

A LUMINOSITY FUNCTION OF Ly α -EMITTING GALAXIES AT $z \approx 4.5$ ^{1,2}

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ABSTRACT

We present a catalog of 59 $z \approx 4.5$ Ly α -emitting galaxies spectroscopically confirmed in a campaign of Keck DEIMOS follow-up observations to candidates selected in the Large Area Ly α (LALA) narrowband imaging survey. We targeted 97 candidates for spectroscopic follow-up; by accounting for the variety of conditions under which we performed spectroscopy, we estimate a selection reliability of $\sim 76\%$. Together with our previous sample of Keck LRIS confirmations, the 59 sources confirmed herein bring the total catalog to 73 spectroscopically confirmed $z \approx 4.5$ Ly α -emitting galaxies in the ≈ 0.7 deg² covered by the LALA imaging. As with the Keck LRIS sample, we find that a nonnegligible fraction of the confirmed Ly α lines have rest-frame equivalent widths ($W_{\lambda}^{\text{rest}}$) that exceed the maximum predicted for normal stellar populations: 17%–31% (93% confidence) of the detected galaxies show $W_{\lambda}^{\text{rest}} > 190$ Å, and 12%–27% (90% confidence) show $W_{\lambda}^{\text{rest}} > 240$ Å. We construct a luminosity function of $z \approx 4.5$ Ly α emission lines for comparison to Ly α luminosity functions spanning $3.1 < z < 6.6$. We find no significant evidence for Ly α luminosity function evolution from $z \approx 3$ to $z \approx 6$. This result supports the conclusion that the intergalactic medium remains largely reionized from the local universe out to $z \approx 6.5$. It is somewhat at odds with the pronounced drop in the cosmic star formation rate density recently measured between $z \sim 3$ and $z \sim 6$ in continuum-selected Lyman-break galaxies, and therefore potentially sheds light on the relationship between the two populations.

Subject headings: cosmology: observations — early universe — galaxies: evolution — galaxies: formation — galaxies: high-redshift

Online material: color figures

1. INTRODUCTION

Observational cosmology has recently witnessed a tremendous increase in proficiency in the identification of galaxies at the earliest cosmic epochs. Thanks in large part to the availability of large-format mosaic CCDs well suited for wide-field imaging and spectroscopic multiplexing, we are now transitioning from exotic, single detections of high-redshift galaxies (e.g., Dey et al. 1998; Weymann et al. 1998; Ellis et al. 2001; Ajiki et al. 2002; Dawson et al. 2002; Hu et al. 2002; Cuby et al. 2003; Taniguchi et al. 2003; Nagao et al. 2004; Rhoads et al. 2004; Stern et al. 2005) to the assembly of statistically robust samples spanning the earliest accessible redshifts. Robust samples of this kind are necessary for understanding the systematics of selection criteria and

of the spatial distribution of the galaxies themselves. Deficiencies in such understanding are the main source of uncertainty in inferred luminosity functions (LFs) and universal star formation rates (SFRs), which in turn are the keys to understanding the cosmic history of star formation, galaxy assembly and evolution, and even the early ionization history of the intergalactic medium (IGM; e.g., Malhotra & Rhoads 2004; Stern et al. 2005).

Searches for high-redshift galaxies typically follow the by-now familiar strategy of targeting redshifted Ly α emission at increasing wavelengths with narrowband imaging in windows of low night-sky emission (e.g., Cowie & Hu 1998; Hu et al. 1998, 2004; Rhoads et al. 2000; Kodaira et al. 2003; Maier et al. 2003; Taniguchi et al. 2005), or by photometric selection in broadband imaging of the redshifted Lyman break (e.g., Steidel et al. 1996; Madau et al. 1996; Lowenthal et al. 1997; Spinrad et al. 1998; Lehnert & Bremer 2003; Ando et al. 2004; Bouwens et al. 2004; Dickinson et al. 2004; Ouchi et al. 2004; Stanway et al. 2004a, 2004b; Yan & Windhorst 2004). These two techniques are complementary; Ly α searches at typical sensitivities can identify galaxies with UV continua too faint to be detected by the Lyman-break method, but such surveys only select that fraction of galaxies with strong line emission.

The Large Area Ly α (LALA) survey (Rhoads et al. 2000) has recently identified in deep narrowband imaging a large sample of Ly α -emitting galaxies at redshifts $z \approx 4.5$ (Malhotra & Rhoads 2002), $z \approx 5.7$ (Rhoads & Malhotra 2001; Rhoads et al. 2003), and $z \approx 6.5$ (Rhoads et al. 2004). In Dawson et al. 2004 (hereafter Paper I), we reported on the spectroscopic confirmation with the W. M. Keck Observatory's Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) of 17 Ly α -emitting galaxies selected in the LALA $z \approx 4.5$ survey. The resulting sample of confirmed Ly α emission lines showed large equivalent widths (median $W_{\lambda}^{\text{rest}} \approx 80$ Å) but narrow velocity widths

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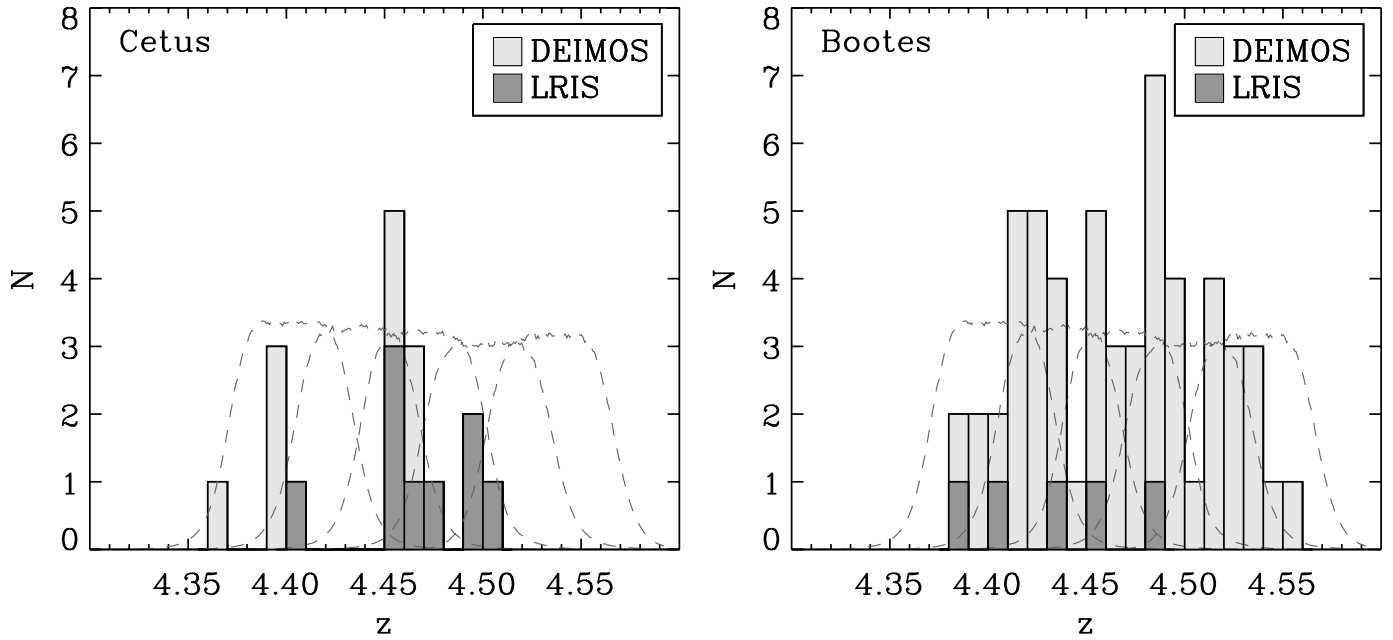


FIG. 1.—Distribution of redshifts for spectroscopically confirmed Ly α emission lines in the Cetus field (*left*; $02^{\text{h}}05^{\text{m}}20^{\text{s}}$, $-04^{\circ}55'$ [J2000.0]) and in the Boötes field (*right*; $14^{\text{h}}25^{\text{m}}57^{\text{s}}$, $+35^{\circ}32'$ [J2000.0]). The redshifts labeled “DEIMOS” denote galaxies confirmed with our campaign of Keck DEIMOS spectroscopy, described in this paper. The redshifts labeled “LRIS” denote galaxies confirmed with our campaign of Keck LRIS spectroscopy, described in Paper I. The overlays are arbitrarily scaled transmission curves for the five narrowband filters employed in the imaging component of this survey.

(FWHM $\Delta v < 500 \text{ km s}^{-1}$), indicating that the Ly α emission in these sources derives from star formation, not from active galactic nucleus (AGN) activity. Models of star formation in the early universe predict that a small fraction of Ly α -emitting galaxies at $z \approx 4.5$ may be nascent, metal-free objects (e.g., Scannapieco et al. 2003), and indeed we found with 90% confidence that three to five of the confirmed sources exceed the maximum Ly α equivalent width predicted for normal stellar populations. However, we did not detect the He II $\lambda 1640$ emission expected to be characteristic of primordial star formation. Specifically, the He II $\lambda 1640$ flux in a composite of the 11 highest resolution spectra in the Keck/LRIS sample was formally consistent with zero, with a 2σ (3σ) upper limit of 13% (20%) of the flux in the Ly α line. In other words, although these galaxies may be young, they show no evidence of being truly primitive, Population III objects.

We have recently more than quadrupled our catalog of spectroscopically confirmed Ly α -emitting galaxies at $z \approx 4.5$ with a spectroscopic campaign using the W. M. Keck Observatory’s Deep Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003), targeting candidates selected from the LALA survey. Together with the detections presented in Paper I (and accounting for minor overlap in the samples), the 59 Ly α emitters confirmed with Keck DEIMOS bring the total catalog to 73 spectroscopically confirmed $z \approx 4.5$ Ly α -emitting galaxies in the $\approx 0.7 \text{ deg}^2$ imaged by LALA. In this paper, we use these additional confirmations to update the results of Paper I and to construct a luminosity function of $z \approx 4.5$ Ly α emission lines for comparison to Ly α LFs spanning $3.1 < z < 6.6$. We describe our imaging and spectroscopic observations in § 2, and we summarize the results of the spectroscopic campaign in § 3. In § 4, we investigate the distribution of the Ly α lines in equivalent width, we construct Ly α LFs for our sample and for several extant samples, and we discuss the implications of the LFs for the relationship between Ly α emitters and Lyman-break galaxies (LBGs) and for the history of reionization. Throughout this paper we adopt a Λ -cosmology with $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Spergel

et al. 2003). At $z = 4.5$, such a universe is 1.3 Gyr old, the look-back time is 90.2% of the total age of the universe, and an angular size of $1.0''$ corresponds to 6.61 comoving kpc.

2. OBSERVATIONS

2.1. Narrowband and Broadband Imaging

The LALA survey concentrates on two primary fields, “Boötes” ($14^{\text{h}}25^{\text{m}}57^{\text{s}}$, $+35^{\circ}32'$ [J2000.0]) and “Cetus” ($02^{\text{h}}05^{\text{m}}20^{\text{s}}$, $-04^{\circ}55'$ [J2000.0]). Each field is $36' \times 36'$ in size, corresponding to a single field of the 8192×8192 pixel Mosaic CCD cameras on the 4 m Mayall Telescope at Kitt Peak National Observatory and on the 4 m Blanco Telescope at Cerro Tololo Inter-American Observatory. The $z \approx 4.5$ search uses five overlapping narrowband filters each with full width at half-maximum (FWHM) $\approx 80 \text{ \AA}$ (Fig. 1). The central wavelengths are 6559, 6611, 6650, 6692, and 6730 \AA , giving a total redshift coverage of $4.37 < z < 4.57$ and a survey volume of 7.4×10^5 comoving Mpc^3 per field. In roughly 6 hr per filter per field, we achieve 5σ line detections in $2.3''$ apertures of $\approx 2 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1}$.

The primary LALA survey fields were chosen to lie within the NOAO Deep Wide-Field Survey (NDWFS; Jannuzi & Dey 1999). Thus, deep NDWFS broadband images are available in a custom B_W filter ($\lambda_0 = 4135 \text{ \AA}$, FWHM = 1278 \AA ; Jannuzi & Dey 1999; B. Jannuzi et al. 2008, in preparation) and in the Harris set Kron-Cousins R and I , as well as J , H , K , and K_s . The LALA Boötes field benefits from additional deep V - and SDSS z' -filter imaging. The imaging data reduction is described in Rhoads et al. (2000), and the candidate selection is described in Rhoads & Malhotra (2001) and Malhotra & Rhoads (2002). Briefly, candidates are selected based on a 5σ detection in a narrowband filter, the flux density of which must be twice the R -band flux density and must exceed the R -band flux density at the 4σ confidence level. To guard against foreground interlopers, we require an observed equivalent width $W_\lambda^{\text{obs}} > 80 \text{ \AA}$ and a nondetection in the B_W band (at the $< 2\sigma$ level).

2.2. Spectroscopic Observations

Between 2003 March and 2004 May we obtained spectroscopy of 97 $z \approx 4.5$ candidate Ly α -emitters with DEIMOS (Faber et al. 2003), a second-generation camera on the Keck II telescope with high multiplexing capabilities and improved red sensitivity. Each slit mask included approximately 15 candidate Ly α emitters (mixed in with roughly 50 other spectroscopic targets) and was observed for 1.5–2.0 hr in 0.5 hr increments. Six slit masks targeting a total of 80 candidates were observed in the Boötes field; the air mass in these observations never exceeded 1.5. One slit mask targeting 17 candidates was observed in the Cetus field; the air mass for this slit mask was constrained to less than 1.8. The seeing in all observations ranged from 0.5'' to 1.0''. We estimated the seeing by examining the alignment stars observed during the direct-imaging phase of setting up the slit mask; that is, the stars were imaged through the BAL12 (clear) filter with the grating angle set such that zero-order light fell on the detector.

All observations employed 1.0'' wide slitlets and the 600ZD grating ($\lambda_{\text{blaze}} = 7500 \text{ \AA}$; $0.65 \text{ \AA pixel}^{-1}$ dispersion; $\Delta\lambda_{\text{FWHM}} \approx 4.5 \text{ \AA} \approx 200 \text{ km s}^{-1}$).⁸ The wavelength range covered by a typical slitlet was roughly $5000 \text{ \AA} \lesssim \lambda \lesssim 10000 \text{ \AA}$. The precise wavelength coverage depended somewhat on the location of the slitlet on the slit mask but never exceeded 4390 \AA at the low extremum or 1.1 \mu m at the high extremum. No order-blocking filter was used; since the targets were primarily selected to have red colors, second-order light should not be of concern. Most nights suffered from some cirrus; relative flux calibration was achieved from observations of standard stars from Massey & Gronwall (1990) observed during the same observing run. It should also be noted that the position angle of an observation was set by the desire to maximize the number of targets on a given slit mask, so observations were generally not made at the parallactic angle.

We processed the two-dimensional data using the DEEP2 DEIMOS pipeline.⁹ We performed small (0.5'') dithers between exposures on our initial observing run; to reduce these data, we supplemented the DEEP2 DEIMOS pipeline with additional home-grown routines. We extracted spectra with the IRAF¹⁰ package (Tody 1993) using the optimal extraction algorithm (Horne 1986), following standard slit-spectroscopy procedures.

Prior experience with faint-object spectroscopy dictates that a small but significant error in the measured flux of faint continua may be introduced by sky subtraction during the processing of the two-dimensional spectra. We investigated this possibility with ~ 10 additional nonoverlapping extractions in source-free regions in each two-dimensional spectrum, parallel to and along the same trace as the extraction of the neighboring Ly α -emitting galaxy. We then fitted these blank-sky spectra over the same region that we fitted for the continuum redward and blueward of the emission line in the object extraction. For 15 sources, these fits yielded a tiny residual signal, which we interpreted as a systematic error in the two-dimensional sky subtraction and applied as a correction to quantities derived from the object spectra. The typical correction

⁸ We measured the instrumental resolution by autocorrelating one-dimensional extracted spectra of night-sky emission lines. The autocorrelation results in an effective average line profile with a high signal-to-noise ratio, which we fit with a Gaussian to obtain the FWHM. We performed this test on ~ 50 night-sky spectra with the result $\Delta\lambda_{\text{FWHM}} = 4.47 \pm 0.03 \text{ \AA}$. The quoted uncertainty is the error in the mean and does not include possible systematic effects due to blended night-sky lines.

⁹ See <http://astron.berkeley.edu/~cooper/deep/spec2d/>.

¹⁰ 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.

was $\sim 0.04 \pm 0.02 \text{ \mu Jy}$, but the correction reached as high as $\sim 0.1 \pm 0.07 \text{ \mu Jy}$ in three cases. Sky-subtraction residuals of this kind generally resulted when a small spectroscopic slit contained a bright serendipitous detection in addition to the target, the combination of which made it difficult to fit the sky background.

3. SPECTROSCOPIC RESULTS

Out of 97 spectroscopic candidates, we achieved 73 detections, 59 of which constitute Ly α confirmations according to the criteria outlined below. A histogram of these confirmations appears in Figure 1, and a set of sample spectra are shown in Figure 2. The spectroscopic properties of the Ly α confirmations are summarized in Table 1. One detected galaxy lacks an emission line but shows a large spectral discontinuity identified as the onset of foreground Ly α -forest absorption at $z = 4.462$.¹¹ Three of the detections are identifiably low-redshift interlopers (two resolved [O II] $\lambda 3727$ doublets at $z \sim 0.8$; one complex of [O III] $\lambda\lambda 4959, 5007$ and H β at $z \sim 0.3$) which survived the candidate selection thanks to their unusually high equivalent widths (e.g., $W_{\lambda}^{\text{obs}} > 2000 \text{ \AA}$). In 10 cases, we see a possible low signal-to-noise ratio (≤ 1) emission line located at the correct location in both wavelength space and physical position to be associated with the narrowband-selected target. However, even if these ‘‘detections’’ are real, they cannot be reliably identified as either Ly α or as low-redshift interlopers. If these 10 cases were in fact low signal-to-noise ratio detections of Ly α emission, then the ‘‘success rate’’ of the Keck DEIMOS campaign would be 72%, identical to that of the Keck LRIS sample described in Paper I (but also subject to all the caveats listed therein). We do not include unconfirmed sources in any of the ensuing discussion.

The remaining 24 targets were classified as nondetections. Five of these slitlets suffered from some kind of instrument or reduction issue; e.g., the target was dithered off the slitlet and so did not reproduce across the individual integrations, or irregularities in the machining of the slit mask resulted in defects in the data processing. Of the final 19 nondetections, 13 targets were observed under adverse conditions (e.g., variable cloud coverage and/or poor seeing) for which the general spectroscopic yield was low. Our failure to confirm these targets as $z \approx 4.5$ Ly α emitters should not be taken to bear on the efficacy of candidate selection.

Six nondetections were observed under photometric conditions with subarcsecond seeing for which the spectroscopic yield was otherwise high. However, subsequent inspection of the imaging revealed that five of these targets were suboptimal candidates for one of a variety of reasons: two candidates sit on weak satellite trail residuals; one candidate appears in an initial epoch of imaging but not in subsequent epochs, suggesting that it is a variable source or a spurious detection; and two candidates are marginal or irregular detections in the imaging. This leaves just one otherwise viable candidate Ly α emitter that was not confirmed in spectroscopy, even though the conditions for spectroscopy were favorable. Since this source (J1424398+353801) was a single-band detection in the narrowband imaging, it is possible that it represents a spurious false positive and not a genuine candidate. Given the large number ($10^{6.5}$) of independent resolution elements in the images, we expect about one false positive at the 5σ level per LALA field per narrowband filter, and this number could be larger

¹¹ A sufficiently bright LBG can be selected as a narrowband excess object when the narrow filter lies redward of the Ly α forest, so that neutral hydrogen absorption significantly reduces the broadband flux without affecting the narrowband flux.

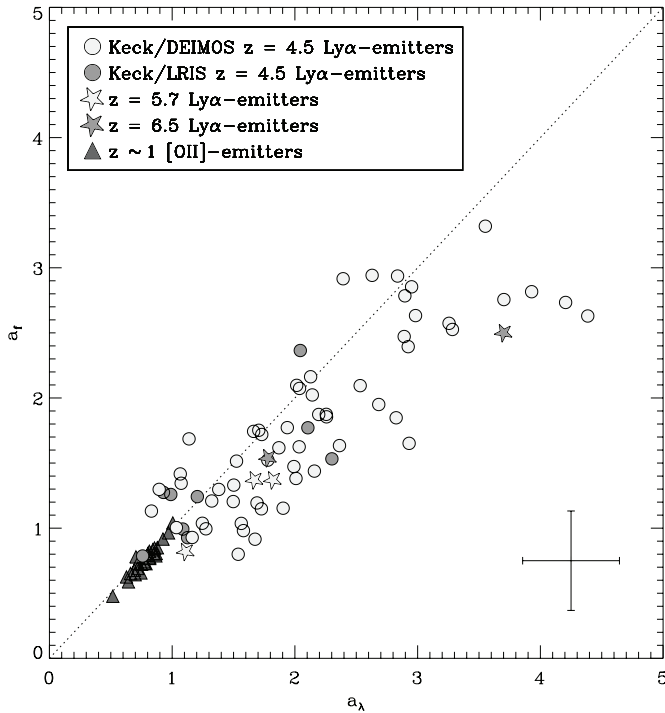


FIG. 6.— Scatter plot comparing the flux-based asymmetry statistic a_f and the wavelength-based asymmetry statistic a_λ of known high-redshift Ly α emitters to a sample of [O II] $\lambda 3727$ emitters at $z \sim 1$, updated from Paper I. The points labeled “DEIMOS” denote galaxies confirmed with our campaign of Keck DEIMOS spectroscopy, described in this paper. The points labeled “LRIS” denote galaxies confirmed with our campaign of 400 lines mm^{-1} grating Keck LRIS spectroscopy, described in Paper I. The three Ly α emitters at $z = 5.7$ are from Rhoads et al. (2003), and the two Ly α emitters at $z = 6.5$ are from Rhoads et al. (2004) and Stern et al. (2005). The 28 [O II] $\lambda 3727$ emitters at $z \sim 1$ were provided by the DEEP2 team (Davis et al. 2003; A. Coil 2004, private communication); their Keck DEIMOS 1200 lines mm^{-1} grating spectra were smoothed to the Keck LRIS 400 lines mm^{-1} grating resolution by convolution with a Gaussian kernel. The representative error bar (*bottom right*) is the median of the errors on the individual a_f and a_λ for the combined Keck LRIS and Keck DEIMOS sample. [See the electronic edition of the Journal for a color version of this figure.]

for our sample, where λ_p is the wavelength of the peak of the emission line and $\lambda_{10,b}$ and $\lambda_{10,r}$ are the wavelengths at which the line flux first exceeds 10% of the peak on the blue side and on the red side of the emission line, respectively (see Rhoads et al. 2003, 2004, and Paper I).¹² Each of the confirmed Ly α emitters in this sample satisfies $a_f > 1.0$ or $a_\lambda > 1.0$, and 52 out of 59 sources satisfy both. As we found for the lower resolution Keck LRIS sample in Paper I, the present Ly α sample, observed with higher spectral resolution using Keck DEIMOS, is systematically segregated from low-redshift [O II] $\lambda 3727$ in a_f - a_λ space.

As a final diagnostic, we note that in each of our confirmed Ly α emitters for which the continuum is sufficiently well detected the spectrum shows a continuum decrement consistent with the onset of absorption by the Ly α forest at $\lambda_{\text{rest}} = 1216 \text{ \AA}$. The break amplitude is typically characterized by $1 - f_\nu^{\text{short}}/f_\nu^{\text{long}}$, where we define f_ν^{short} as the variance-weighted flux density in a 1200 \AA window beginning 30 \AA below the emission line; f_ν^{long} is the same, but above the emission line. In the 24 sources for which f_ν^{long} is detected to better than 2 σ , all but two sources have

¹² As in Paper I, the error bars on a_λ and a_f were determined with Monte Carlo simulations in which we modeled each emission line with the truncated Gaussian profile described in Hu et al. (2004) and Rhoads et al. (2004), added random noise in each pixel according to the photon counting errors, and measured the widths $\sigma(a_\lambda)$ and $\sigma(a_f)$ of the resulting distributions of a_λ and a_f for the given line. That is, for each $a_{\lambda,i}$, the error $\delta a_{\lambda,i} = \sigma(a_{\lambda,i})$, and similarly for each $a_{f,i}$.

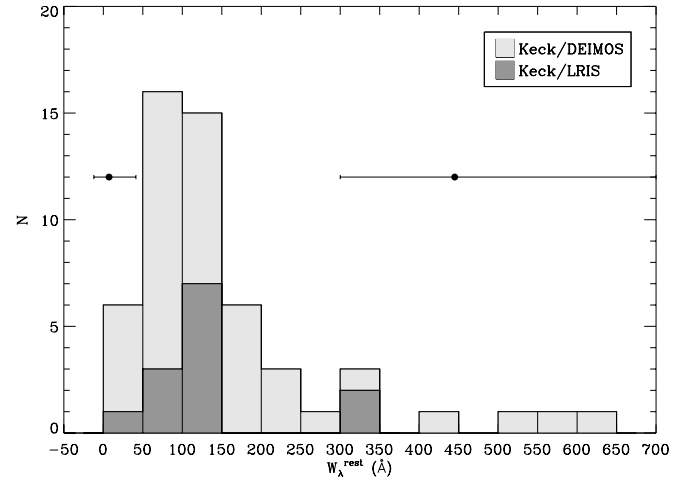


FIG. 7.— Histogram of the spectroscopic rest-frame equivalent widths for the $z = 4.5$ population, determined with $W_\lambda^{\text{rest}} = (F_l/f_{\lambda,r})/(1+z)$, where F_l is the flux in the emission line and $f_{\lambda,r}$ is the measured red-side continuum flux density. The sources labeled “DEIMOS” denote galaxies confirmed with our campaign of Keck DEIMOS spectroscopy, described in this paper. The sources labeled “LRIS” denote galaxies confirmed with our campaign of Keck LRIS spectroscopy, described in Paper I. Representative error bars on the equivalent widths are plotted at left and right. Notably, the highest equivalent widths are generally the least certain, as they correspond to the faintest (and hence least certain) continuum estimates.

$1 - f_\nu^{\text{short}}/f_\nu^{\text{long}} > 0.5$, consistent with continuum-break amplitudes at $z = 4.5$ in theoretical models (e.g., Madau 1995; Zhang et al. 1997), in the lower resolution Keck LRIS sample presented in Paper I and in other similar data sets (see Stern & Spinrad 1999 and references therein).

4. DISCUSSION

Together with the observations presented in Paper I (and accounting for minor overlap in the samples), the 59 Ly α emitters confirmed herein bring the total catalog of spectroscopically confirmed $z \approx 4.5$ Ly α -emitting galaxies to 73 objects in the $\approx 0.7 \text{ deg}^2$ surveyed by the LALA imaging. We now update the characteristics of this population as they were estimated in Paper I by investigating the distribution of the total sample in equivalent width. We then construct a $z \approx 4.5$ Ly α LF, carefully accounting for survey incompleteness and for spectroscopic sensitivity, and we compare the result to Ly α LFs spanning $3.1 < z < 6.6$.

4.1. The Equivalent-Width Distribution

As in Paper I, we determine the rest-frame equivalent widths directly from the spectra according to $W_\lambda^{\text{rest}} = (F_l/f_{\lambda,r})/(1+z)$, where F_l is the flux in the emission line and $f_{\lambda,r}$ is the measured red-side continuum flux density. The resulting equivalent-width distribution is plotted in Figure 7, together with the equivalent widths measured in Paper I.

Before interpreting this distribution, one should be cautioned that the W_λ^{rest} determination is very sensitive to uncertainty in the measured continuum. Since the continuum estimate enters into the denominator of the expression for W_λ^{rest} , the characteristically small continuum values and their large fractional uncertainties cause significant scatter in the measurement and the resulting error is neither Gaussian nor symmetric about the measured value. Especially problematic is the fact that the largest values of W_λ^{rest} are also the least certain. Detailed discussions of the uncertainties in measuring W_λ^{rest} in high-redshift Ly α emitters, along with the complicating effects of dust content, gas kinematics, and intergalactic absorption, are given in Hu et al. (2004) and in Paper I.

With these caveats in mind, we rigorously treated the error bars on the equivalent-width estimates, and we restricted the analysis to sources with red-side continuum signal-to-noise ratios ≥ 1 . To determine the equivalent-width error bars, we first associated each measured line flux $F_{l,i} \pm \delta F_{l,i}$ with a Gaussian probability-density function (PDF) centered on $F_{l,i}$ with width $\sigma = \delta F_{l,i}$; we proceeded similarly for the measured continuum fluxes. We then generated a grid of line flux versus continuum flux on which each node has an associated equivalent width and is assigned a weight given by the probability distribution on each of its flux axes. Next, we collapsed the grid into a histogram of equivalent widths, adding the weight from each grid point to the appropriate equivalent-width bin. The result is a non-Gaussian PDF $P_i(w)$ for which $P_i(w)dw$ is the probability of observing $W_{\lambda,i}^{\text{rest}}$ in the interval $w < W_{\lambda,i}^{\text{rest}} < w + dw$. The error bars δw_+ and δw_- are then 1σ confidence intervals determined by integrating over the probability density functions $P_i(w)$. They are symmetric in probability density space in the sense that $\int_{w-\delta w_-}^w P_i(w')dw' = \int_w^{w+\delta w_+} P_i(w')dw' = 0.34$.

We find the resulting distribution to be broadly consistent with the equivalent widths presented in Fujita et al. (2003) for $z \sim 3.7$ and in Hu et al. (2004) for $z \sim 5.7$. While the majority of sources can be understood as comparatively young (1–10 Myr) galaxies with Salpeter initial mass functions (IMFs), a nonnegligible fraction exceeds the largest rest-frame equivalent widths expected from such stellar populations. Malhotra & Rhoads (2002) use a Salpeter IMF, an upper mass cutoff of $120 M_{\odot}$, and a metallicity of $1/20$ solar to find maximum Ly α equivalent widths of 300, 150, and 100 Å for stellar populations of ages 10^6 , 10^7 , and 10^8 yr, respectively. Adopting a correction factor of 0.64 as an upper limit to the effect of IGM absorption on the measurement of $W_{\lambda}^{\text{rest}}$ in spectroscopy effectively reduces these upper limits to 190, 100, and 60 Å (see discussion in Paper I). Owing to the lower metallicity used in their models, the pre-IGM-corrected values of Malhotra & Rhoads (2002) are slightly higher than the canonical limiting Ly α rest-frame equivalent width of 240 Å given by Charlot & Fall (1993).

Using the ensemble of $P_i(w)$ described above, we find that 12%–27% (90% confidence) of the galaxies in this sample show $W_{\lambda}^{\text{rest}} > 240$ Å, and 17%–31% (93% confidence) show $W_{\lambda}^{\text{rest}} > 190$ Å. Both results are nearly identical to the values given in Paper I. On the simplest interpretation, these galaxies are required to be very young (age $< 10^6$ yr) or to have IMFs skewed in favor of the production of massive stars. The possibility that AGNs in our sample are producing stronger-than-expected Ly α emission seems unlikely due to the comparatively narrow velocity widths of the Ly α lines and to the absence of the high ionization state UV emission lines symptomatic of AGN activity. Moreover, deep (~ 170 ks) *Chandra X-Ray Observatory* ACIS imaging of LALA $z \approx 4.5$ candidates in both Boötes (Malhotra et al. 2003) and in Cetus (Wang et al. 2004) resulted in X-ray non-detections to an average 3σ limiting luminosity of $L_{2-8\text{keV}} < 2.8 \times 10^{42}$ ergs s^{-1} . This limit is roughly an order of magnitude fainter than what is typically observed for even the heavily obscured, type II AGNs (e.g., Stern et al. 2002; Norman et al. 2002; Dawson et al. 2003). By comparing the upper limit on the typical X-ray-to-Ly α luminosity ratio for the Ly α galaxy sample to the observed values of this ratio for quasar and Seyfert galaxy samples, Malhotra et al. (2003) and Wang et al. (2004) concluded that AGNs account for $\lesssim 5\%$ of the Ly α galaxy sample.

4.2. Empirical Cumulative Luminosity Function

In Figure 8, we present an empirical cumulative Ly α line LF computed for our sample at $z \sim 4.5$ and compare this to LFs

computed for several other samples spanning $3.1 < z < 6.6$. The cumulative LF gives for each Ly α line luminosity $L(\text{Ly}\alpha)$ the total number density of Ly α lines brighter than $L(\text{Ly}\alpha)$. The comparison samples are drawn from spectroscopic follow-up of narrowband surveys with roughly comparable flux limits and candidate-selection criteria (except where noted below). We do not include nonspectroscopic Ly α -emitter LFs (e.g., Ouchi et al. 2003) among the comparison samples. In each case, we converted the reported Ly α line fluxes to line luminosities using a Λ -cosmology with $\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s^{-1} Mpc $^{-1}$, and we made a minimal attempt to account for incompleteness.¹³ Specifically, the volume from which Ly α -emitting candidates were selected by their narrowband excess is simply defined by the solid angle covered by the narrowband imaging and the redshift range allowed by the narrowband filter. However, the *effective* volume surveyed by the spectroscopic follow-up is smaller than the imaging survey volume by a factor of $N_{\text{spec}}/N_{\text{cand}}$, where N_{cand} is the total number of Ly α -emitting candidates discovered in the imaging, and N_{spec} is the number of candidates actually targeted for spectroscopy. We estimated the uncertainties in the cumulative LFs with Monte Carlo simulations. Assuming the errors in the Ly α line fluxes are Gaussian, we created synthetic data sets by drawing randomly from the Gaussian Ly α flux PDFs for each object in each sample. The result for each sample was then a distribution of cumulative LFs, which may be used to define upper and lower confidence intervals. Figure 8 depicts 95% confidence intervals; where more than one survey is plotted, just the confidence intervals for the survey with the largest range in line fluxes is depicted.

No strong evolution is readily evident in the cumulative Ly α LFs between $z \sim 3$ and $z \sim 6$. The only significant scatter between LFs occurs between the various $z \sim 3$ surveys, and that scatter likely finds its origin in differences in the manner in which the experiments were performed. Foremost, the area surveyed by the Cowie & Hu (1998) effort is comparatively small: just 25 arcmin 2 in each of two fields (HDF and SSA 22), as opposed to 300 arcmin 2 in Kudritzki et al. (2000) and 132 arcmin 2 in Fujita et al. (2003). Cowie & Hu (1998) note that the number counts in their HDF field appears to be 2.5 times richer in narrowband excess objects than their SSA 22 field, highlighting the susceptibility of small survey areas to cosmic variance. Separately, as noted by Hu et al. (2004) the Fujita et al. (2003) data may comparatively underrepresent the density of Ly α emitters due to their more stringent equivalent width criterion of $W_{\lambda}^{\text{obs}} > 250$ Å, as opposed to $W_{\lambda}^{\text{obs}} > 77$ Å in Cowie & Hu (1998) and effectively $W_{\lambda}^{\text{obs}} \gtrsim 100$ Å in Kudritzki et al. (2000).

4.3. The V/V_{max} Estimate

We now perform a more rigorous measurement of the $z \approx 4.5$ Ly α LF using a modified version of the V/V_{max} method (e.g., Hogg et al. 1998; Fan et al. 2001). For each galaxy, V_{max} is the volume over which Ly α of a given luminosity could be located and still be detected by our survey; the LF is then the sum of the inverse volumes of all galaxies in the given luminosity bins. Our modifications to the V/V_{max} method account for incompleteness in two senses. First, not every galaxy candidate identified in imaging was targeted in follow-up spectroscopy. Following Hogg et al. (1998) Figure 9 shows the fraction of

¹³ Hu et al. (2004) provided fluxes for their $z \sim 5.7$ sources as measured in narrowband imaging, rather than Ly α line fluxes as measured in spectroscopy. As such, we adopt the conversion given in Stern et al. (2005) to estimate $f_{\nu}^{\text{Ly}\alpha}$ from f_{ν}^{NB} .

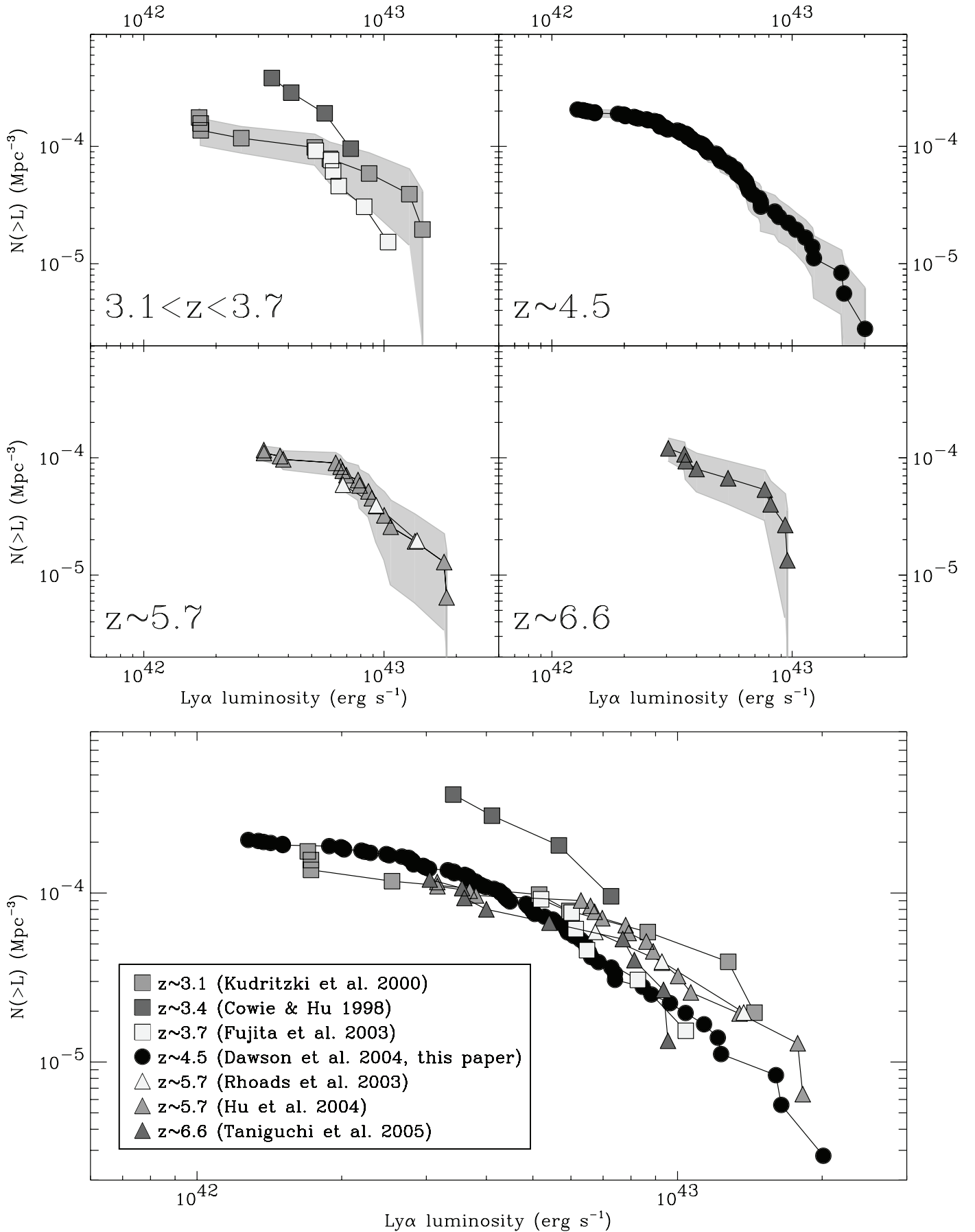


Fig. 8.—Comparison of empirical, cumulative $\text{Ly}\alpha$ LFs computed with only minimal completeness correction for several spectroscopic surveys spanning $3.1 < z < 6.6$. The cumulative LF gives for each $\text{Ly}\alpha$ line luminosity $L(\text{Ly}\alpha)$ the total number density of $\text{Ly}\alpha$ lines brighter than $L(\text{Ly}\alpha)$. The shaded regions represent 95% confidence intervals based on the Monte Carlo simulations described in § 4.2. Where more than one survey is plotted, just the confidence intervals for the survey with the largest range in line fluxes is depicted. No strong evolution is evident over the redshift range depicted. [See the electronic edition of the Journal for a color version of this figure.]

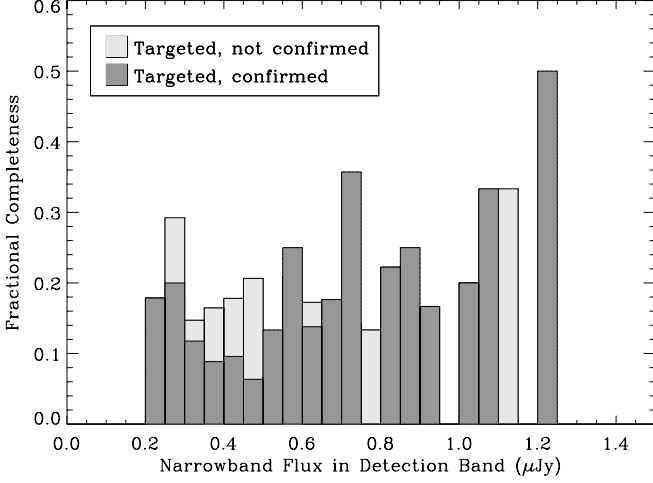


FIG. 9.—Probability as a function of narrowband flux that a candidate Ly α emitter was targeted for spectroscopy, divided into the fraction of targets that were confirmed and the fraction of targets that were not.

narrowband-selected candidate Ly α emitters that were targeted for spectroscopy as a function of flux in the band in which the candidate was detected. We label this a priori completeness function η_{try} ; the candidate Ly α flux $f_{\text{Ly}\alpha}$ can be roughly estimated from the flux in the narrow band f_{ν}^{NB} with $f_{\text{Ly}\alpha} = w_n(f_{\nu}^{\text{NB}} - f_{\nu}^{\text{R}})$, where w_n is the width of the narrowband filter and f_{ν}^{R} is the flux of the candidate in the R band.

Second, even if a candidate Ly α emitter was selected for spectroscopy, its inclusion in the LF depends on the detection and identification of the Ly α line. Our spectroscopic sensitivity to Ly α emission as a function of flux and redshift is shown in Figure 4; we label this function p_{detect} . As discussed in § 3.1, p_{detect} can be interpreted as the probability that a putative Ly α emission line of a given flux and a given redshift would have been detected in our spectroscopic campaign.

In the presence of these selection effects, the available volume for a galaxy with Ly α emission of flux $f_{\text{Ly}\alpha}$ is

$$V_{\text{max}} = \int_{z_1}^{z_2} \eta_{\text{try}}(f'_{\text{Ly}\alpha}) p_{\text{detect}}(f'_{\text{Ly}\alpha}, z') \frac{d^2 V_c}{d\Omega dz'} \Delta\Omega dz', \quad (5)$$

where the comoving volume element in a solid angle $d\Omega$ and redshift interval dz is the familiar

$$\frac{d^2 V_c}{d\Omega dz} = \left(\frac{c}{H_0}\right)^3 \left[\int_0^z \frac{dz'}{E(z')}\right]^2 \frac{1}{E(z)}, \quad (6)$$

with

$$E(z) = [\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda]^{1/2}. \quad (7)$$

In equation (5), $\Delta\Omega$ is the solid angle covered by the LALA survey, and $f'_{\text{Ly}\alpha}$ is the Ly α line flux for the source in question if it were located at redshift z' . The lower limit of integration z_1 is set by the lowest wavelength at which Ly α could be detected by our narrowband filters, corresponding to $z \approx 4.37$. The upper limit of integration z_2 is set in one of two ways. If the Ly α luminosity for a source is bright enough that the line remains above the survey flux limit out to the highest redshift accessible by our filter set, then z_2 is simply equal to the upper redshift

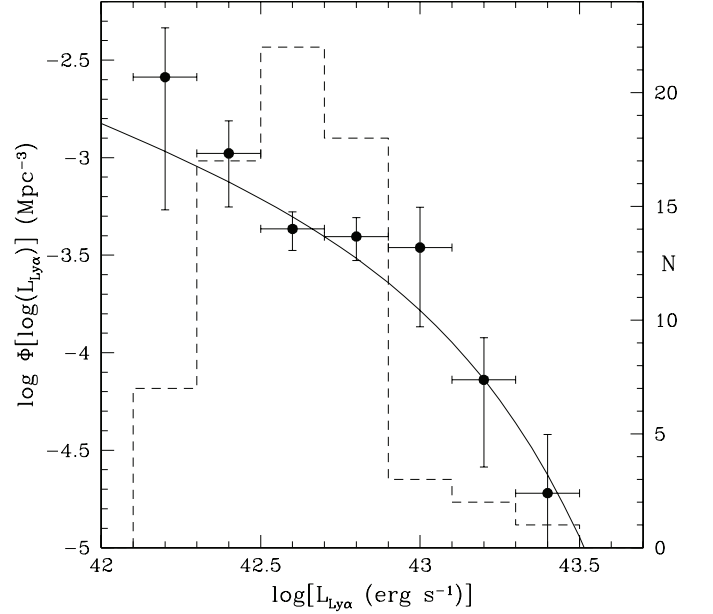


FIG. 10.—Differential Ly α LF for our $z \approx 4.5$ sample, computed using the V/V_{max} method. The sample includes both the Keck DEIMOS data presented in this paper and the Keck LRIS data presented in Paper I. The error bars are the 1σ statistical uncertainties given by the root variance shown in eq. (10). The background histogram (*dashed*) gives the number of individual sources contributing to each luminosity bin. The solid curve shows the best-fitting Schechter function model, with $L^* = (10.9 \pm 3.3) \times 10^{42}$ ergs s^{-1} , $\Phi^* = (1.7 \pm 0.2) \times 10^{-4}$ Mpc^{-3} , and a fixed faint-end slope $\alpha = -1.6$.

limit for the survey, $z \approx 4.57$. For fainter sources, z_2 is taken to be the redshift at which the Ly α flux falls below the survey flux limit; in this case, $4.37 < z_2 < 4.57$.

Having computed V_{max} for each galaxy, we may compute the differential Ly α LF $\Phi(L)$, the number density of galaxies per logarithmic interval in Ly α luminosity. In a given luminosity bin of width $\Delta \log L$ centered on L_i , this is given by

$$\Phi(L_i) = \frac{1}{\Delta \log L} \sum_j \frac{1}{V_{\text{max},j}}. \quad (8)$$

Here, the index i denotes the luminosity bin and j denotes the galaxies within the bin, where the galaxies summed in a given bin are selected by their Ly α luminosities according to

$$|\log L_j - \log L_i| < \frac{\Delta \log L}{2}. \quad (9)$$

Finally, the uncertainty in the LF may be estimated with

$$\sigma[\Phi(L_i)] = \frac{1}{\Delta \log L} \left[\sum_j \left(\frac{1}{V_{\text{max},j}} \right)^2 \right]^{1/2}. \quad (10)$$

In Figure 10, we present the resulting differential Ly α LF at $z \approx 4.5$. We also fit the data with a Schechter function. If $\Phi(L) dL$ is the comoving number density of galaxies with luminosities in the range $(L, L + dL)$, then the corresponding Schechter function is

$$\Phi(L) dL = \frac{\Phi^*}{L^*} \left(\frac{L}{L^*} \right)^\alpha \exp\left(-\frac{L}{L^*}\right) dL, \quad (11)$$

where Φ^* is the normalization, L^* is the characteristic break luminosity, and α sets the slope at the faint end. This is related to the number density of galaxies in *logarithmic* intervals by

$$\Phi(L) d(\log L) = \left(\frac{L}{\log e} \right) \left(\frac{\Phi^*}{L^*} \right) \left(\frac{L}{L^*} \right)^\alpha \exp\left(-\frac{L}{L^*}\right) d(\log L),$$

and it is this function that we fit to our data. As in van Breukelen et al. (2005), because the binned data points are few, we choose to fix $\alpha = -1.6$ so as to fit with only two free parameters, Φ^* and L^* . This choice fits well with the luminosity distribution of both LBGs and Ly α -emitters at $z \approx 3$ (Steidel et al. 1999, 2000). We find best-fit LF parameters $L^* = (10.9 \pm 3.3) \times 10^{42}$ ergs s $^{-1}$ and $\Phi^* = (1.7 \pm 0.2) \times 10^{-4}$ Mpc $^{-3}$ [or equivalently, $\log(L^*) = 43.04 \pm 0.14$ and $\log(\Phi^*) = -3.77 \pm 0.05$]. The error bars on L^* and Φ^* are the 1 σ formal errors computed from the covariance matrix in the nonlinear least-squares fit, scaled by the measured value of χ^2 . That is, $\delta L^* = \sigma_{L^*} (\chi^2/n_{\text{DOF}})^{1/2}$, and similarly for $\delta \Phi^*$ (Press et al. 1992).

Our $z \approx 4.5$ sample provides one of the best measured Ly α LFs to date. We can study redshift evolution of the Ly α LF by comparing to results from the literature. Recognizing that the uncertainties in L^* and Φ^* are strongly correlated, we examine not only the individual parameters but also the product $L^* \Phi^*$, which is proportional to Ly α luminosity density, and which generally has smaller uncertainties than the individual parameters. For our sample, $\log(L^* \Phi^*) = 39.27$.

At lower redshift, there is a $z \approx 3.1$ LF by (Gronwall et al. 2007), who fitted all three parameters. They found $\alpha = -1.49^{+0.45}_{-0.34}$, $\log(L^*) = 42.64^{+0.26}_{-0.15}$, and $\log(\Phi^*) \approx -2.89 \pm 0.04$, whence $\log(L^* \Phi^*) \approx 39.75$. At the high-redshift end, we compare to LFs at $z = 6.5$ by Malhotra & Rhoads (2004) and Kashikawa et al. (2006), and at $z = 5.7$ by Malhotra & Rhoads (2004) and Shimasaku et al. (2006), all derived by fixing the faint-end slope $\alpha = -1.5$ and fitting L^* and Φ^* . At $z = 6.5$, the LFs are similar to our $z = 4.5$ result: Malhotra & Rhoads (2004) found $\log(L^*) = 42.6$, $\log(\Phi^*) = -3.3$, and $\log(L^* \Phi^*) = 39.3$, while Kashikawa et al. (2006) found (for their combined spectroscopic plus photometric sample) $\log(L^*) = 42.6$, $\log(\Phi^*) = -2.88$, and $\log(L^* \Phi^*) = 39.72$. At $z = 5.7$, Malhotra & Rhoads (2004) found $\log(L^*) = 43.0$, $\log(\Phi^*) = -4.0$, and $\log(L^* \Phi^*) = 39.0$, while Shimasaku et al. (2006) found $\log(L^*) = 42.9 \pm 0.14$, $\log(\Phi^*) = -3.2 \pm 0.17$, and $\log(L^* \Phi^*) = 39.7$. The obvious differences between the LFs at each redshift may be caused by any combination of (1) simple uncertainty in deriving the LF from modest-sized samples, (2) field-to-field variations in Ly α galaxy density, or (3) differences in the methods used to derive Schechter function parameters, and in part to local variations in Ly α galaxy density. The Kashikawa et al. (2006) and Shimasaku et al. (2006) LFs are derived from larger total samples, but from a single survey field, while the Malhotra & Rhoads (2004) LFs are based on a combination of several older, smaller samples from a few widely separated fields. Regardless, if we take the difference between these various $z \sim 6$ LFs as an empirical indication of total present uncertainties, the $z \approx 4.5$ LF derived in the present paper supports a roughly constant Ly α luminosity density over the range $z = 4.5 \pm 1.5$.

4.4. Comparison to LBGs

It is interesting to compare this result to the evolution of the rest-UV luminosity density and cosmic star formation rate density (SFRD) derived from LBGs over the same redshift range. Estimates of the $z \approx 6$ SFRD based on the Great Observatories Ori-

gins Deep Survey (GOODS), done with the Advanced Camera for Surveys (ACS; Giavalisco et al. 2004a), and the Hubble Ultra Deep Field (HUDF; Beckwith et al. 2006) show a factor of 1.5–6 drop between $z \sim 3$ and $z \sim 6$ (Bunker et al. 2004; Bouwens et al. 2006; Giavalisco et al. 2004b).

What does this mean for the Ly α -selected galaxies? Steidel et al. (2000) reported that Ly α selection with an equivalent-width criterion typical of narrowband surveys would return 20%–25% of their $z \approx 3$ LBGs. If Ly α emitters are merely a subset of the LBG population which happen to have been detected during a stage of strong Ly α production, then we would expect the Ly α luminosity density to decline beyond $z \sim 3$, in step with the global SFR density. Integrating the LFs discussed in § 4.3 shows no compelling evidence for such a decline. Although a modest decline cannot be firmly ruled out, we may nonetheless speculate that the Ly α emitters as a population are evolving differently from the LBGs.

The bolometric luminosities of Ly α galaxies are typically lower than LBGs and provide a hint that they are less massive. Detailed spectral energy distribution fitting (Gawiser et al. 2006; Finkelstein et al. 2007; Pirzkal et al. 2007) bears out this preliminary inference, showing typical masses of $\sim 10^8 M_\odot$ and ages $\sim 10^7$ – 10^8 yr. The correlation strengths of Ly α galaxies and LBGs are similar (Ouchi et al. 2003; Kovač et al. 2007), indicating similar masses of halos. From the expected halo mass one can predict volume number density of Ly α emitters. Comparing the expected and observed number densities implies a duty cycle of Ly α emission in the range 6%–50% (Kovač et al. 2007). A similar duty cycle, 7.5%–15%, is inferred from stellar population modeling of the photometric sample (Malhotra & Rhoads 2002).

4.5. Implications for Reionization

The spectroscopic observations of the $z > 6$ quasars yielded the first detections of the long-awaited Gunn-Peterson trough, implying at least the end of reionization at $z \approx 6$ (Becker et al. 2001; Djorgovski et al. 2001; Fan et al. 2002). Subsequently, the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) identified a large-amplitude signal in the temperature-polarization maps of the cosmic microwave background (Spergel et al. 2003; Page et al. 2007) indicating a large optical depth to Thomson scattering and favoring reionization instead at $z \approx 11$. The *WMAP* results are not necessarily inconsistent with those of the quasar Gunn-Peterson troughs. Only a small neutral fraction ($x_{\text{HI}}^{\text{IGM}} \sim 0.001$) is required to produce the Gunn-Peterson effect, so one plausible scenario is that reionization may have been an extended event, beginning early but not completing until $z \approx 6$. Alternatively, a variety of theoretical models now suggest that reionization occurred twice, first at $z \approx 20$ with the onset of zero-metallicity Population III stars, and then again by massive Population II stars formed after a partial recombination (e.g., Cen 2003; Haiman & Holder 2003; Somerville et al. 2003).

High-redshift Ly α -emitting galaxies offer another perspective on this issue, as the visibility of Ly α emission should be a sensitive function of the IGM neutral fraction (e.g., Haiman & Spaans 1999; Santos 2004). Malhotra & Rhoads (2004) and Stern et al. (2005) presented first attempts to exploit this fact by comparing LFs of Ly α emitters at $z \sim 5.7$ and $z \sim 6.6$. They found no measurable evolution between these epochs, from which they inferred that the IGM remains largely reionized from the local universe out to $z \approx 6.5$ (but see Haiman & Cen 2005). Kashikawa et al. (2006), applying the same test, found possible evidence for observed Ly α LF differences between $z = 5.7$ and 6.5 at the factor of 2 level. They suggest neutral gas at $z \approx 6.5$ as the explanation, although Dijkstra et al. (2007) argued that the observations could

equally well be explained by the ongoing growth of cosmic structure from $z = 6.5$ to $z = 5.7$.

By using the Ly α galaxy sample from Taniguchi et al. (2005), Malhotra & Rhoads (2006) showed that at least 30% of the IGM by volume is ionized at $z \approx 6.5$. This is corroborated by dark gap statistics in Gunn-Peterson troughs (Fan et al. 2006). All the Ly α tests of reionization assume that there is no intrinsic evolution in the Ly α LFs between $z = 5.7$ and 6.5 . In this paper we show that there is little evolution in Ly α LF from $z = 6.6$ to $z = 3.1$, thus strengthening the conclusion that the IGM is not substantially neutral at $z = 6.5$.

Significantly, the related question of what is responsible for reionization remains at large. It has long been recognized that AGNs at early epochs are insufficient, owing to their rapid decline in space density at high redshift (e.g., Madau et al. 1999; Barger et al. 2003). Based on their analysis of the HUDF, Bunker et al. (2004) concluded that the cosmic SFR in directly observed $z \approx 6$ LBGs was roughly 5 times too low to reionize the universe. Yan & Windhorst (2004) and Bouwens et al. (2006) argued that the ionizing photon budget is sufficient provided one accounts for sample incompleteness using a sufficiently steep slope at the faint end of the LF.

Malhotra et al. (2005) argued that the ionizing flux density may be very inhomogeneous due to large-scale structure, as seen in galaxies in the HUDF, and that the directly observed galaxies at $z \approx 6$ do produce sufficient photons for reionization in overdense regions.

We estimate that the contribution to the cosmic SFR from Ly α emitters at this epoch is lower than that of the LBGs [$\rho_{\text{SFR}}(\text{Ly}\alpha) \approx 0.003 M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$, as compared to $\rho_{\text{SFR}}(\text{LBG}) \approx 0.005 M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$] when integrated over the same limits. Consequently, although high-redshift Ly α emitters are proving to be a useful probe of the history of reionization, they are evidently not its cause. While extinction corrections could occasionally be large (Chary et al. 2005) and could modify this conclusion, most well-studied Ly α galaxies have very modest extinction (Finkelstein et al. 2007; Pirzkal et al. 2007).

When we compare the LF of Ly α emitters at $z \approx 4.5$ to LFs for similarly assembled samples spanning $3.1 < z < 6.6$, we find no evidence for evolution over these epochs. This result

bolsters the conclusion by Malhotra & Rhoads (2004) and Stern et al. (2005) that the IGM remains largely reionized from the local universe out to $z \approx 6.5$. However, it is somewhat at odds with the factor of 1.5–6 drop in the cosmic SFR density measured by (Bunker et al. 2004; Bouwens et al. 2006; Giavalisco et al. 2004a) between $z \sim 3$ and $z \sim 6$ in LBGs selected in the exceptional imaging of the HUDF. It seems that these two populations, Ly α emitters and LBGs, follow different evolutionary histories. The disentanglement of this issue will likely rely on extensive follow-up observations of large samples so that we can study the continuum and absorption lines of many Ly α galaxies, and conversely the Ly α properties of the break-selected galaxies.

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