THE LUMINOSITY FUNCTION OF Lyα EMITTERS AT REDSHIFT $z = 7.7$

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1. INTRODUCTION

Lyα emitting galaxies offer a powerful probe of both galaxy evolution and the reionization history of the universe. Lyα emission can be used as a prominent signpost for young galaxies whose continuum emission may be below usual detection thresholds. It is also a tool to study their star formation activity and a handle for spectroscopic follow-up.

The intergalactic medium (IGM) will obscure Lyα emission from view if the neutral fraction exceeds ~50% (Furlanetto et al. 2006; McQuinn et al. 2007). Recently, Lyα emitters have been used to show that the IGM is $\lesssim$50% neutral at $z = 6.5$ (Rhoads & Malhotra 2001; Malhotra & Rhoads 2004; Stern et al. 2005; Kashikawa et al. 2006; Malhotra & Rhoads 2006). This complements the Gunn–Peterson lower bound of $x_{HI} \gtrsim 1$% at $z \approx 6.3$. Completely independently, polarization of the cosmic microwave background suggests a central reionization redshift $z_{re} = 10.5 \pm 1.2$ (Komatsu et al. 2010).

In addition to their utility as probes of reionization, Lyα emitters are valuable in understanding galaxy formation and evolution at the highest redshifts. This is especially true for low mass galaxies, as Lyα emitters are observed to have stellar masses $M_* \lesssim 10^9 M_\odot$ (Gawiser et al. 2006; Pirzkal et al. 2007; Finkelstein et al. 2007; Pentericci et al. 2009), appreciably below the stellar masses of Lyman break selected galaxies (LBG; Steidel et al. 1996) at similar redshifts (e.g., Papovich et al. 2001; Shapley et al. 2001; Stark et al. 2009).

Narrowband imaging is a well-established technique for finding high redshift galaxies (e.g., Rhoads 2000; Rhoads et al. 2003, 2004; Malhotra & Rhoads 2002, 2004; Cowie & Hu 1998; Hu et al. 1999, 2002, 2004; Kudritzki et al. 2000; Fynbo et al. 2001; Pentericci et al. 2000; Ouchi et al. 2001, 2003, 2008; Stiavelli et al. 2001; Shimasaku et al. 2006; Kodaira et al. 2003; Ajiki et al. 2004; Taniguchi et al. 2005; Venemans et al. 2004; Kashikawa et al. 2006; Iye et al. 2006; Nilsson et al. 2007; Finkelstein et al. 2009b). The method works because Lyα emission redshifted into a narrowband filter will make the emitting galaxies appear brighter in images through that filter than in broadbands of similar wavelength. A supplemental requirement that the selected emission line galaxies be faint or undetected in filters blueward of the narrowband filter effectively weeds out lower redshift emission line objects (e.g., Malhotra & Rhoads 2002). This has proven to be very efficient for selecting star-forming galaxies up to $z \lesssim 7$ and remains effective even when those galaxies are too faint in their continuum emission to be detected in typical broadband surveys.

While large samples of Lyα emitters have been detected at $z < 6$, both survey volumes and sample sizes are much smaller at $z > 6$. Since the Lyα photons are resonantly scattered in neutral IGM, a decline in the observed luminosity function (LF) of Lyα emitters would suggest a change in the IGM phase, assuming the number density of newly formed galaxies remains constant at each epoch. Malhotra & Rhoads (2004) found no significant evolution of Lyα LF between $z = 5.7$ and $z = 6.6$, while Kashikawa et al. (2006) suggested an evolution of bright end of the Lyα LF in this redshift range. At even higher redshifts, $z = 6.5–7$, some authors (Iye et al. 2006; Ota et al. 2008) suggest an evolution of the Lyα LF however based on a single detection. Recently, Hibon et al. (2010) found seven Lyα candidates at $z = 7.7$ using the Wide-Field InfraRed Camera on the Canada–France–Hawaii Telescope. If these seven candidates

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are real and high redshift galaxies, the derived Lyα LF suggests no strong evolution from \( z = 6.5 \) to \( z = 7.7 \). Stark et al. (2007) found six candidate Lyα emitters at \( z \approx 8–10 \) in a spectroscopic survey of gravitationally lensed Lyα emitters. Other searches (e.g., Parkes et al. 1994; Willis & Courbin 2005; Cuby et al. 2007; Willis et al. 2008; Sobral et al. 2009) at redshift \( z \geq 8 \) either had insufficient volume or sensitivity, and hence did not find any Lyα emitters.

In this paper, we present a search for Lyα emitting galaxies at \( z = 7.7 \), selected using custom-made narrowband filters that avoid night sky emission lines and therefore are able to obtain low sky backgrounds. This paper is organized as follows. In Section 2, we describe in detail the data and reduction. In Section 3, we describe our selection of Lyα galaxy candidates. In Section 4, we discuss possible sources of contamination in the sample and our methods for minimizing such contamination. In Section 5, we estimate the number of Lyα galaxy candidates expected in our survey using a full Monte Carlo simulation. In Section 6, we discuss the Lyα LF and in Section 7, we compare the Lyα equivalent widths (EWs) with the previous work. We summarize our conclusions in Section 8. Throughout this work, we assumed a flat \( \Lambda \)CDM cosmology with parameters \( \Omega_m = 0.3 \), \( \Omega_{\Lambda} = 0.7 \), and \( h = 0.71 \) where \( \Omega_m \), \( \Omega_{\Lambda} \), and \( h \) correspond, respectively, to the matter density, dark energy density in units of the critical density, and the Hubble parameter in units of \( 100 \, \text{km s}^{-1} \text{Mpc}^{-1} \). All magnitudes are in AB magnitudes unless otherwise stated.

2. DATA HANDLING

2.1. Observations and NEWFIRM Filters

We observed the Large Area Lyman Alpha survey (LALA) Cetus field (R.A. 02:05:20, decl. –04:53:43; Rhoads et al. 2000b) during a six night observing run with the NOAO7 Extremely Wide-Field Infrared Mosaic (NEWFIRM) imager (Autry et al. 2003) at the Kitt Peak National Observatory’s (KPNO) 4 m Mayall Telescope during 2008 October 1–6.

We used the University of Maryland 1.063 μm ultra-narrowband (UNB) filter, for a total of 28.7 hr of integration time, along with 5.3 hr integration in the broadband \( J \) filter. Both narrow- and \( J \)-band data were obtained on each clear night of observing. NEWFIRM covers a 28′ × 28′ field of view using an array of four detector chips arranged in a 2 × 2 mosaic, with adjacent chips separated by a gap of 35′. Each chip is a 2048 × 2048 pixel ALADDIN InSb array, with a pixel scale of 0.4 pixel \( ^{-1} \). The instantaneous solid angle coverage of the NEWFIRM camera is about 745′′.

The LALA Cetus field has been previously studied at shorter wavelengths, most notably by the LALA survey (Malhotra & Rhoads 2002; Wang et al. 2009) in narrowbands with \( \lambda_c \approx 656, 660, 664, 668, \) and 672 nm, and \( \Delta \lambda \approx 80 \, \text{Å} \); the NOAO Deep Wide Field Survey (NDWFS; Jannuzi & Dey 1999), with broadband optical \( B, R, \) and \( I \) filters; using MMT/Megacam \( g', r', i' \), and \( z' \) filters (Finkelstein et al. 2007); and \( Chandra \), with 180 ks of ACIS-I imaging (Wang et al. 2004, 2007). In summary, we use narrowband UNB and broadband \( J \) data obtained using NEWFIRM, and previously obtained \( B, R, \) and \( J \)-band data (NDWFS) for this study. The MMT/Megacam images cover about 55% of the area we observed with NEWFIRM, and we used these deeper optical \( g', r', i' \), and \( z' \) images (Finkelstein et al. 2007) to check our final Lyα candidates where possible (see Section 3).

The \( J \) filter on NEWFIRM follows the Tokunaga et al. (2002) filter specifications, with \( \lambda_c = 1.25 \, \text{μm} \) and an FWHM of 0.16 μm. The UNB filter is an ultra-narrowband filter, similar to the DAzLE narrowband filters (Horton et al. 2004), centered at 1.063 μm with an FWHM of 8.1 Å. We used Fowler 8 sampling (non-destructive readout) in all science frames. In the UNB filter, we used single 1200 s exposures between dither positions; in the \( J \) band, two co-added 30 s frames.

The NEWFIRM filter wheel places the filters in a collimated beam. As a consequence, the effective central wavelength of the narrowband filter varies with position in the field of view. Beyond a radius of 12′, the central wavelength of the UNB filter shifts sufficiently to include two weak OH emission lines in the bandpass, which appear as concentric rings in the narrowband images, and which limit the survey area where the filter’s maximum sensitivity (limited by only the inter-line sky background) can be achieved. Figure 1 shows the narrowband filter transmission curve along with night sky OH emission lines. The UNB filter is designed to avoid OH lines.

2.2. Data Reduction

We reduced UNB and \( J \)-band data using a combination of standard IRAF8 tasks, predominantly from the mscred (Valdes 1998) and nfextern9 (Dickinson & Valdes 2009) packages, along with custom IDL10 reduction procedures.

To remove OH rings from UNB data, we created a radial profile for each individual exposure, smoothed over a small radius interval \( dr \), and subtracted this profile from the exposure.

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7 National Optical Astronomy Observatory.

8 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

9 An external IRAF package for NEWFIRM data reduction.

10 Interactive Data Language.
We now assess the accuracy of the sky subtraction method, to understand the noise distribution we constructed sky background, and background noise maps using SExtractor (Bertin & Arnouts 1996). The sky subtraction is sufficiently uniform throughout the image except in the corners, i.e., beyond the OH line affected regions. The noise, due to sky brightness, is also consistent with the expected Poisson noise distribution from sky photons.

To evaluate the uncertainty in the astrometric calibration, we compared the world coordinates of the sources in the UNB stack (obtained using SExtractor) and the corresponding object coordinates from the 2MASS catalog. We found that the uncertainty in the astrometric calibration is very small and independent of the position in the UNB image. The rms of the matched coordinates of UNB and 2MASS is about 0.12 and 0.13 in RA and decl., respectively.

We obtained reduced stacks of deep optical broadband data in the $B_v$, $R$, and $I$ filters, previously observed by the NDWFS. At the end, we have one deep UNB stack, along with five single-night UNB stacks, four broadband stacks in $J$, $B_v$, $R$, and $I$ filters, and four deep stacks in $g'$, $r'$, $i'$, and $z'$ (Finkelman et al. 2009b). All the stacks were then geometrically matched for ease of comparison.

2.3. Photometric Calibration

We performed photometric calibration of UNB and $J$-band ($J_{2M}$) data by comparing unsaturated point sources, extracted using SExtractor, with 2MASS stars. From the 2MASS catalog we selected only those stars that had $J$-band ($J_{2M}$) magnitudes between 13.8 and 16.8 AB mag, and errors less than 0.1 mag. Since four quadrants of the UNB stack had slightly different zero points, we scaled three quadrants, selected geometrically, to the fourth quadrant, which was closest to the mean zero point, by multiplying each quadrant with suitable scaling factors so as to make the zero point uniform throughout the image. We then obtained zero points for UNB and $J_{2M}$ by minimizing the difference between UNB and $J_{2M}$, and between $J_{2M}$ and $J_{NF}$, respectively. This left 0.09 rms mag between $J_{2M}$ and $J_{NF}$ magnitudes, and 0.07 rms mag between UNB and $J_{2M}$ magnitudes. The photometric calibration was based on about 30 and 80 2MASS stars for narrowband and $J$ band, respectively. So, the accuracy of the photometric zero points is about ±0.02 mag in both $J$ and UNB filters.

In addition to the error we have already estimated, there is some uncertainty arising due to different filter widths and differing central wavelengths of the 2MASS and UNB filter. To estimate this uncertainty, we constructed observed spectral energy distributions (SEDs) of stars that were common to both, the UNB image, and the $g'$, $r'$, $i'$, $z'$, $J$, $H$, and $K$ images. From each SED, linearly interpolated flux at central wavelengths of the UNB filter and $J$ filter was measured. From these SEDs, we found the median offset between the UNB and $J$ band to be <0.1 mag. This residual color-term uncertainty in the photometric zero points is smaller than the photometric flux uncertainty in any of our Lyα candidates.

Before we proceed to calculate the limiting magnitudes, we estimate the sky brightness between the OH lines in the UNB image. To estimate this sky value, we construct the UNB stack in the same way as described in Section 2.2 but omitting the OH ring subtraction and sky subtraction. In addition, we subtracted dark current counts from each raw frame. We
estimated the average sky brightness in the UNB image by selecting 30 random regions avoiding astronomical objects and OH rings. This gives us the sky brightness, between the OH lines, of about 21.2 mag arcsec$^{-2}$ equivalent to 162 photons s$^{-1}$ m$^{-2}$ arcsec$^{-2}$ $\mu$m$^{-1}$. This sky brightness is much fainter than the J-band sky brightness which is about 16.1 mag arcsec$^{-2}$ equivalent to 17,000 photons s$^{-1}$ m$^{-2}$ arcsec$^{-2}$ $\mu$m$^{-1}$ (Maihara et al. 1993). However, more careful analysis is needed to estimate the interline sky brightness in the UNB images.

2.4. Limiting Magnitudes

To obtain limiting magnitudes of stacked images, we performed a series of artificial source simulations. In each, we introduced 400 artificial point sources in a 0.1 mag bin of flux in the final stacked image. The positions were chosen randomly, but constrained to avoid places close to bright stars and already existing sources. We then ran SExtractor, with the same parameters as were used for the real source detection (see Section 3), to calculate the fraction of recovered artificial sources. We ran 20 such simulations in each 0.1 mag bin from UNB = 21 to 24 mag. The 50% completeness level is UNB = 22.5 mag, which corresponds to an emission line flux of $6 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$. The very narrow bandpass results in a relatively bright continuum limit (compared to more conventional narrowband filters with 1%–1.5% bandpass), but the conversion between narrowband magnitude and line flux is extremely favorable, so that our line flux limits are competitive with any narrowband search in the literature. The 50% completeness for other filters $B_w$, $R$, $I$, and $J_{SP}$ correspond to 26.3, 25.4, 25.0, and 23.5 mag, respectively.

3. Ly$\alpha$ Candidate Selection

We identified sources in the stacked narrowband image using SExtractor. To measure their fluxes at other wavelengths, we first identified sources in the stacked narrowband image using SExtractor in dual-image mode to be combined and extracting the pixels that are dominated by object flux. We then used SExtractor with the same parameters as were used for the real source detection (see Section 3), to calculate the fraction of recovered artificial sources. We ran 20 such simulations in each 0.1 mag bin from UNB = 21 to 24 mag. The 50% completeness level is UNB = 22.5 mag, which corresponds to an emission line flux of $6 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$. The very narrow bandpass results in a relatively bright continuum limit (compared to more conventional narrowband filters with 1%–1.5% bandpass), but the conversion between narrowband magnitude and line flux is extremely favorable, so that our line flux limits are competitive with any narrowband search in the literature. The 50% completeness for other filters $B_w$, $R$, $I$, and $J_{SP}$ correspond to 26.3, 25.4, 25.0, and 23.5 mag, respectively.

3.1. Constant Flux Test

In our constant flux test (criterion 5 above), we looked at the variation of flux of each Ly$\alpha$ candidate over five nights. We reject any source having individual night stack fluxes close to zero or showing flux variations above a certain chi-square value. To do this, we generated light curves of each candidate using individual night stacks of UNB, and then determined the $\chi^2$ of the data with respect to the best-fitting constant flux. Since we had five nights of data, we selected only those candidates that had a chi-square $<5$. This is in addition to requiring signal-to-noise ratio $S/N > 5$, which guards against peaks in the sky noise entering the candidate list.

We also eliminated all the sources that were very close to the chip boundaries. Combining these criteria with the set of criteria from Section 3, we had six Ly$\alpha$ emitter candidates. To increase the reliability of these candidates, we finally selected four candidates after independent visual inspection by four of the authors. Figure 2 shows postage stamps of all four Ly$\alpha$ candidates. The candidates are clearly visible in the UNB images (middle panel), while undetected in the combined optical (left panel), and J-band images (right panel). We provide the coordinates of our Ly$\alpha$ candidates in Table 1.

4. Contamination of the Sample

While we have carefully selected Ly$\alpha$ candidates based on photometric and geometric criteria, it is possible that our Ly$\alpha$ candidates can be contaminated by sources that include transient objects such as supernova, cool stars (L and T dwarfs), foreground emission line sources, and electronic noise in the detector. We now discuss the possible contribution of sources that can contaminate our Ly$\alpha$ candidate sample.

4.1. Foreground Emission Line Objects

Our Ly$\alpha$ candidate selection can include foreground emission line sources including [O II] emitters ($\lambda = 3727$ Å) at $z = 1.85$, [O III] ($\lambda = 5007$ Å) emitters at $z = 1.12$, and H$\alpha$($\lambda = 6563$ Å) emitters at $z = 0.62$, if they have strong emission line flux but faint continuum emission. We now estimate the number of foreground emitters that can pass our Ly$\alpha$ candidate selection criteria.

In our UNB stack, the 50% completeness limit corresponds to a flux of $6 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$. Therefore, the minimum luminosities required by the foreground emission line sources to be detected in our survey are $1.5 \times 10^{41}$ erg s$^{-1}$, $4 \times 10^{40}$ erg s$^{-1}$, $L_*$, and $L_{Edd}$.
and $1 \times 10^{40} \text{ erg s}^{-1}$ for [O II], [O III], and Hα emitters, respectively.

Given the depth of our combined optical image, we can calculate the minimum observer frame EW ($\text{EW}_{\text{min}}$) that would be required for an emission line object to be a Lyα emitter candidate. We calculated the observer frame EW using the following relation (Rhoads & Malhotra 2001):

$$\text{EW}_{\text{min}} \approx \left[ \frac{f_{\text{nb}}}{f_{\text{bb}}} - 1 \right] \Delta \lambda_{\text{abs}} = \left[ \frac{5\sigma_{\text{nb}}}{2\sigma_{\text{bb}}} - 1 \right] \Delta \lambda_{\text{abs}},$$  \hspace{1cm} (1)

where $f_{\text{nb}}$ and $f_{\text{bb}}$ are flux densities in UNB and the combined optical image, respectively, $\Delta \lambda_{\text{abs}}$ is the UNB filter width, and $\sigma_{\text{nb}}$ and $\sigma_{\text{bb}}$ are the uncertainties in flux measurements in UNB and the combined optical image, respectively. (The implicit approximation that the continuum contributes negligibly to the narrowband flux, is well justified for our 9 Å bandpass.) With $5\sigma_{\text{nb}} = 7.8 \times 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$ and $2\sigma_{\text{bb}} = 1.5 \times 10^{-30} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$, we found that the foreground emission line sources would require $\text{EW}_{\text{min}} \gtrsim 460 \text{ Å}$ to contaminate our Lyα candidate sample.

### 4.1.1. Foreground [O II] and [O III] emitters

Unfortunately, the EW distribution of [O II] emitters has not been directly measured at $z = 1.85$. However, several authors (Teplitz et al. 2003; Kakazu et al. 2007; Straughn et al. 2009) have studied [O II] emitters at $z < 1.5$. Here, we use [O II] EW distribution, obtained by Straughn et al. (2009) at $z \approx 1$ in the GOODS-South field, with the assumption that there is no significant evolution of the [O II] LF from $z = 1$ to $z = 1.85$. In our Lyα candidate selection, emission line sources with $f_{\text{AB}}$ fainter than 25.9 mag, and with $\text{EW}_{\text{obs}} > 460 \text{ Å}$ can contaminate our sample. We determined which sources from Straughn et al. (2009) would have passed these criteria if redshifted to $z = 1.85$, and scaled the result by the ratio of volumes between the two surveys. We find that less than one (0.1) [O II] emitter is expected to contaminate our Lyα candidate sample. To be conservative, even if we relax the above magnitude cut by 0.5 mag to account for any color correction, and lower the $\text{EW}_{\text{obs}} > 200 \text{ Å}$, we find that less than 0.3 [O II] emitters should be expected to contaminate our sample.

We apply a similar methodology to estimate the contamination from foreground [O III] emitters (Kakazu et al. 2007; Hu et al. 2009; Straughn et al. 2009, 2010) at $z \approx 1.1$ in our NEWFIRM data using the [O III] emission line sources at $z = 0.5$ in Straughn et al. (2009).

We found that less than two (1.7) [O III] emitters can be misidentified as Lyα emitters in our survey. In addition to the above estimate, we used a recent sample of emission line galaxies obtained from the Hubble Space Telescope WFC3 early release science data (Straughn et al. 2010). This sample of [O III] emitters is closer in redshift, with median $z = 1.1$, to our foreground [O III] interloper redshift of $z = 1.12$, thus minimizing the error in our [O III] estimate due to possible evolution in the LF of [O III] emitters. Using this recent sample, we found that about one [O III] emitter is expected to contaminate our Lyα candidate sample.

### 4.1.2. Foreground Hα emitters

As mentioned earlier, Hα emitters at $z = 0.62$ can contaminate our Lyα candidate sample. Several authors (Tresse et al. 2002; Straughn et al. 2009) have studied Hα emitters at similar redshift. Tresse et al. (2002, see their Figure 6) have plotted the Hα luminosity versus the continuum $B$-band magnitude of Hα emitters. To pass our selection criteria, an Hα emitter would require a luminosity greater than $1 \times 10^{40} \text{ erg s}^{-1}$ and flux density $f_{B_{\text{w}}} < 7.5 \times 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$ which corresponds to $M_{\text{AB}} = -15.97 \text{ mag}$. Any source brighter than $M_{\text{AB}} = -15.97 \text{ mag}$ would be detected in the $B_{\text{w}}$ image, and hence rejected from the Lyα candidate list. From Figure 6 of Tresse et al. (2002), we expect to find no sources that can pass this selection criterion. In addition, we used Hα emitters at $z = 0.27$ (Straughn et al. 2009) and found that less than one (0.4) Hα emitters are expected to contaminate our Lyα candidate sample.

### 4.2. Other Contaminants

Transient objects: we rule out the possibility of contamination of our Lyα candidates by transient objects such as supernovae, because these objects would appear in both UNB and $J$-band stacks. Both UNB and $J$ data were obtained on each clear night of the run.

L and T dwarfs: following Hibon et al. (2010) we determined the expected number of L/T dwarfs in our survey. From the spectral type versus absolute magnitude relations given by Figure 9 in Tinney et al. (2003), we infer that we could detect L dwarfs at a distance of 400–1300 pc and T dwarfs at a distance of 150–600 pc, from the coolest to the warmest spectral types.

Our field is located at a high galactic latitude, so that we would be able to detect L/T dwarfs well beyond the Galactic disk scale height. However, only a Galactic disk scale height of 350 pc is applicable to the population of L/T dwarfs (Ryan et al. 2005). We then derive a sampled volume of $\sim 750 \text{ pc}^3$. Considering a volume density of L/T dwarfs of a few $10^{-3} \text{ pc}^{-3}$, we expect no more than one L/T dwarf in our field.

While we expect about one L/T dwarf in our survey, we further investigate if any of the observed L/T dwarfs pass our selection criteria. To do this, we selected about 160 observed spectra of L/T dwarfs (Golimowski et al. 2004; Knapp et al. 2004; Chiu et al. 2006), and calculated the flux transmitted through the UNB and $J$-band filter. We found that none of the L/T dwarfs has sufficient narrowband excess to pass our selection criteria. Therefore, it is unlikely that our Lyα candidate sample is contaminated by L/T dwarfs.

Noise spikes: noise in the detector can cause random flux increase in the UNB filter. To avoid contamination from such noise spikes, we constructed light curves of each candidate using individual night stacks, i.e., we selected candidates only if their flux was constant over all nights. This method of candidate selection based on the constant flux in the individual night stacks also eliminates the possible contamination from persistence.

Contribution from false detection: finally, we performed a false detection test to estimate the number of false detection that can pass our Lyα selection criteria. To do this we multiplied the UNB stack by $-1$ and repeated the exact same procedure as the real Lyα candidate selection (see Section 3). We did not get any false detections passing our selection criteria.

### 5. MONTE CARLO SIMULATIONS

Based on the above estimates, less than two [O III] emitters are expected to be misidentified as Lyα emitters in our survey.

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13 http://staff.gemini.edu/~sleggett/LTdata.html
To estimate the number of sources that should be detected in our survey for a given Ly$\alpha$ LF, we performed detailed Monte Carlo simulations. This is needed, since the width of the filter is comparable to or slightly smaller than the expected line width in these galaxies, so many of the sources will not be detected at their real line fluxes. In these simulations, we used the $z = 6.6$ Ly$\alpha$ LF derived by Kashikawa et al. (2006).

First, we generated one million random galaxies distributed according to the observed Ly$\alpha$ LF at $z = 6.6$ (Kashikawa et al. 2006). Each of these galaxies was assigned a Ly$\alpha$ luminosity in the range $1 \times 10^{42}$ erg s$^{-1} < L_{\text{Ly}\alpha} < 1.5 \times 10^{43}$ erg s$^{-1}$. Here we assumed that the Ly$\alpha$ LF does not evolve from $z = 6.6$ to $z = 7.7$. Each galaxy was then assigned a random redshift $z_L < z < z_H$, where $z_L$ and $z_H$ correspond to the minimum and maximum wavelengths, where the transmission of the UNB filter drops to zero.

Next, to each galaxy we assigned a flux $F = L_{\text{Ly}\alpha}/4\pi d_L^2$, where $d_L$ is the luminosity distance. We distribute this flux in wavelength using an asymmetric Ly$\alpha$ line profile drawn from the $z = 5.7$ spectra of Rhoads et al. (2003). The flux transmitted through the UNB filter was then determined as $f_{\text{trans}} = \int f_T d\lambda$, where $f_T$ is the filter transmission and $f_\lambda$ is the flux density of the emission line. This accounts for the loss of the Ly$\alpha$ flux that results from a filter whose width is comparable to the line width (and not much greater as would be the case for a 1% filter). We then created a histogram of magnitudes after converting the convolved flux to magnitudes calculated using the following relation:

$$\text{mag}_{\text{AB}} = -2.5 \log_{10} \left( \frac{f_{\text{trans}}}{f_0} \right), \quad (2)$$

and

$$f_0 = \frac{3.6 \text{ kJy} \times c}{(1.06 \mu^2) \times \int T_\lambda d\lambda} \text{ erg s}^{-1}\text{cm}^{-2}, \quad (3)$$

with $c$ being the speed of light.

Finally, to include the instrumental effects, we multiplied the number of galaxies in each magnitude bin by the corresponding recovery fraction obtained from our artificial source simulations in our UNB image (see Section 2.4). We then converted each magnitude bin to a Ly$\alpha$ luminosity bin and counted the number of detected galaxies in each luminosity bin.

We repeated this simulation 10 times, and taking an average, we found that about one Ly$\alpha$ emitter should be expected in our survey. It should be noted that we assumed a non-evolving Ly$\alpha$ LF from $z = 6.6$ to $z = 7.7$, and that every Ly$\alpha$ emitter has the same asymmetric Ly$\alpha$ line profile. While we expect about one Ly$\alpha$ emitter in our survey there are large uncertainties mainly due to the Poisson noise, and field-to-field variation or cosmic variance. Tilvi et al. (2009) have estimated field-to-field variation of Ly$\alpha$ emitters to be $\geq 30\%$ for a volume- and flux-limited Ly$\alpha$ survey with a survey volume $\sim 2 \times 10^5$ Mpc$^3$. We expect a larger field-to-field variation for smaller survey volumes. We also estimated the cosmic variance expected in our survey using the cosmic variance calculator (Trenti & Stiavelli 2008). For our survey, we should expect a cosmic variance of about 58% assuming an intrinsic number of Ly$\alpha$ sources at $z = 7.7$ in agreement with a non-evolving Ly$\alpha$ LF from $z = 6.6$ (Kashikawa et al. 2006) to $z = 7.7$. On the other hand, our candidate counts are quite consistent with the LF at $z = 5.7$ (Ouchi et al. 2009).

6. **LY$\alpha$ Luminosity Function at $z = 7.7$**

Using a large sample of Ly$\alpha$ candidates, Ouchi et al. (2008) found no significant evolution of Ly$\alpha$ LF between $z = 3.1$ and $z = 5.7$. The evolution of the Ly$\alpha$ LF between $z = 5.7$ and $z = 6.5$ is not conclusive. For example, Malhotra & Rhoads (2004) found no significant evolution of the Ly$\alpha$ LF between $z = 5.7$ and $z = 6.5$, while Kashikawa et al. (2006) suggest an evolution of the bright end of the LF in this redshift range. On the theoretical front, several models (Thommes & Meisenheimer 2005; Furlanetto et al. 2005; Le Delliou et al. 2006; Dijkstra et al. 2007; Kobayashi et al. 2007; McQuinn et al. 2007; Dayal et al. 2008; Nagamine et al. 2008; Samui et al. 2009; Tilvi et al. 2009) have been developed to predict the redshift evolution of the Ly$\alpha$ LF. While several models (e.g., Samui et al. 2009; Tilvi et al. 2009) predict no significant evolution of the Ly$\alpha$ LF at $z \leq 7$, the predictions differ greatly among different models. These differences among the models can be attributed to differing input assumptions, which in turn stem from our imperfect understanding of the physical nature of Ly$\alpha$ galaxies and from the small samples currently available at high redshift.

At $z > 6.5$, there are only a few searches for Ly$\alpha$ emitters. Iye et al. (2006) found one spectroscopically confirmed LAE at $z = 6.96$, and currently there are no spectroscopically confirmed LAEs at $z > 7$. However, there are few photometric searches (Parkes et al. 1994; Willis & Courbin 2005; Cuby et al. 2007; Hibon et al. 2010) for Ly$\alpha$ galaxies, and constraints on the Ly$\alpha$ LF at $z > 7$. Table 2 shows details of different Ly$\alpha$ searches at $z > 7$.

After careful selection of Ly$\alpha$ candidates and eliminating possible sources of contamination, we have found four Ly$\alpha$ emitter candidates in a survey area of $28 \times 28$ arcmin$^2$, with a limiting flux of $6 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$. The fluxes of these four candidates are 1.1, 0.91, 0.84, and 0.72 in units of $10^{-17}$ erg s$^{-1}$ cm$^{-2}$. Figure 3 shows the resulting cumulative Ly$\alpha$ LF. Solid filled circles show the Ly$\alpha$ LF derived from our
candidates, while open circles represent the Lyα LF s from Hibon et al. (2010). Arrows indicate that this is the upper limit on the Lyα LF and upper error bars are the Poisson errors. The dotted and dashed lines show the Lyα LFs from Ouchi et al. (2008) and Kashikawa et al. (2006), respectively. The open square is the Lyα LF at $z = 6.96$ (Iye et al. 2006).

If all of our Lyα candidates are $z = 7.7$ galaxies, the LF derived from our sample shows moderate evolution compared to the LF at $z = 6.5$ (Kashikawa et al. 2006). On the other hand, conservatively, if only one of the candidates is a $z = 7.7$ galaxy, then the Lyα LF does not show any evolution compared to the $z = 6.6$ Lyα LF. Hibon et al. (2010) conclude that the observed Lyα LF at $z = 7.7$ does not evolve significantly compared to Lyα LF at $z = 6.5$ (Kashikawa et al. 2006), if they consider that all of their candidates are real. Finally, while our Lyα LF lies above the LF obtained by Hibon et al. (2010), the counts are consistent with the number of star-forming galaxies in the HUDF with inferred Lyα line fluxes $> 6 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ (Finkelstein et al. 2009a), and also consistent with the Lyα LF at $z = 5.7$ (Ouchi et al. 2008).

As described in Section 5, all surveys for Lyα emitters at $z > 6$ suffer from cosmic variance. We do expect to see field-to-field variation in number counts even at the same redshift. Therefore, it is important to get statistics from more than one field for each redshift. The field-to-field variation is expected to be stronger for brighter sources. Therefore the higher redshift surveys, which are more sensitivity limited, are hit the hardest.

7. Lyα EQUIVALENT WIDTH

Several studies have found numerous Lyα emitters having large rest-frame EWs, $\text{EW}_{\text{rest}} > 240$ Å (Malhotra & Rhoads 2002; Shimasaku et al. 2006; Dawson et al. 2007; Gronwall et al. 2007; Ouchi et al. 2008). These exceed theoretical predictions for normal star-forming galaxies.

Since the $J$-band filter does not include the Lyα line, we have used the following relation to calculate the rest-frame Lyα EWs for our four Lyα candidates:

$$\text{EW}_{\text{rest}} = \frac{f_{\text{NB}}}{f_{\lambda, \text{BB}}} \times \frac{1}{(1 + z)}.$$  (4)

Here $f_{\text{NB}}$ and $f_{\lambda, \text{BB}}$ are the UNB line flux (erg s$^{-1}$ cm$^{-2}$), and $J$-band flux (erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$), respectively. Since none of the four candidates are detected in the $J$ band, we used the $J$ band limiting magnitude to calculate a lower limit on the Lyα EWs. We note that the Lyα EW will depend on the exact redshift, shape, and precise position of the Lyα line in the UNB filter. However, for simplicity and because we only put lower limits on EWs, we assume that the UNB filter encloses all the Lyα line flux in calculating EWs.

For our Lyα candidates, with line flux estimates from 7 to $11 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$, and our broadband limit $J_{\text{NF}} \geq 23.5$ mag, we find Lyα EW$_{\text{rest}} \gtrsim 3$ Å.

This EW limit is considerably smaller than the EW$_{\text{rest}} > 9$ Å obtained by Hibon et al. (2010) for their Lyα candidates at $z = 7.7$. This difference arises due to the smaller bandwidth of our UNB filter and our somewhat shallower $J$-band imaging. Deep $J$-band observations will help in getting either measurements or stricter lower limits on the line EWs, but will also be observationally challenging.

8. SUMMARY AND CONCLUSIONS

We have performed a deep, wide field search for $z = 7.7$ Lyα emitters on the NEWFIRM camera at the KPNO 4 m Mayall telescope. We used a UNB filter with width 9 Å and central wavelength of 1.063 μm, yielding high sensitivity to narrow emission lines.

After careful selection of candidates by eliminating possible sources of contamination, we detected four candidate Lyα emitters with line flux $> 6 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ in a comoving volume of $1.4 \times 10^{4}$ Mpc$^3$. While we have carefully selected these four Lyα candidates, we note that the number of Lyα candidates is more than the expected number obtained by using the $z = 6.6$ LF of Kashikawa et al. (2006), though quite consistent with the $z = 5.7$ LF of Ouchi et al. (2008). Hence, our results would allow for a modest increase in the Lyα LF from $z = 6.5$ to $z \approx 8$. Spectroscopic confirmation of more than two candidates would show that such an increase is in fact required. However, more surveys are needed to account for the uncertainty due to cosmic variance.

In order to use the Lyα LFs as a test of reionization, we need to be able to detect variations in $L^*$, the characteristic luminosity, of factors of 3 or 4. This will require larger samples, spectroscopic confirmations, and a measure of field-to-field variation.

It is therefore premature to draw any conclusions about reionization from the current sample. It is, however, encouraging that we are able to reach the sensitivity and volume required to detect multiple candidates robustly.

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