming large-aperture photometry of the field stars to similar measurements of the spectrophotometric standards Feige 56 and Hiltner 600 (Stone 1977) taken on three separate nights. The dispersion in the photometric zero point computed from our standard-star measurements was 0.03 mag.

2.1. Derivation of Monochromatic Fluxes

The fast optics of wide-field instruments, such as the MOSAIC camera at the CTIO 4 m telescope, present an especially difficult challenge for narrowband imaging. The transmission of an interference filter depends critically on the angle at which it is illuminated: light entering at the normal will constructively/destructively interfere at a different wavelength than light coming in at an angle (Eather & Reasoner 1969). As a result, when placed in a fast-converging beam, an interference filter will have its bandpass broadened and its peak transmission decreased by a substantial amount. This effect is important, for without precise knowledge of the filter bandpass, it is impossible to derive accurate monochromatic fluxes or estimate equivalent widths.

To derive the filter transmission, we began with the through-put information provided by the CTIO observatory. This curve, which represents the expected transmission of the $[O \, \text{iii}]$ interference filter in the $f/3.2$ beam of the Blanco telescope, was computed by combining laboratory measurements of the filter tipped at several different angles from the incoming beam (for a discussion of this procedure, see Jacoby et al. 1989). We then shifted this curve 2 Å to the blue, to compensate for the thermal contraction of the glass at the telescope, and compared this model bandpass to the measured emission-line wavelengths obtained from follow-up spectroscopy (P. Lira et al. 2007, in preparation). Interestingly, redshift measurements of 72 galaxies detected in three independent MUSYC fields confirm the shape of the filter’s transmission curve, but not its central wavelength: according to the spectroscopy, the mean wavelength of the filter is 10 Å bluer than given by CTIO (Gawiser et al. 2007). Examining the source of this discrepancy is beyond the scope of this paper. However, the data do confirm that when placed in the beam of the CTIO 4 m prime focus MOSAIC camera, the bandpass of the CTIO $[O \, \text{iii}]$ interference filter is nearly Gaussian in shape. This bandpass is reproduced in the left-hand panel of Figure 4.

This nonguare bandpass has important consequences for the analysis of large samples of emission-line galaxies. The first of these involves the definition of survey volume. Because the transmission of the filter declines away from the bandpass center, the volume of space sampled by our observations is a strong function of line strength. This is illustrated in the center panel of Figure 4. Objects with bright line emission can be detected even if their redshifts place $Ly_{\alpha}$ in the wings of the filter; hence the volume covered for these objects is relatively large. Conversely, weak $Ly_{\alpha}$ sources must have their line emission near the center of the bandpass to be observable. As a result, the “effective”
volume for our integrated sample of galaxies is a function of the galaxy emission-line luminosity function.

A second concern deals with the sample’s flux calibration. In order to compare the flux of an emission-line object to that of a spectrophotometric standard star (i.e., a continuum source), one needs to know both the filter’s integral transmission and its monochromatic transmission at the wavelength of interest (Jacoby et al. 1987, 1989). When observing objects at known redshift, the latter requirement is not an issue. However, when measuring a set of galaxies that can fall anywhere within a Gaussian-shaped transmission curve, the transformation between an object’s (bandpass dependent) AB magnitude and its monochromatic flux is not unique. In fact, if we assume that galaxies are (on average) distributed uniformly in redshift space, then the number of emission-line objects present at a given transmission, $T$, is simply proportional to the amount of wavelength associated with that transmission value. Consequently, the observed distribution of emission-line fluxes will be related to the true distribution via a convolution, whose (unity normalized) kernel, $G(T)$, is

$$G(T)dT = \left\{ \frac{d\lambda}{dT} \right\}_{\text{blue}} dT + \left\{ \frac{d\lambda}{dT} \right\}_{\text{red}} dT,$$  \hspace{1cm} (1)

where the first term describes the filter’s response blueward of the transmission peak and the second term gives the response redward of the peak. The center panel of Figure 4 displays this kernel for the filter used in our survey. The curve shows that for roughly half of the detectable galaxies in our field, the effect of our filter’s nonsquare bandpass is minimal. However, for the other ~50% of galaxies, the shape of the bandpass is extremely important, and the inferred fluxes for some objects can be off by over a magnitude.

Any analysis of the ensemble properties of our LAEs must consider the full effect that the nonsquare bandpass and the odd-shaped convolution kernel has on the sample. We do this in §§ 4 and 5. However, one often wants to quote the monochromatic flux and equivalent width for an individual LAE. To do this, we need to adopt an appropriate “mean” value for the transmission of our filter. The most straightforward way to define this number is via the filter’s peak transmission. This is where the survey depth is greatest, and choosing $T_{\text{max}}$ is equivalent to assigning each galaxy its “most probable” monochromatic flux. Unfortunately, by defining the transmission in this way, we underestimate the flux from all galaxies whose line emission does not fall exactly on this peak. Alternatively, we can attempt to choose a transmission that globally minimizes the flux errors of all the galaxies detected in the survey. This can be done by weighting each transmission by the number of galaxies one expects to observe at that wavelength: the greater the transmission, the deeper the survey, and the more galaxies present in the sample. The difficulty with this “expectation value” approach is that it requires prior knowledge of the distribution of emission-line fluxes, which is one of the quantities we are attempting to measure. That leads us to a third possibility: approximating the filter’s expectation value using some “characteristic” transmission, $T_C$, which is independent of the galaxy luminosity function but still takes the filter’s changing transmission into account. The arrow in Figure 4 identifies the transmission we selected as being characteristic of the filter; the justification for this value is presented in § 5. We emphasize that $T_C$ is only a convenient mean that enables us to quote the likely emission-line strengths of individual galaxies. When analyzing the global properties of an ensemble of LAEs, the full non-Gaussian nature of the filter’s convolution kernel must be taken into account.

Using this transmission and our knowledge of the filter curve, we converted the galaxies’ AB magnitudes to monochromatic fluxes at $\lambda = 5000$ Å via

$$F_{5000} = 3.63 \times 10^{-20} \, 10^{-m_{\text{AB}}/2.5} \frac{c}{\lambda^2} \frac{\int T_C d\lambda}{T_C},$$ \hspace{1cm} (2)

where $F_{5000}$ is given in ergs cm$^{-2}$ s$^{-1}$ (Jacoby et al. 1987). Equivalent widths then followed via

$$EW = \frac{F_{5000}}{f_{B+V}} - \Delta \lambda,$$ \hspace{1cm} (3)

where $f_{B+V}$ is the objects’ AB flux density in the $B + V$ continuum image, and $\Delta \lambda$, the FWHM of the narrowband filter, represents the contribution of the galaxy’s underlying continuum within the bandpass. Both these equations are only applicable to objects whose line emission dominates the continuum within the narrowband filter’s bandpass. Since we are limiting our discussion to galaxies with narrowband minus broadband AB
magnitudes more negative than $-1.03$, this approximation is certainly valid. However, we do note that by using $T_C$ instead of $T_{\text{max}}$, we are intentionally overestimating the flux and equivalent width of some galaxies, in order to minimize the errors in others. So, while the application of $T_C$ formally translates our $\Delta m = -1.03$ criterion into a minimum emission-line equivalent width of 90 Å, galaxies with emission lines that fall near the peak of the filter transmission function can have equivalent widths that are $\sim 12\%$ smaller. This implies that the absolute minimum equivalent width limit for our sample of LAEs is 80 Å.

2.2. Sample of LAE Candidates

Tables 2 and 3 give the coordinates of each candidate emission-line galaxy, along with its inferred monochromatic flux and equivalent width. In total, 259 objects are listed, although many are beyond the limit of our completeness. To determine this limit, we followed the procedures of Feldmeier et al. (2003) and added 1,000,000 artificial stars (2000 at a time) to our narrowband frame. By running our detection algorithms on these modified frames, we were able to compute the flux level below which the object recovery fraction dropped below the 90% threshold. This value, which corresponds to a monochromatic flux of $1.5 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ ($\log F_{5000} = -16.82$) is our limiting magnitude for statistical completeness; 162 galaxies satisfy this criterion.

Before proceeding further with our analysis, we performed one additional check on our data. To eliminate obvious AGNs from our sample, we cross-correlated our catalog of emission-line objects with the lists of X-ray sources found in the 1 Ms exposure of the Chandra Deep Field–South (Alexander et al. 2003) and the four 250 ks exposures of the Extended Chandra Deep Field–South (Lehmer et al. 2005; Virani et al. 2006). Two of our LAE candidates were detected in the X-ray band. The first, which is our brightest LAE, has a $0.5–8$ keV flux of $3.4 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ (i.e., $L_X \sim 2.8 \times 10^{44} h_7^{2.5}$ ergs s$^{-1}$ at $z = 3.1$) and exhibits C iv emission at 1550 Å (P. Lira et al. 2007, in preparation). The other is an interloper: a $z = 1.6$ AGN detected via its strong C iii] line at 1909 Å. For the remaining 160 objects that were not detected individually in the X-ray band, we used stacking analyses to constrain their mean X-ray power output (see Lehmer et al. 2007 for details). We find that the stacked X-ray signal, which corresponds to a $\sim 40$ Ms effective exposure on an average LAE, does not yield a $3 \sigma$ detection in any of three X-ray bandpasses ($0.5–8$ keV, $0.5–2.0$ keV, and $2–8$ keV). These results imply a $3 \sigma$ upper limit of $\sim 3.8 \times 10^{41} h_7^{2.5}$ ergs s$^{-1}$ on the mean $0.5–2.0$ keV luminosity for our LAEs, which demonstrates that few of our Ly$\alpha$ sources harbor low-luminosity AGNs. Similarly, if we use the conversion of Ranalli et al. (2003) we can translate this X-ray nondetection into an upper limit for a typical LAE’s star formation rate. This limit, $85 h_7^{-2}$ $M_\odot$ yr$^{-1}$, is roughly an order of magnitude greater than the rates inferred from the objects’ Ly$\alpha$ emission or UV continua (see § 6).

For the remainder of this paper, we will treat our $z = 3.1$ X-ray source as AGN and exclude it from the analysis. This leaves us with a sample of 160 objects, which we assume are all star-forming galaxies. We note that because all of our objects have equivalent widths greater than 80 Å, they are unlikely to be [O iii] emitters. At $z \sim 0.34$, our survey volume is only $\sim 7300 h_7^{-2}$ Mpc$^3$, which, through the luminosity functions of Hogg et al. (1998), Gallego et al. (2002), and Treblitz et al. (2003), implies a total population of between $\sim 20$ and $\sim 200$ [O iii] emission-line galaxies above our completeness limit. Since less than 2% of these objects will have rest-frame equivalent widths greater than $\sim 60$ Å (Hogg et al. 1998), the number of [O iii] interlopers in our sample should be negligible. This estimate is confirmed by follow-up spectroscopy: of the 52 LAE candidates observed with sufficient signal-to-noise ratios for a redshift determination, all are confirmed LAEs (Gawiser et al. 2006a; P. Lira et al. 2007, in preparation).

Figure 5 shows the spatial distribution of the LAEs above our completeness limit. The sources are obviously clustered, falling along what appear to be “walls” or “filaments.” The GOODS region has a below-average number of $z = 3.1$ LAEs, and there are almost no objects in the northwestern part of the field. Conversely, the density of LAEs east and northeast of the field center is quite high. This type of data can be an extremely powerful probe of cosmological history, but we will defer a discussion of this topic to a future paper (Gawiser et al. 2007).

3. THE CONTINUUM PROPERTIES OF THE EMITTERS

To investigate the continuum properties of our LAEs, we measured the brightness of each LAE on the broadband $UBVR$ images of the MUSYC survey (Gawiser et al. 2006b). Since the catalog associated with this data set has a $5 \sigma$ detection threshold of $U = 26.0$, $B = 26.9$, $V = 26.4$, and $R = 26.4$, our knowledge of the LAEs’ positions (obtained from the narrowband frames) allows us to perform photometry well past this limit.
Figure 6 displays the $B - R$ color-magnitude diagram for 88 of the LAEs brighter than $R_{AB} = 27.25$. The diagram, which shows the galaxies’ rest-frame continua at 1060 and 1570 Å, has several features of note.

The first involves the color distribution of our objects. According to the figure, LAEs with $B - R$ magnitudes brighter than $R = 25$ have a median color of $B - R = 0.53$. This value agrees with the blue colors found by Venemans et al. (2005) for a sample of LAEs at $z = 3.13$, and is the value expected for a $\sim 10^8$ yr old stellar system evolving with a constant star formation rate (Fujita et al. 2003; Bruzual & Charlot 2003). This median color is also consistent with the results of Gawiser et al. (2006a), who stacked the broadband fluxes of 18 spectroscopically confirmed $z = 3.1$ LAEs and showed that the typical age of these systems is in the range 0.01 Gyr $< t < 2$ Gyr. It does, however, stand in marked contrast to the results of Stiavelli et al. (2001), who claimed that LAEs at $z = 2.4$ are very red ($B - I \sim 1.8$). The blue colors of our galaxies confirm their nature as young, star-forming systems. There is no evidence for excessive reddening in these objects, and if the galaxies do possess an underlying population of older stars, the component must be quite small.

On the other hand, as the LAE color distribution indicates, LAEs are not, as a class, homogeneous. At $R = 25$, the MUSYC $B - R$ colors have a typical photometric uncertainty of $\sigma_{B - R} = 0.25$ mag. This contrasts with the observed color dispersion for our galaxies, which is $\sim 0.4$ mag for objects with $R < 25$. Thus, there is at least a $\sim 0.3$ mag scatter in the intrinsic colors of these objects. Either there is some variation in the star formation history of LAEs, or dust is having an effect on the emergent colors.

Finally, it is worth noting that our LAEs are substantially fainter in the continuum than objects found by the Lyman break technique. At $z \sim 3$, L$^*$ galaxies have an apparent magnitude of $R \sim 24.5$ (Steidel et al. 1999), and ground-based Lyman break surveys typically extend only $\sim 1$ mag beyond this value (see Giavalisco 2002 for a review). Furthermore, spectroscopic surveys of LBG candidates rarely target galaxies fainter than $R = 24$. In our emission-line sample, the median continuum magnitude is $R \sim 26.7$, and many of the galaxies have aperture magnitudes significantly fainter than $R \sim 28$. In general, LAEs do inhabit the same location as LBGs in the $U - V$ versus $V - R$ color-color space (see Fig. 7), but their extremely faint continuum sets them apart.

This is also illustrated in Figure 8, which compares the rest-frame 1570 Å luminosity function of our complete sample of LAEs (those with monochromatic fluxes greater than $1.5 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$) with the rest-frame 1700 Å luminosity function of $z = 3.1$ LBGs (Steidel et al. 1999). When plotted in this way, our sample of LAEs appears incomplete, since for $R \gtrsim 26.5$ only the brightest emission-line sources will make it into our catalog. The plot also implies that at $z = 3.1$, $R < 25.5$, LAEs are $\sim 3$ times rarer than comparably bright LBGs. Since this ratio is virtually identical to that measured by Steidel et al. (2000) within an extremely rich $z = 3.09$ protocluster, this suggests that the number is not a strong function of galactic environment. But most strikingly, our observations demonstrate the LAEs sample the entire range of the (UV continuum) luminosity function. The median UV luminosity of LAEs in our sample is $\leq 0.2 L^*$, and the faintest galaxy in the group is no brighter than $\sim 0.02 L^*$. Just as broadband observations detect all objects at the bright-end of the continuum luminosity function but sample the entire range of emission-line strengths, our narrowband survey finds all the brightest emission-line objects but draws from the entire range of continuum brightness.
The contribution of each LAE's emission line to its magnitudes excludes them from the "spectroscopic" samples studied by Steidel (Shapley et al. 2003). Although most LAEs have LBG-like colors, their line emitters make it into our sample. In the magnitude range is the LBG selection region; the solid curve is the track of an LBG template spectrum with no spectroscopy. The dots are the entire 84,410 object catalog. The polygon with insufficient signal-to-noise ratios for classification, and the crosses are objects associated with our narrowband photometry vary considerably, ranging from ~0.02 mag at the bright end to ~0.2 mag near the completeness limit (see Table 4). These errors will scatter objects from heavily populated magnitude bins into bins with fewer objects, and flatten the slope of the luminosity function. Because the change in slope goes as the square of the measurement uncertainty (Eddington 1913, 1940), the effect of this convolution is most important for objects near the survey limit.

2. The filter transmission function.—As described in § 2.1, the narrowband filter used for this survey has a transmission function that is nearly Gaussian in shape. This creates an odd-shaped convolution kernel (Fig. 4, right), which systematically decreases the measured line emission of objects falling away from the peak of the transmission curve. Moreover, because the objects' equivalent widths are also reduced by this bandpass effect, some fraction of the LAE population will be lost from our EW > 80 Å sample. The result is that the normalization of this filter transmission kernel is not unity. Instead, it depends on the intrinsic equivalent width distribution of the galaxies, since that is the function that defines the fraction of galaxies (at each redshift) that can still make it into our sample.

These effects are illustrated in the top panel of Figure 9, which displays a histogram of the rest-frame equivalent widths for our candidate Lyα galaxies. As the dotted line shows, the data appear to be well fit by an exponential that has an e-folding length of $w_{\text{obs}} = 214^{+19}_{-15}$ Å. However, because the bandpass of our narrowband filter is more Gaussian-shaped than square, the line strength of the galaxies has been systematically underestimated. In fact, the true distribution of equivalent widths is broader than that measured: when we perform a maximum likelihood analysis using a series of exponential laws, convolved with the filter bandpass and photometric error kernels, we obtain a most-likely scale length of $w_{\text{obs}} = 311^{+47}_{-33}$ Å, or $w_0 = 76^{+11}_{-8}$ Å in the rest frame of the sample.

Such a distribution is quite different from that reported by Malhotra & Rhoads (2002). In their survey of 150 $z = 4.5$ LAEs, ~60% of the objects had extremely high rest-frame equivalent

| TABLE 4 | PHOTOMETRIC UNCERTAINTIES |
|---------|---------------------------|
| log $F_{5000}$ | $\sigma$ (mag) | log $F_{5000}$ | $\sigma$ (mag) |
| ~15.30 | 0.031 | ~16.00 | 0.078 |
| ~15.40 | 0.026 | ~16.10 | 0.082 |
| ~15.50 | 0.031 | ~16.20 | 0.086 |
| ~15.60 | 0.033 | ~16.30 | 0.104 |
| ~15.70 | 0.038 | ~16.40 | 0.125 |
| ~15.80 | 0.042 | ~16.50 | 0.158 |
| ~15.90 | 0.050 | ~16.60 | 0.204 |
| ~16.00 | 0.058 | ~16.70 | 0.264 |
| ~16.10 | 0.073 | ~16.80 | 0.329 |
widths, i.e., $\text{EW}_0 > 240 \text{ Å}$. Since stellar population models, such as those by Charlot & Fall (1993), cannot produce such strong line emission, Malhotra & Rhoads (2002) postulated the presence of a top-heavy initial mass function and perhaps the existence of Population III stars. However, in our sample only 3 out of 160 LBGs ($\approx 2\%$) have observed rest-frame equivalent widths greater than this 240 Å limit. Even when we correct for the effects of our filter’s nonsquare bandpass, the fraction of strong line emitters does not exceed $\sim 12\%$. This is less than the $\sim 20\%$ value estimated by Dawson et al. (2004) via Keck spectroscopy of a subset of the Malhotra & Rhoads (2002) objects. Thus, at least at $z \approx 3.1$, there is no need to invoke a skewed initial mass function to explain the majority of our LBGs.

The equivalent width distribution of Figure 9 also differs dramatically from that found by Shapley et al. (2003) for a sample of $z \sim 3$ LBGs. In their data set, rest-frame equivalent widths $e$-fold with a scale length of $\sim 25$ Å, rather than the $\sim 75$ Å value derived from our LAE survey. This difference is not surprising given that the former data set is selected to be bright in the continuum, while the latter is chosen to be strong in the emission line. Moreover, when Shapley et al. (2003) analyzed the $\sim 25\%$ of LBGs with rest-frame equivalent widths greater than 20 Å, they found a correlation between line strength and continuum ($R$ band) magnitude, in the sense that fainter galaxies had higher equivalent widths. We see that same trend in our data, but it is largely the result of a selection effect. (Faint galaxies with low equivalent widths fall below our monochromatic flux limit.) A comparison of emission-line flux with equivalent width for our statistically complete sample shows no such correlation.

The lower two panels of Figure 9 demonstrate this another way. In the diagram, our sample of LAEs is divided in half, with the middle panel showing the equivalent width distribution for objects with monochromatic Lyα luminosities greater $2 \times 10^{42} \text{ ergs s}^{-1}$, and the bottom panel displaying the same distribution for less luminous objects. As the figure illustrates, the distribution of equivalent widths is relatively insensitive to the absolute brightness of the galaxy. To first order this is expected, since both the UV continuum and the Lyα emission-line flux are driven by star formation. However, one could imagine a scenario wherein the amount, composition, and/or distribution of dust within the brighter (presumably more metal-rich) LAEs differs from that within their lower luminosity counterparts. Since the effect of this dust on resonantly scattered Lyα photons is likely to be different from that on continuum photons, this change in extinction can theoretically produce a systematic shift in the distribution of Lyα equivalent widths. There is no evidence for such a shift in our data; this constancy argues against the importance of dust in these objects.

5. THE Lyα EMISSION-LINE LUMINOSITY FUNCTION

Figure 10 shows the distribution of monochromatic fluxes for our sample of emission-line galaxies. The function looks like a power law, with a faint-end slope of $\alpha \sim -1.5$ that steepens as one moves to brighter luminosities. However, to quantify this behavior, we once again have to correct the observed flux distribution for the distortions caused by photometric errors and the nonsquare bandpass of the filter. In addition, we must also consider the censoring effect our equivalent width cutoff has on the data: some line emitters whose redshifts are not at the peak
of the filter transmission function will fall out of our sample completely.

To deal with these effects, we fit the observed distribution of Lyα emission-line fluxes to a Schechter (1976) function via the method of maximum likelihood (e.g., Hanes & Whittaker 1987; Ciardullo et al. 1989). We applied our two convolution kernels (including the equivalent width censorship) to a series of functions of the form

$$\phi(L) d(L/L^*) \propto (L/L^*)^{-\alpha} e^{-L/L^*} d(L/L^*), \quad (4)$$

treated each curve as a probability distribution (i.e., with a unity normalization), and computed the likelihood that the observed sample of Lyα fluxes is drawn from the resultant distribution. The results for the three parameters of this fit, $\alpha$, log $L^*$, and $N$, the integral of the Schechter function down to our limiting flux (in units of galaxies Mpc$^{-3}$), are shown in Figure 11; Table 5 lists the best-fitting parameters, along with their marginalized most-likely values and uncertainties. For completeness, Table 5 also gives the value of $\phi^*$ that is inferred from our most likely solution. As expected, the plots illustrate the familiar degeneracy between $L^*$ and $\alpha$: our best-fit solution has $\alpha \sim -1.5$, but if $L^*$ is forced to brighter luminosities, $\alpha$ decreases. The contours also demonstrate an asymmetry in the solutions, whereby extremely bright values of $L^*$ are included within the 3 $\sigma$ contours of probability, but faint values of the same quantity are not.

But perhaps the most interesting feature of the analysis concerns the effect of the flux limit on the survey volume. As described in $\S$ 2.1, the amount of space sampled by the observations depends critically on each galaxy’s Lyα luminosity and equivalent width. Bright line emitters with large equivalent widths can be identified well onto the wings of the filter; hence the survey volume associated with these objects is relatively large. Conversely, weak line emitters, and objects with small equivalent widths, can only be detected if they lie at the peak of the filter transmission curve. Thus, the survey volume for these objects is quite small. The effective volume for our observations is therefore a weighted average, which depends on the intrinsic properties of the entire LAE sample. This average can be computed from the data displayed in Figure 11. According to the figure, the space density of galaxies with emission-lines brighter than $1.5 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ (i.e., $L_{\text{Ly}\alpha} > 1.3 \times 10^{42} h^{-2}_{70}$ ergs s$^{-1}$) is extremely well defined, $(1.46 \pm 0.12) \times 10^{-3} h^{-3}_{70}$ galaxies Mpc$^{-3}$. Since this measurement comes from the detection of 160 galaxies brighter than the completeness limit, the data imply an effective survey volume of $\sim 1.1 \times 10^5 h^{-3}_{70}$ Mpc$^3$. This is not the volume one would infer from the interference filter’s FWHM: it is 25% smaller, or roughly the full width of the filter at two-thirds maximum.

This difference is illustrated in Figure 10. The points show the true density of Lyα galaxies one would derive simply by using the filter’s FWHM to define the survey volume; the solid line gives the Schechter (1976) function that best fits the data. The offset between the solid line and the dashed line, which represents the function after the application of the two convolution kernels, confirms the need for careful analysis when working with narrowband data taken through a nonsquare bandpass.

The results of our maximum likelihood calculation also suggest a simple definition for the effective transmission of our filter. As described in $\S$ 2.1, a “characteristic” transmission is needed to convert the (bandpass dependent) AB magnitude of an individual galaxy to monochromatic Lyα flux. Rather than use the maximum transmission (which would underestimate the flux of all galaxies not at the filter peak), or adopt some complicated scheme that involves iterating on the luminosity function, one can simply choose the filter’s mean transmission within some limited wavelength range. Based on the results above, the filter’s full width at two-thirds maximum seems an appropriate limit. This transmission, which is indicated by the arrow in Figure 4, is the value used to derive the fluxes and equivalent widths of Tables 2 and 3. If one were to use to filter’s peak transmission.

![Graph](image)

**Table 5**

| Parameter | Best Solution | Marginalized Values |
|-----------|---------------|---------------------|
| log $L/L^*$ (ergs s$^{-1}$) | 42.66 | 42.64$^{+0.26}_{-0.15}$ |
| $\alpha$ | -1.36 | -1.49$^{+0.45}_{-0.34}$ |
| $N(>1.3 \times 10^{42} h^{-2}_{70}$ ergs s$^{-1}$) (Mpc$^{-3}$) | $1.46 \times 10^{-3}$ | $1.46_{-0.11}^{+0.14} \times 10^{-3}$ |
| $\phi^*$ (Mpc$^{-3}$) | $1.28 \times 10^{-3}$ | . . . |
instead of this characteristic value, the tabulated emission-line fluxes and equivalent widths would all be \( \sim 12\% \) smaller.

The error bars quoted above for the space density of LAEs represent only the statistical uncertainty of the fits. They do not include the possible effects of large-scale structure within our survey volume. Specifically, if the linear bias factor for LAEs is two (see Gawiser et al. 2007 for an analysis of the objects’ clustering), then the expected fluctuation in the density of LAEs measured within a \( \sim 10^5 h^{-1}_{70} \) Mpc\(^3\) volume of space is \( \sim 30\% \). This value should be combined in quadrature with our formal statistical uncertainty.

Since Ly\(\alpha\) galaxies have been observed at a number of redshifts, it is tempting to use our data to examine the evolution of the LAE luminosity function. Unfortunately, the samples obtained to date are not yet robust enough for this purpose. An example of the problem is shown in Figure 12, which compares our cumulative luminosity function (and our Schechter fit for \( \alpha = -1.5 \)) to two measures of Ly\(\alpha\) galaxies at \( z = 5.7 \). As the figure illustrates, there are large differences between the measurements. If the Malhotra & Rhoads (2004) luminosity function is correct, then LAEs at \( z = 3.1 \) are a factor of \( \sim 2.5 \) brighter and/or more numerous than their \( z = 5.7 \) counterparts. However, if the \( z = 5.7 \) LAE luminosity function of Shimasaku et al. (2006) is correct, then evolution is occurring in the opposite direction, i.e., the star formation rate density is declining with time. Without better data, it is difficult to derive any conclusions about the evolution of these objects.

Figure 12 also plots our data against the predictions of a hierarchical model of galaxy formation (Le Delliou et al. 2005, 2006). As this comparison demonstrates, our luminosity function for \( z = 3.1 \) LAEs lies slightly below that generated by theory. This is not surprising: one of the key parameters of the model, the escape fraction of Ly\(\alpha\) photons, was set using previous estimates of the density of \( z \sim 3 \) LAEs. Unfortunately, these measurements were based on extremely small samples of objects, specifically, \( 9 z = 3.1 \) emitters from Kudritzki et al. (2000) and 10 \( z = 3.4 \) LAEs from Cowie & Hu (1998). Since these surveys inferred a larger space density of LAEs than measured in this paper, a mismatch between our data and the Le Delliou et al. (2006) models is neither unexpected nor significant.

6. STAR FORMATION RATE DENSITY AT \( z \sim 3.1 \)

Perhaps the most interesting result of our survey comes from a comparison of the galaxies’ Ly\(\alpha\) emission with their R-band magnitudes. Both quantities measure star formation rate: Ly\(\alpha\) via the combination of case B recombination theory and the H\(\alpha\) versus star formation relation,

\[
\text{SFR(Ly}\alpha\text{)} = 9.1 \times 10^{-43} L(\text{Ly}\alpha) M_\odot \text{yr}^{-1}
\]

(Kennicutt 1998; Hu et al. 1998), and R via population synthesis models of the rest-frame UV (21570),

\[
\text{SFR(UV)} = 1.4 \times 10^{-28} L_\nu M_\odot \text{yr}^{-1}
\]

(Kennicutt 1998). If both of these calibrations hold for our sample of LAEs, then a plot of the two SFR indicators should scatter about a one-to-one relation.

Figure 13 displays this plot. In the figure, galaxies with Ly\(\alpha\) star formation rates less than \( \sim 1.15 M_\odot \text{yr}^{-1} \) are excluded by our 1.5 \( \times 10^{-17} \) ergs cm\(^{-2}\) s\(^{-1}\) monochromatic flux limit, while objects with large UV star formation rates but weak Ly\(\alpha\) are eliminated by our equivalent width criterion. The latter is not a hard limit, since LAE colors are in the range \( 0 \leq (B + V) - R \leq 2.5 \) and it is the \( B + V \) continuum that is used to define equivalent width. Nevertheless, if we adopt 1.4 as the upper limit on the median color of an Ly\(\alpha\) emitting galaxy [i.e., 1 \( \sigma \) above the median...
(B + V) - R ≈ 0.65 color of the population], we obtain the dotted line shown in the figure.

Despite these selection effects, the Lyα and UV continuum star formation rates do seem to be correlated. However, there is an offset: the rates inferred from the UV are, on average, about 3 times higher than those derived from Lyα. While the Lyα SFR measurements are generally less than 10 $h_7^2 M_{\odot}$ yr$^{-1}$, the rest-frame UV values extend up to $\approx 50 h_7^2 M_{\odot}$ yr$^{-1}$. This discrepancy has previously been seen in a sample of 20 LAEs at $z = 5.7$ (Ajiki et al. 2003), and has two possible explanations.

The most likely cause of the offset is the galaxies’ internal extinction. By studying local starburst galaxies, Calzetti (2001) has shown that a system’s ionized gas is typically attenuated more than its stars. In other words, while optical and IR emission-line ratios can usually be reproduced with a simple screen model, the shape of the UV continuum requires that the dust and stars be intermingled. For a self-consistent solution, Calzetti (2001) suggests

$$E(B - V)_{\text{stars}} = 0.44E(B - V)_{\text{gas}}.$$ (7)

If we apply the Calzetti (2001) law to our sample of $z = 3.1$ LAEs, then for the UV and Lyα star formation rates to be equal, the extinction within our LAEs must be as shown in Figure 14. According to the figure, in most cases it only requires a small amount of dust [$E(B - V)_{\text{stars}} < 0.05$] to bring the two indicators into agreement. Figure 14 also suggests that internal extinction becomes more important in the brighter galaxies. This is consistent with observations of local starburst systems (e.g., Meurer et al. 1995), and is expected if the mass-metallicity relation seen in the local universe carries over to dust content.

Alternatively, the discrepancy between the Lyα and UV continuum star formation rates may simply be due to uncertainties in their estimators. Models that translate UV luminosity into star formation rate have almost a factor of 2 scatter and rely on a number of parameters, including the initial mass function and the timescale for star formation. The latter is particularly problematic. Lyα photons are produced almost exclusively by extremely young (<30 Myr), massive (>10 $M_{\odot}$) stars that ionize their surroundings. It therefore registers the instantaneous star formation occurring in the galaxy. Conversely, continuum UV emission (at 1570 Å) can be produced by populations as old as $\approx$ 1 Gyr; thus, it is a time-averaged quantity. If the star formation rate in our LAEs has declined over time, then it is possible for UV measurements to systematically overestimate the present-day star formation (Glazebrook et al. 1999).

If we assume that Lyα emission is an accurate measure of star formation, then it is possible to integrate the Schechter function to estimate the total contribution of LAEs to the star formation rate density of the $z = 3.1$ universe. We note that this procedure does carry some uncertainty. If we just consider galaxies brighter than our completeness limit (1.5 × 10$^{-17}$ ergs cm$^{-2}$ s$^{-1}$ or $L_{\text{Lyα}} > 1.3 \times 10^{42} h_{70}^2$ ergs s$^{-1}$), then the star formation rate density associated with LAEs is $\approx 3.6 \times 10^{-3} h_{70} M_{\odot}$ yr$^{-1}$ Mpc$^{-3}$, or $1.2 \times 10^{-2} h_{70} M_{\odot}$ yr$^{-1}$ Mpc$^{-3}$ if the internal extinction in these objects is $E(B - V)_{\text{stars}} > 0.05$. However, to compute the total star formation rate density, we need to extrapolate the LAE luminosity function to fainter magnitudes, and even 160 objects is not sufficient to define $\alpha$ to better than $\approx$ 25%. Consequently, our data admit a range of solutions.

This is illustrated in Figure 15, which displays SFR likelihoods derived from the probabilities illustrated in Figure 11. As the figure shows, the most likely value for the LAE star formation rate density of the $z = 3.1$ universe (uncorrected for internal extinction) is $6.5 \times 10^{-3} h_{70} M_{\odot}$ yr$^{-1}$ Mpc$^{-3}$, while the median value of this quantity (defined as the point with equal amounts of probability above and below) is $8.6 \times 10^{-3} h_{70} M_{\odot}$ yr$^{-1}$ Mpc$^{-3}$. Moreover, these numbers are likely to be lower limits: if the discrepancy seen in Figure 13 is due to internal extinction, then the true SFR density is probably $\approx$ 3.5 times higher.

The numbers above indicate that at $z = 3.1$, the star formation rate density associated with LAEs is comparable to that in LBGs.
LBGs. Before correcting for extinction, our number for the LAE star formation rate density is $8.6 \times 10^{-3} \, h_70 \, M_\odot \, yr^{-1} \, Mpc^{-3}$. For comparison, the LBG star formation rate density at $z = 3.1$ (before extinction) is $\sim 0.01 \, h_70 \, M_\odot \, yr^{-1} \, Mpc^{-3}$ (Madau et al. 1998; Steidel et al. 1999). It is true that internal extinction within LBGs is typically larger than it is in our LAEs, $E(B - V) \sim 0.15$ (Steidel et al. 1999). However, according to the Calzetti (2001) extinction law, the effect of dust on the emission-line flux of a galaxy is much greater than that on the stellar continuum. Consequently, our dust-corrected SFR density for LAEs, $\sim 0.03 \, h_70 \, M_\odot \, yr^{-1} \, Mpc^{-3}$, is $\sim 75\%$ of the LBG value. Of course, given the extrapolations and corrections required to make this comparison, this number is highly uncertain.

7. DISCUSSION

The space density of $z = 3.1$ LAEs shown in Figure 11 translates into a surface density of $4.6 \pm 0.4 \, arcmin^{-2}$ per unit redshift interval above our completeness limit. This number is similar to that derived by Thommes & Meisenheimer (2005) under the assumption that the LAE phenomenon is associated with the creation of elliptical galaxies and spiral bulges. It is also consistent with the semianalytical hierarchical structure calculations of Le Delliou et al. (2005), although the latter predict a slightly larger number of $z \sim 3$ LAEs than found in this paper. This difference is not significant, since the Le Delliou et al. (2005) models have been adjusted to match the previous small-volume Ly$\alpha$ surveys of Kudritzki et al. (2000) and Cowie & Hu (1998). A $\sim 30\%$ rescaling of the escape fraction of Ly$\alpha$ photons solves the discrepancy and maintains the match between the predictions and the faint-end slope of the galaxy luminosity function.

More notable is the excellent agreement between the Le Delliou et al. (2006) simulations and the observed distribution of Ly$\alpha$ equivalent widths (Fig. 9). Both are very well fit via an exponential with a large ($\sim 75$ Å) scale length. Moreover, the models also predict that the scale length observed for a magnitude-limited sample of galaxies (such as that produced by the Lyman break technique) will be much smaller than that found via an emission-line survey. This is consistent with the LBG results found by Shapley et al. (2003).

Nevertheless, we should emphasize that the LAEs detected in this survey are probably not primordial galaxies in their initial stages of star formation. Very few of the objects have the extremely high equivalent widths calculated for stellar populations with top-heavy initial mass functions. More importantly, the scatter in the galaxies’ $m_{1000} - m_{1570}$ colors, along with the offset between the Ly$\alpha$ and UV continuum star formation rates, suggests that these objects possess a nonnegligible amount of dust. The existence of this dust argues against the Population III interpretation of $z \sim 3$ LAEs (Jimenez & Haiman 2006).

The extremely strong line emission associated with LAEs makes these objects especially suitable for probing the evolution of galaxies and structure in the distant universe. The space density of $z = 3.1$ emitters shown in Figure 11 translates into a surface density of $4.6 \pm 0.4 \, arcmin^{-2}$ per unit redshift interval above our completeness limit. This, coupled with our measured luminosity function, implies that in the absence of evolution, there are $\sim 12$ LAE arcmin$^{-2}$ brighter than $1.5 \times 10^{-17} \, ergs \, cm^{-2} \, s^{-1}$ in the redshift range $2 < z < 4$. Wide-field integral field units, such as those being designed for ESO (Henault et al. 2004) and the Hobby-Eberly Telescope (Hill et al. 2006), will therefore be able to find large numbers of LAEs in a single pointing. Moreover, because the faint-end of the luminosity function is steep ($\alpha \sim -1.5$), the density of LAEs goes linearly with survey depth. Dropping the flux limit by a factor of 2 (to $7.5 \times 10^{-18} \, ergs \, cm^{-2} \, s^{-1}$) will roughly double the number of LAEs in the sample.

With an integral-field spectrograph, it is also possible to increase the sample of high-redshift galaxies by identifying objects with equivalent widths lower than our detection threshold of 80 Å ($\sim 20$ Å in the LBG rest frame). However, the gain in doing so is likely to be small: according to Figure 9, Ly$\alpha$ rest-frame equivalent widths $\epsilon$-fold with a scale length of $\sim 75$ Å. If this law extrapolates to weaker lined systems, as suggested by the models of Le Delliou et al. (2006), then most LAEs are already being detected, and pushing the observations to lower equivalent widths will only increase the number counts by $\sim 20\%$. Furthermore, as the data of Hogg et al. (1998) demonstrate, contamination by foreground [O ii] objects increases rapidly once the equivalent width cutoff drops below $\sim 50$ Å in the observers frame (or $\sim 12$ Å in the rest frame of Ly$\alpha$). Unless one can accept a large increase in the fraction of contaminants, surveys for high-redshift galaxies need to either stay above this threshold or extend to the near-IR (to detect H$\beta$ and [O ii] $\lambda 5007$ in the interlopers).

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