A LUMINOUS Lyα-EMITTING GALAXY AT REDSHIFT z = 6.535:
DISCOVERY AND SPECTROSCOPIC CONFIRMATION

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ABSTRACT

We present a redshift z = 6.535 galaxy discovered by its Lyα emission in a 9180 Å narrowband image from the Large Area Lyman Alpha survey. The Lyα line luminosity (1.1 × 1041 ergs s−1) is among the largest known for star-forming galaxies at z ∼ 6.5. The line shows the distinct asymmetry that is characteristic of high-redshift Lyα. The 2σ lower bound on the observer-frame equivalent width is greater than 530 Å. This is hard to reconcile with a neutral intergalactic medium (IGM) unless the Lyα line is intrinsically strong and is emitted from its host galaxy with an intrinsic Doppler shift of several hundred km s−1. If the IGM is ionized, it corresponds to a rest-frame equivalent width greater than 40 Å after correcting for Lyα forest absorption. We also present a complete spectroscopic follow-up of the remaining candidates with line flux greater than 2 × 10−17 ergs cm−2 s−1 in our 1200 arcmin2 narrowband image. These include another galaxy with a strong emission line at 9136 Å and no detected continuum flux, which, however, is most likely an [O iii] λ5007 source at z = 0.824, on the basis of a weak detection of the [O iii] λ4959 line.

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

Dedicated to the memory of Jim De Veny

1. INTRODUCTION

Observational study of the redshift range 6 ≤ z ≤ 7 is crucial for understanding the reionization of intergalactic hydrogen, which was the most recent major phase transition for most of the baryonic matter in the universe. While polarization of the microwave background measured by the Wilkinson Microwave Anisotropy Probe satellite indicates that substantial ionization had begun as early as z ∼ 15 (Spergel et al. 2003), both the opaque Gunn-Peterson troughs observed in the spectra of z ≥ 6.3 quasars (Becker et al. 2001; Fan et al. 2002) and the high temperature of the intergalactic medium (IGM) at z ∼ 4 (Theuns et al. 2002; Hui & Haiman 2003) imply that a large part of the reionization was relatively recent, with substantial neutral gas lasting up to z ∼ 6.

Lyα emission has proved the most effective tool so far for identifying star-forming galaxies at redshifts z > 6; indeed, all but two of the about six galaxies that have been spectroscopically confirmed at z > 6 were found through their Lyα line emission in either narrowband or spectroscopic searches (Hu et al. 2002, hereafter H02; Kodaira et al. 2003, hereafter K03; Cuby et al. 2003; this work; Kneib et al. 2004), and at least one of the continuum-selected sources is also a Lyα emitter (Cuby et al. 2003).

We present the extension of the Large Area Lyman Alpha (LALA) survey to the z ∼ 6.5 window. We have obtained spectra for each of the three z ∼ 6.5 candidates that pass all photometric selection criteria. Two of these show strong emission lines in the narrowband filter bandpass. In one case, the line is identified as Lyα at z ∼ 6.535 on the basis of its asymmetric profile and the absence of other detected lines down to faint flux levels. The second object is identified as an [O iii] λ5007 source at z ≈ 0.824 on the basis of a probable (4σ) detection of the [O iii] λ4959 line.

2. IMAGING OBSERVATIONS AND ANALYSIS

The LALA survey’s z ∼ 6.5 search is based on a deep 9180 Å narrowband image of our Bootes field, which is 36′ × 36′ with center at R.A. = 14h25m57s, decl. = 35°32′ (J2000.0). The image was obtained using the CCD mosaic-1 Camera at the 4 m Mayall Telescope of the Kitt Peak National Observatory, together with a custom narrowband filter whose central wavelength of λc ≈ 9182 Å and FWHM of 84 Å place it in a gap between the night-sky airglow lines.

Narrowband imaging data were obtained on UT 2001 June 15–17 and 24–25 and 2002 April 5 and 18–19. The total exposure time was 28 hr.
Data reduction followed the same procedures used in the $z = 4.5$ and 5.7 LALA images (Rhoads et al. 2000; Rhoads & Malhotra 2001). To summarize, we remove electronic cross-talk between Mosaic chip pairs sharing readout electronics, subtract overscan and bias frame corrections, and flat field with dome flats. Next, we subtract a pupil ghost image caused by internal reflections in the KPNO 4 m corrector. We remove residual large-scale imperfections in the sky flatness using a smoothed supersky flat derived from the science data, followed by subtraction of a polynomial surface fit to the sky flux. A fringe frame was constructed from the data, fitted to the blank-sky regions of each exposure, and subtracted. Cosmic rays were rejected in each exposure using the algorithm of Rhoads (2000).

The world coordinate systems of individual frames were adjusted to the USNO-A2 star catalog (Monet et al. 1998). Satellite trails were flagged by hand for exclusion from the final stacks. The eight-chip Mosaic-I images were then mapped onto a rectified, common coordinate grid using the mscimage task from the IRAF MSCRED package (Valdes & Tody 1998; Valdes 1998). The seeing, throughput, and sky brightness in each exposure were measured and used to compute a set of weights for image stacking using the ATTWEIGHT algorithm (Fischer & Kochanski 1994). Finally, the exposures were stacked, with an additional $\sigma$-clipping applied to reject discrepant data not previously flagged. The majority of the weight comes from the final two nights of imaging data, and only 24% of the total weight is from the 2001 observing season.

The final stack has seeing of $\theta_{0.2}$ and a $5 \sigma$ sensitivity limit of 0.7 $\mu$Jy within a 9 pixel $[2''32]$ diameter aperture, corresponding to $2.0 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ for a pure line source at these wavelengths or to an AB magnitude of 24.3 for a pure continuum source. The magnitude zero point was determined by comparison with a deep $z'$-filter image obtained earlier (see Rhoads & Malhotra 2001), which was in turn calibrated to $z'$-filter standard stars from the Sloan Digital Sky Survey (SDSS) standard star lists.

### 3. Candidate Selection

Ly$\alpha$ galaxy candidates were selected following the criteria used successfully in lower redshift LALA searches (Rhoads & Malhotra 2001; Dawson et al. 2004). In summary, these include (1) significance of the narrowband detection greater than 5 $\sigma$; (2) a narrowband excess of at least 0.75 mag, so that $\geq 50\%$ of the narrowband flux comes from an emission line; (3) significance of the narrowband excess greater than 4 $\sigma$; and (4) no detection in filters blueward of the expected Lyman break location at greater than the 2 $\sigma$ level.

To implement the blue flux “veto” criterion, we used a weighted sum of six NOAO Deep Wide-Field Survey (NDWFS; Jannuzi & Dey 1999) and LALA survey filters blueward of 6850 Å, where the Lyman break would fall for galaxies whose Ly$\alpha$ line falls within the 9180 Å narrow band. The weights were chosen to achieve optimal depth for objects of approximately median color. Most of the weight in this combined “veto image” comes from the NDWFS $B_r$ filter, with additional contributions from NDWFS $R$-band data, the LALA survey’s $V$ band, and three of the redshifted H$\alpha$ narrowband filter observations. This stack reaches a final 2 $\sigma$ limiting AB magnitude of 27.1 at an effective central wavelength near 5000 Å. Formally, some flux may be expected in the $R$-band filter for $z \approx 6.5$ sources, but in practice intergalactic hydrogen absorption attenuates this flux so severely that it is quite safe to include $R$-band data in the veto stack as we have done. Photometry for candidate selection was done using SExtractor (Bertin & Arnouts 1996). All color tests were applied using a 9 pixel diameter aperture, corresponding to $2''32$, and using SExtractor’s two-image mode to ensure photometry from the same regions in all filters.

In addition to high-redshift Ly$\alpha$ sources, three types of contaminants may enter the sample. The first is noise spikes in the narrowband image. Assuming Gaussian statistics, we should expect about one noise peak above our 5 $\sigma$ detection threshold among the $\sim 10^{6.5}$ independent resolution elements in the narrowband image, and more may be found if the noise properties of the image are not perfectly Gaussian. The second is time-variable sources (either transient or moving objects). These may mimic emission-line objects in our catalog because different filters were observed at widely varying times. For typical LALA survey depths, the expected rate of high-redshift supernovae is about one per filter per field (A. G. Riess 2001, private communication; see also L. G. Strolger et al. 2004, in preparation). The third is low-redshift emission-line galaxies of extremely high equivalent width. The expected numbers of such foreground objects are difficult to estimate from either theory or present data—the LALA data themselves are likely to considerably refine the statistics of such contaminating sources.

These criteria yielded a total of three high-quality candidate $z \approx 6.5$ Ly$\alpha$ galaxies. Formally, six objects passed selection using an old veto filter stack from 2001, but two of these were ruled out completely, and a third was strongly disfavored by detections in a new NDWFS $R$-band image from 2002 April 10. One of these excluded candidates is almost certainly a supernova at moderate redshift; such an event would not be surprising given the area and depth of our survey. Properties of the four best candidates are summarized in Table 1.

### 4. Keck and Gemini Spectra

Two of the $z = 6.5$ candidates (LALA J142441.20+353405.1 and LALA J142544.41+353327.7) were observed using the DEIMOS spectrograph (Faber et al. 2003) on the Keck II telescope of the W. M. Keck Observatory on the night of UT 2003 May 1. Observations of LALA J142441.20+353405.1 were also obtained on UT 2003 April 1. All observations were made using the 600 line mm$^{-1}$ ($\lambda_b = 8500$ Å) grating through slit masks with slit widths of 10$. This setup gives a dispersion of $\approx 0.63$ Å pixel$^{-1}$ and a spatial plate scale of $0''1185$ pixel$^{-1}$. The total exposure times were 2.5 hr for LALA J142441.20+353405.1 (1 hr on Apr 1 and 1.5 on May 1) and 2.0 hr for LALA J142445.41+353327.7. These were broken into individual exposures of 1800 s, with 250 spatial offsets between exposures to facilitate the removal of fringing at long wavelengths. The nights were clear and the seeing was typically $0''5$–$0''8$. The data were reduced using the UC Berkeley pipeline reduction software (Davis et al. 2004, in preparation) adapted from programs developed for the SDSS (S. Burles & D. Schlegel 2004, in preparation), and further adapted to our observing mode. The spectra were extracted and analyzed using IRAF (Tody 1993).

The candidates LALA J142441.20+353405.1 and LALA J142442.24+353400.2 were observed on UT 2003 May 8 and June 29 using the GMOS spectrograph on Gemini North (Hook et al. 2003) in nod-and-shuffle mode (Glazebrook & Bland-Hawthorn 2001). The observations were made using the R400+G5305 grating (400 lines mm$^{-1}$, central wavelengths at 756–768 nm) through slit masks with slit widths of...
### TABLE 1

**PHOTOMETRY**

| ID | 918 nm Flux ($\mu$Jy) | z'-Flux ($\mu$Jy) | I Flux ($\mu$Jy) | R Flux ($\mu$Jy) | Photometric Line Flux<sup>a</sup> | $W_{\lambda}^{2\sigma}$ (Å) Limit | Comments |
|----|------------------------|-------------------|------------------|------------------|-----------------------------|-------------------------------|----------|
| LALA J142441.20+353405.1 | 0.763 ± 0.139 | -0.214 ± 0.111 | -0.0145 ± 0.045 | -0.0372 ± 0.029 | 4–6.6<sup>b</sup> | >620 | z = 0.824 |
| LALA J142442.24+353400.2 | 0.767 ± 0.137 | -0.081 ± 0.113 | -0.064 ± 0.045 | -0.061 ± 0.028 | 2.26 ± 0.40 | >70 | z = 6.535 |
| LALA J142544.41+353327.7 | 0.706 ± 0.138 | -0.051 ± 0.106 | -0.073 ± 0.044 | -0.021 ± 0.029 | 2.08 ± 0.41 | Noise spike |
| LALA J142610.55+354557.6 | 0.797 ± 0.121 | -0.137 ± 0.110 | 0.011 ± 0.046 | 0.057 ± 0.030 | 2.35 ± 0.36 | Unknown |

**NOTES.**—Photometric properties of the candidate $z = 6.5$ LALA sources. The 2 $\sigma$ lower bounds on equivalent width are derived from the narrow- and broadband photometry for LALA J142442.24+353400.2 and from DEIMOS spectra for LALA J142441.20+353405.1 and are corrected to the spectroscopically determined redshift. Tabulated values are not corrected for IGM absorption.

<sup>a</sup> Units are $10^{-17}$ ergs cm$^{-2}$ s$^{-1}$.

<sup>b</sup> The line for LALA J142441.20+353405.1 falls on the edge of the narrowband filter, where throughput is a rapid function of wavelength. The dominant uncertainty in the photometric line flux is the resulting throughput correction at 9136 Å, and we quote a range of flux values based on the plausible range of this throughput correction. See text.
10. On each night, the total exposure time was broken into five individual exposures of 900 s per nod position. Subsequent exposures were offset by 0′′2 in the spatial direction and 3 nm in wavelength, to remove the instrumental features (such as the horizontal stripes in the individual exposures) and to cover the chip gaps. Since the two objects appear on both the target and sky exposures (i.e., on both shuffle A and B), the effective exposure time for the two sources is 9000 s or 2.5 hr per night, for a grand total of 5 hr on-source integration. In addition, a second GMOS slit mask was observed for a total of 3.5 hr total integration time on UT 2003 July 2 (0.5 hr) and July 3 (3.0 hr), covering the (lower grade) candidate LALA J142610.55+354557.6.

The data were reduced using the Gemini GMOS packages (ver. 1.4) within IRAF through the standard procedures.8 The wavelength calibrations were performed on the basis of the CuAr lamp spectra and were double-checked against the night-sky lines. The uncertainties in the extracted spectra were obtained empirically by measuring the rms flux among all spatially distinct pixels at each wavelength in the rectified two-dimensional spectra.

Additional targets were of course included on all slit masks, including lower redshift emission-line galaxies, continuum-selected Lyman break galaxies (LBGs), intermediate-redshift elliptical galaxies, and X-ray sources from the 172 ks LALA Bootes field Chandra ACIS observation (Wang et al. 2004; Malhotra et al. 2003). Results for these other targets will be presented elsewhere.

5. SPECTROSCOPIC RESULTS

Two of our candidates, LALA J142442.24+353400.2 and LALA J142441.20+353405.1, yielded emission lines within the bandpass of the narrowband filter. Of these, one (LALA J142442.24+353400.2) is confirmed as a Lyα galaxy, while the other (LALA J142441.20+353405.1) is identified as [O iii] λ5007.

LALA J142442.24+353400.2.—LALA J142442.24+353400.2 was confirmed by Gemini-N+GMOS on 2003 May 8 and June 29. No DEIMOS data were obtained for this object. There is a single isolated emission line at 9160 Å, corresponding to z = 6.535 (see Figs. 1 and 2). No other lines are seen in the observed wavelength range, 6098 ≤ λ ≤ 10484.

There is no evidence for continuum emission in either our images or the GMOS spectrum. The observer-frame equivalent width of the line is greater than 530 Å at the 2σ level. We obtained this limit from our LALA survey narrow- and broadband photometry as follows. First, let \( f_{i,b} \) and \( f_{i,n} \) be the system throughput in the broad- and narrowband filters as a function of wavelength, which we base on the filter transmission curves and quantum efficiency of the Mosaic camera. Then, given the line wavelength \( \lambda_i \), we define \( w_b \equiv \left( \frac{\int f_{i,b}(\lambda) \, d\lambda}{\int f_{i,b}(\lambda) \, d\lambda} \right) \) and \( w_n \equiv \left( \frac{\int f_{i,n}(\lambda) \, d\lambda}{\int f_{i,n}(\lambda) \, d\lambda} \right). \) For a narrow line atop a flat (i.e., constant \( f_i \)) continuum, one can show that

\[
EW = w_b w_n (f_{i,n} - f_{i,b}) / (f_{i,n} w_b - f_{i,n} w_n),
\]

where \( f_{i,b} \) and \( f_{i,n} \) are the flux densities measured in the broad- and narrowband filters, respectively. We compute a 2σ limit on \( EW \) by inserting \( f_{i,b} \rightarrow f_{i,obs} + 2\sigma f_{i,obs} \) into the above expression. We ignore the uncertainty in the narrowband flux \( f_{i,n} \), because it is too small to much affect the EW measurement. For Lyα at \( z = 6.535 \), the rest-frame equivalent width would be greater than 70 Å (2σ) if we do not correct for attenuation by the IGM. The IGM is expected to attenuate the \( z' \)-filter flux by a factor of \( \approx 0.36 \) at \( z = 6.535 \) (Madau 1995). The correction to the line flux depends on the IGM neutral content, IGM velocity structure, and intrinsic line profile. For a symmetric line centered on a galaxy’s systemic velocity, the line flux would be reduced by a factor of 0.51 in a predominantly ionized IGM (i.e., all the red-side flux but only \( \sim 2\% \) of the blue-side flux would be transmitted). The IGM-corrected rest-frame equivalent width would then be greater than 40 Å (2σ), which we regard as a conservative lower bound. A largely neutral IGM or a line profile not symmetric about the systemic velocity would change this result appreciably (see § 6.2).

The line width in this source could in principle be consistent with [O iii] \( \lambda\lambda3726, 3729 \). However, this would imply a
rest-frame equivalent width greater than 215 Å (2 σ), which is outside the usual range for this line. Two large continuum-selected samples (Cowie et al. 1996; Hogg et al. 1998) and one Hα line–selected sample (Gallego et al. 1996) found no [O ii] λλ3726, 3729 sources with EW > 140 Å and a very small minority with 100 < EW < 140. In addition, star-forming galaxies usually show blue continuum emission, so that our Bw and R-filter nondetections again argue against [O ii] λλ3726, 3729 models.

The LALA J142442.24+353400.2 emission line has a measured width of 13 Å FWHM. This substantially exceeds the instrumental resolution (estimated at 6 Å on the basis of the GMS spectrum of LALA J142441.20+353405.1) and thus allows quantitative asymmetry measurements. We apply the line asymmetry statistics presented in Rhoads et al. (2003). First among these is $L_{\text{sym}}$, the likelihood of obtaining the observed data under the best-fitting symmetric line model. We find $L_{\text{sym}} \approx 0.02$ for LALA J142442.24+353400.2, supporting the visual impression of asymmetry.

To go further and quantify this asymmetry, we have further developed the asymmetry statistics $a_i$ and $a_f$ that were presented in Rhoads et al. (2003). These statistics depend on the determination of the wavelengths $\lambda_j$, where the line flux peaks, and $\lambda_{10,b}$, $\lambda_{10,r}$, where the flux drops to 10% of its peak value. To mitigate the effects of noise in the spectrum, all three wavelengths can be measured after a light smoothing. The asymmetry statistics are then defined as $a_i = (\lambda_{10,r} - \lambda_j)/(\lambda_j - \lambda_{10,b})$ and $a_f = \int_{\lambda_{10,b}}^{\lambda_{10,r}} f_\lambda \, d\lambda/\int_{\lambda_{10,b}}^{\lambda_{10,r}} f_\lambda \, d\lambda$. To determine the appropriate smoothing, we simulated observations of a line having a truncated Gaussian profile (described below) and the (wavelength dependent) noise level achieved in our GMOS data. We find that the asymmetry of the line is most reliably recovered using a Gaussian smoothing near 3 pixels (FWHM). We also experimented with the threshold level for the $\lambda_b$ and $\lambda_r$ measurements but found no clear benefit to raising this threshold. Using 3 pixel smoothing, we find $a_i = 1.78 \pm 0.71$ and $a_f = 1.54 \pm 0.53$, where the error bars are drawn from simulated spectra and defined as a “percentile-based σ,” i.e., 84% of simulated spectra lie within $\pm 2\sigma$ of the median simulated $a$-statistic.

The LALA J142442.24+353400.2 line can be well fitted with a truncated Gaussian model of the form suggested by Hu et al. (2004): The profile is taken to be a Gaussian of width $\sigma_i$ on the red side of a peak wavelength $\lambda_0$ and a step function to zero intensity blueward of the peak but then convolved with a second Gaussian of width $\sigma_f$ to reflect instrumental resolution effects. In LALA J142442.24+353400.2, we obtain $\chi^2/\text{dof} = 0.93$, where “dof” indicates “degrees of freedom,” using $\sigma_i = 8$, $\sigma_f = 1.2$, and $\lambda_0 = 9158$ Å. If we fix $\sigma_f = 2.5$ Å (the value obtained by assuming that the emission line in LALA J142441.20+353405.1 is unresolved by GMOS), the best fit deteriorates slightly to $\chi^2/\text{dof} = 1.17$.

Given that we see no other significant lines in the spectrum of LALA J142442.24+353400.2, we can rule out [O iii] $\lambda5007$ and Hβ transitions quite strongly. The remaining possibility, besides Lyα, is [O ii] λλ3726, 3729. However, the line ratio for [O ii] λλ3726, 3729 sources under the usual astrophysical conditions is $f_{3729}/f_{3726} \approx 1.3$, yielding an asymmetry opposite that of Lyα when the doublet is blended. We have tried modeling the data with [O ii] λλ3726, 3729 doublets, broadened by the instrumental resolution and an internal velocity dispersion (taken as a free parameter). Fixing the line ratio at 1.3 makes it impossible to achieve $\chi^2/\text{dof} \leq 1.9$, which is clearly worse than the truncated Gaussian model for Lyα. If we allow the line ratio to vary arbitrarily, we can achieve $\chi^2/\text{dof} = 1.0$, but only for $f_{3729}/f_{3726} \approx 0.4$, which would require an electron density $\leq 10^4$ cm$^{-3}$ ($T/10^4$ K)$^{-1/5}$ (e.g., Keenan et al. 1999). Extragalactic H ii regions do not approach these densities, and their line ratios cluster in a tight range: $1.2 \leq f_{3729}/f_{3726} \leq 1.4$ (O’Dell & Castaneda 1984). The observed range from galaxies at $z \sim 1$ in the DEEP2 survey is similar, from 1.26 to 1.41, with a typical ratio of $\approx 1.36$ for the high equivalent width emitters (J. Newman 2004, private communication). If we fix the line ratio at 1.3, we find that simulated spectra yield $a_f$(O ii) $> 1.78$ in only 6.7% of simulations. The corresponding probability for $a_f$ is slightly higher, at 12.9%. Thus, the best interpretation of this line is clearly Lyα, from both its asymmetry and its equivalent width.

LALA J142441.20+353405.1.—The second of these galaxies, LALA J142441.20+353405.1, was spectroscopically detected in both our Keck+DEIMOS data (covering 5160–9525 Å) and Gemini-N+GMOS data (covering 6177–10484 Å). A strong emission line is seen at the wavelength 9136 Å (see Figs. 3 and 4). This line is most likely [O iii] $\lambda5007$ at the redshift $z = 0.824$, on the basis of a careful search for other emission lines. Unfortunately, the expected locations of the [O iii] $\lambda4959$ and Hβ lines both fall atop night-sky OH emission features. The interpretation of this object depends critically on these features (Lyα is the best interpretation if no secondary lines exist).

We therefore fitted Gaussian line profiles at the expected locations of both [O iii] $\lambda4959$ and Hβ, using fitting weights derived from the observed profile of the 9136 Å line and from the observed noise as a function of wavelength in sky-subtracted spectra. This approach optimally exploits any part of the satellite line profile that is not obscured by night-sky line residuals. We obtained a 4 σ detection of the [O iii] $\lambda4959$ line and a line flux ratio of $0.33 \pm 0.08$ [$f(4959)/f(5007)$] from our two-dimensional DEIMOS data. A similar exercise...
using the one-dimensional GMOS data gave another $4\sigma$ detection at the expected [O iii] $\lambda$4959 wavelength and a line ratio of $0.35 \pm 0.09$. The consistency of these results with one another and with the theoretically expected line ratio of 0.33 leads us to believe this interpretation of the data. Further fitting yields also a marginal H$\beta$ detection in the DEIMOS data (3 $\sigma$, line ratio 0.111 $\pm$ 0.04) but nothing significant in the GMOS data. Measurement of the [O iii] $\lambda$3726, 3729 lines with this method is more difficult, since the expected position of [O ii] $\lambda$3726, 3729 depends on the spectral trace (which we cannot measure because the continuum in LALA J142441.20+353405.1 is undetected). In practice, we see a hint of the [O ii] $\lambda$3726, 3729 doublet in both data sets, but it is more significant in the GMOS data (2.4 and 6.4 $\sigma$ for 3726 and 3729 $\AA$, respectively) than in the DEIMOS data (3.7 and 1.0 $\sigma$, respectively). Further circumstantial support for the $z = 0.824$ interpretation comes from spectroscopic observations of a red galaxy sample in this field, which show a strong spike in the redshift distribution at $z = 0.824$ (Dey et al. 2004, in preparation). Other foreground emission-line interpretations are ruled out: An H$\alpha$ line at 9136 $\AA$ should imply [O iii] $\lambda$4959, 5007 and H$\beta$ near 6900 $\AA$, which is not seen, and [O ii] $\lambda$3726, 3729 at 9136 $\AA$ would be easily resolved as a close doublet in our DEIMOS data.

The flux of the 9136 $\AA$ line is large but subject to systematic uncertainties. Flux standards from our DEIMOS run imply a line flux of $3 \pm f_{17} \approx 5.7$, where $f_{17} = f/(10^{-17}$ ergs cm$^{-2}$ s$^{-1}$) is the scaled line flux. Our LALA survey narrowband imaging would naively imply a flux $f_{17} = 2.2$, but the measured wavelength places the emission line on the wing of the narrowband filter, where the throughput is low. Correcting by a factor $T_{\text{max}}/T(9136 \AA)$ implies a line flux of $4 \leq f_{17} \leq 6.6$, where the lower value is based on the original filter specifications given to the vendor and the higher value is based on filter transmissions made in 2003 May at NOAO by H. Schweiker and G. Jacoby. We adopt $f_{17} = 4$ as a reasonable best guess.

The line is quite narrow, with an observed FWHM of 3.55 $\AA$ in our DEIMOS data (corresponding to 5.5 DEIMOS pixels, and a velocity width of $\approx 100$ km s$^{-1}$). This width corresponds well to the typical seeing during our observations, which means that the physical line width in LALA J142441.20+353405.01 could be $< 100$ km s$^{-1}$ and also that the angular size of the line-emitting region is no larger than 0$''$.7. Applying our line asymmetry test here, we find $L_{\text{sym}} \approx 0.5$. Because there is no demonstrable asymmetry, we did not pursue measurement of $a_j$ and $a_p$. A Gaussian fit to the line yields a $\chi^2$/dof = 0.84 measured from 9132 to 9140 $\AA$.

We also see no evidence for continuum emission. The best equivalent-width estimate for this source comes from our DEIMOS data, which yield a 2 $\sigma$ lower bound of EW $> 620$ $\AA$ in the rest frame for $z = 0.824$. While large, this is within the observed range for [O iii] $\lambda$5007. We have previously reported a $z = 0.34$ [O iii] $\lambda$5007 source with $\sim 1000$ km s$^{-1}$ rest-frame equivalent width ($\sim 1400$ $\AA$ observed), discovered by its narrowband excess in the LALA Bootes field (Rhoads et al. 2000). Statistical studies of nearby H i galaxies show a range up to $\sim 1700$ $\AA$ (Raimann et al. 2000).

LALA J142441.20+353405.1 and LALA J142442.24+353400.2 lie 13$''$ apart, corresponding to a projected separation of $\approx 80$ kpc (physical). This proximity appears to be a coincidence, given the differing line identifications. If the lines were the same transition, the velocity separation of the two would be $\approx 800$ km s$^{-1}$.

Other candidates.—Of the remaining two candidates, LALA J142544.41+353327.7 was detected only in the 918 nm filter and is probably a noise spike in that filter, on the basis of its nondetection in Keck DEIMOS data. Assuming Gaussian statistics, we should expect about one noise peak above our $5\sigma$ detection threshold among the $\sim 10^{6.5}$ independent resolution elements in the narrowband image, and more may be found if the noise properties of the image are not perfectly Gaussian. The second spectroscopic nondetection, LALA J142610.55+354557.6, may have been a time-variable continuum source rather than a true emission-line object. It was targeted in a GMOS mask observed on 2003 July 2 and 3, with a total integration time exceeding that required to detect LALA J142441.20+353405.1 and LALA J142442.24+353400.2, which have similar narrowband fluxes. It appears as a narrowband excess target when compared with images from 2001 to before but has a marginal R-band detection in NDWFS images from UT 2002 April. This R-band detection is offset from the 918 nm source by about 0$''$.8 and may or may not be the same source, since the faintness of the object renders precise narrowband astrometry difficult. Regardless of its precise nature, it appears not to be a redshift 6.5 Ly$\alpha$ galaxy.

6. DISCUSSION

6.1. Physical Parameters of the Sources

Adopting a cosmology with $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$, and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$ (see Spergel et al. 2003) gives a luminosity distance of $2.00 \times 10^{29}$ cm (65 Gpc) for $z \approx 6.53$. We then obtain a line luminosity of $(1.1 \pm 0.2) \times 10^{43}$ ergs s$^{-1}$ for LALA J142442.24+353400.2. The other three Ly$\alpha$ galaxies so far spectroscopically confirmed at $z \approx 6.5$ have luminosities of $1.0 \times 10^{43}$ ergs s$^{-1}$ (SDF J132415.7+273058; K03), $0.56 \times 10^{43}$ ergs s$^{-1}$ (SDF J132418.3+271455; K03), and $0.3 \times 10^{43}$ ergs s$^{-1}$ (HCM 6A; H02). Thus, LALA J142442.24+353400.2 is comparable to SDF J132415.7+273058 and may be the most luminous Ly$\alpha$ line yet seen at this redshift.

Comparison with Ly$\alpha$ luminosity function fits at $z \approx 6.5$ that we derive in a companion paper (S. Malhotra et al. 2004, in
given that LALA J142442.24+353400.2 is much brighter than or limits on the \[O_3\] luminosities substantially above 10^{42} \text{ ergs s}^{-1}, which yields 11 M_\odot yr^{-1}. This conversion follows from a widely used set of assumptions: a Kennicutt (1983) initial mass function and corresponding conversion between H_\alpha luminosity and star formation rate, plus the Ly\alpha-to-H_\alpha ratio for dust-free case B recombination. These are probably not valid in detail for high-redshift Ly\alpha galaxies, but as we do not yet have a well-justified model, it is convenient to at least use a standard one. Combined with our survey volume of 2.1 \times 10^4 \text{ Mpc}^{-3} (comoving), we obtain a lower bound on the star formation rate density (SFRD) of 5.2 \times 10^{-5} M_\odot yr^{-1} \text{ Mpc}^{-3} from LALA J142442.24+353400.2 alone. Of course, given that LALA J142442.24+353400.2 is much brighter than L*, its contribution to the SFRD is only a small fraction of the total. For comparison, K03 probe farther down the luminosity function and find a lower limit to the SFRD of 5 \times 10^{-4} M_\odot yr^{-1} \text{ Mpc}^{-3}, while the Ly\alpha line found in the H02 survey would imply a 1 \sigma range from 3 \times 10^{-3} to 6 \times 10^{-2}. All these rates are subject to incompleteness corrections for sources falling below the survey detection limits in either Ly\alpha flux or equivalent width and to additional systematic uncertainties associated with the stellar population model assumed and with the radiative transfer of the resonantly scattered Ly\alpha line. In particular, the model used here and elsewhere to convert between Ly\alpha luminosity and star formation rate cannot actually reproduce the observed Ly\alpha equivalent-width distribution at \(\alpha\) = 4.5 (Malhotra & Rhoads 2002). Still, relative comparisons among Ly\alpha samples remain valid and show that sources such as LALA J142442.24+353400.2 are rare and luminous and constitute a fraction \langle 10^{-2} \rangle of the global Ly\alpha production and star formation rate at \(\alpha\) \approx 6.5.

For LALA J142441.20+353405.1, we have flux measurements or limits on the [O iii] \(\lambda 5007, [O ii] \lambda 3727, \text{ and H}\beta\) transitions. These allow us to place general constraints on the metallicity of this galaxy using \(R_{32} \equiv (f(5007)+f(4959)+f(3727))/f(\text{H}\beta)\). We find log \(R_{32} \geq \text{log}[(f(5007)+f(4959))/f(\text{H}\beta)] = 1.1 \pm 0.12\). The additional contribution to the oxygen flux from [O ii] \(\lambda 3727\) is either negligible (using the DEIMOS measurement, for which \(O_{32} \equiv (f(5007)+f(4959))/f(3727) \approx 2\)) or small (using the GMOS measurement, for which \(O_{32} \approx 2.5\)). From Kewley & Dopita (2002), the theoretical maximum for log \(R_{32}\) is 0.97, achieved only for a modestly subsolar metallicity near log (O/H) + 12 \approx 8.38 and a high-ionization parameter \(q > 3 \times 10^{8} \text{ cm s}^{-1}\). (Here the ionization parameter is defined as the ratio of the ionizing-photon flux to the number density of hydrogen; see Kewley & Dopita 2002.) Our observation is consistent with this theoretical maximum but not with \(R_{32}\) substantially below this maximum, and we thus conclude that LALA J142441.20+353405.1 has 12 + log (O/H) \approx 8.4. For comparison, estimates of the solar value for 12 + log (O/H) range from 8.9 (McGaugh 1991) to 8.68 (Allende Prieto et al. 2001).

This places LALA J142441.20+353405.1 in the lowest quartile of metallicity for galaxies at 0.47 < z < 0.92 from the Canada-France Redshift Survey sample (Lilly et al. 2003) but around the midpoint of the metallicity range for LBGs at z \approx 3 (Pettini et al. 2001). The ratio O_{32} also shows a closer physical resemblance to LBGs than to continuum-bright galaxies at 0.47 < z < 0.92: ratios O_{32} > 2 are observed in only 1 of 66 galaxies reported by Lilly et al. (2003) but in four of five LBGs in the Pettini et al. (2001) sample. However, the apparent discrepancy with other z \approx 0.8 galaxies is likely due to the larger characteristic luminosity of the Lilly et al. sample, which has I_{AB} < 22.5. Our I-band limiting magnitude (I_{AB} > 25.9) corresponds to Johnson M_I > -16.9. Using a metallicity-luminosity relation derived by Melbourne & Salzer (2002) for local emission line–selected galaxies, we would expect 12 + log (O/H) = 8.1 \pm 0.27, where the error bar is the empirically determined scatter for the local sample. Thus, LALA J142441.20+353405.1 actually has a slightly high metallicity for its luminosity. This is broadly consistent with the finding of Lilly et al. (2003), that most galaxies at 0.47 < z < 0.92 have metallicity comparable to that of local galaxies of similar luminosity.

Photoionization models show that equivalent widths of \sim 600 \AA\ correspond to starburst ages of 3–4 Myr for metallicity Z \approx \frac{1}{4} Z_\odot (Stasinska & Leitherer 1996), implying that the emission from LALA J142441.20+353405.1 is dominated by a very young stellar population. Combining this age with the gas metallicity implies that this is not the first generation of stars formed in this high-redshift dwarf galaxy. The current star formation rate can be estimated from the emission-line fluxes. The conversion between line flux and star formation rate is better established for H\beta [using the ratio f(\text{H}\alpha)/f(\text{H}\beta) = 2.8 and the Kennicutt (1983) conversion factor] than for [O iii] \lambda 5007. The observed H\beta flux thereby implies a star formation rate of \sim 0.4 M_\odot yr^{-1}, although the combined uncertainty in the line flux and conversion factor is at least a factor of 2.

### 6.2. Implications for Reionization

Because Ly\alpha photons are resonantly scattered by neutral hydrogen, Ly\alpha-emitting galaxies may suffer considerable attenuation of their line flux when embedded in an IGM with a substantial neutral fraction. Thus, a decrease in Ly\alpha galaxy counts may be expected at redshifts substantially before the end of reionization (Rhoads & Malhotra 2001; H02; Rhoads et al. 2003). Typical high-redshift Ly\alpha galaxies have small continuum fluxes, and upper limits can be placed on their expected Stromgren sphere radii \(r_S\) by combining their observed fluxes and equivalent widths with stellar population models (Rhoads & Malhotra 2001). A radius \(r_S < 0.5 \text{ Mpc}\) is typically inferred. For comparison, \(r_S > 1.2 \text{ Mpc}\) is required to avoid a scattering optical depth \(\tau > 1\) at the systemic velocity because of the neutral IGM outside the Stromgren sphere.

Haiman (2002) has argued that the first reported z \approx 6.5 galaxy (H02) could still be embedded in a neutral IGM because (1) emission from the red wing of the emitted line is less strongly scattered than line center, reducing the effective attenuation of the line, and (2) the observed Ly\alpha equivalent width in this object is substantially below the theoretical maximum from stellar population models, so the observed line could in fact be substantially attenuated. Santos (2004) considers additional physical effects, including gas motions and overdensity associated with the formation of Ly\alpha galaxies, which generally increase the Ly\alpha attenuation over that in Haiman’s model. For example, in the case of infall to a forming galaxy, scattering by residual neutrals within the Stromgren sphere can produce large optical depths (\(\tau > 100\)) on the blue side of the Ly\alpha line, between the systemic velocity...
and the gas infall velocity. However, Santos also suggests that the velocity differences observed between Lyα lines and other emission lines in LBGs could be intrinsic to the source, so the entire Lyα line is emitted with an effective redshift of a few hundred km s⁻¹. In this case, the effective Lyα attenuation for z ~ 6.5 is a factor of ~3 and is not very sensitive to model parameters besides the ionization state of the IGM.

LALA J142424.24+353400.2 constrains reionization better than most other z ~ 6.5 galaxies because of its relatively large equivalent width (>70 Å rest-frame, 2σ, before corrections for IGM opacity, or greater than 40 Å with corrections suitable for an ionized IGM; see § 5). The source SDF J132415.7+273058 (K03) has a similar line luminosity, a continuum detection near the upper limit for LALA J142424.24+353400.2, and hence, an equivalent-width measurement quite similar to the 2σ limit of LALA J142424.24+353400.2.

In a neutral universe, these sources would require an intrinsic equivalent width >120 Å even if the Lyα line is redshifted as suggested by Santos and >400 Å in the absence of such a redshift. The former is consistent with the observed Lyα equivalent-width distribution at z ~ 4.5 (Malhotra & Rhoads 2002). The latter is high even for the z ~ 4.5 sample. Thus, the properties of these objects are most easily understood if the universe is mostly ionized at z ~ 6.5. More robust constraints on reionization from individual Lyα galaxies will be difficult because the expected suppression of the Lyα line depends strongly on the velocity offset between emitted Lyα and the galaxy’s systemic velocity, and measuring the latter would in general require spectroscopy in the thermally dominated mid-infrared (Santos 2004).

Stronger constraints on reionization from Lyα galaxies will be possible using statistical samples. Suppression of Lyα by the IGM has a strong effect on the Lyα luminosity function: even a factor of ~3 reduction in Lyα flux will reduce the observed Lyα number counts dramatically. The accessible portion of the Lyα luminosity function is very steep (see S. Malhotra et al. 2004, in preparation), and a factor of 3 in the luminosity threshold corresponds to a factor of >10 in the expected Lyα source counts at fixed sensitivity. Moreover, the effect on the equivalent-width distribution is identical to that on the luminosity function, which would not be generally expected for other factors that could modify the Lyα luminosity function (such as evolution).

7. CONCLUSIONS

We have performed a narrowband search for Lyα-emitting galaxies at z ~ 6.5 in the Bootes field of the Large Area Lyman Alpha survey and have obtained spectra for all our viable candidates. One source, LALA J142424.24+353400.2, is confirmed as Lyα at z = 6.535 on the basis of an isolated, asymmetric emission line. The Lyα luminosity of this source is large, ~1.1×10⁴³ ergs s⁻¹. Objects this bright in the line are rare, occurring at a rate of about one per 2×10⁵ comoving Mpc² (this work; K03). It is therefore likely to correspond to a high peak in the density distribution at redshift z = 6.535. The equivalent width is also larger than most other z ~ 6.5 galaxies, with a 2σ lower bound of greater than 40 Å (rest-frame, corrected for IGM absorption). This is difficult to reconcile with a neutral IGM unless the Lyα line is intrinsically strong and is emitted from its host galaxy with an intrinsic Doppler shift of several hundred km s⁻¹.

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