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A GALAXY AT $z = 6.545$ AND CONSTRAINTS ON THE EPOCH OF REIONIZATION

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ABSTRACT

We report the discovery of a Lyα-emitting galaxy at redshift $z = 6.545$ serendipitously identified in the course of spectroscopic follow-up of hard X-ray sources on behalf of the Serendipitous Extragalactic X-Ray Source Identification (SEXSI) survey. The line flux of the galaxy, 2.1×10^{-17} ergs cm^{-2} s^{-1}, is similar to line fluxes probed by narrowband imaging surveys; the 5.2 arcmin^2 surveyed implies a surface density of $z \approx 6.5$ Lyα emitters somewhat higher than that inferred from narrowband surveys. This source marks the sixth Lyα-emitting galaxy identified at $z \approx 6.5$, a redshift putatively beyond the epoch of reionization when the damping wings of the neutral hydrogen of the intergalactic medium is capable of severely attenuating Lyα emission. By comparing the Lyα luminosity functions at $z \approx 5.7$ and $z \approx 6.5$, we infer that the intergalactic medium may remain largely reionized from the local universe out to $z \approx 6.5$.

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

1. INTRODUCTION

The observation of galaxy and quasar light emitted when the universe was less than a billion years old has opened a window for spectroscopic exploration of the early history of the intergalactic medium. Djorgovski et al. (2001) showed a dramatic increase in the optical depth of the Lyα forest at $z \gtrsim 5.2$ and interpreted this as evidence of the trailing edge of the cosmic reionization epoch. Subsequent discovery of broad, black, Lyα absorption troughs, as predicted by Gunn & Peterson (1965), in the spectra of the highest redshift quasars ($z \gtrsim 6$) indicate that we are beginning to probe the era when hydrogen was reionized by an early generation of stars (Becker et al. 2001; White et al. 2003; Fan et al. 2003). Circa 2001, we thought we had identified where the "dark ages" ended, when the first sources of light in the universe turned on with sufficient strength to dissociate the hydrogen atoms formed when the universe was only ~300,000 years old.

More recently, our picture of the early ionization history of the intergalactic medium (IGM) has become more complicated. The *Wilkinson Microwave Anisotropy Probe* identified a large amplitude signal in the temperature-polarization maps of the cosmic microwave background (Spergel et al. 2003), indicating a large optical depth to Thomson scattering. The straightforward interpretation of this result is that the universe became reionized at $z = 17 \pm 5$ (Kogut et al. 2003). At first glance this appears inconsistent with reionization occurring at $z \sim 6$. However, since a relatively small neutral fraction ($x_{\rm H\,I}^{\rm IGM} \approx 0.001$) suffices to produce black Gunn-Peterson troughs, the microwave results are not necessarily contradictory with the quasar results; perhaps reionization began early and only completed around redshift $z \sim 6$. On the other hand, Wyithe & Loeb (2004a) and Mesinger & Haiman (2004) show that the size of the H II region around the highest redshift quasars provides stronger constraints on the IGM neutral fraction, implying $x_{\rm H\,I}^{\rm IGM} > 0.1$ for typical quasar lifetimes.

There is mounting evidence that the ionization history of the IGM is complex; see, e.g., Loeb & Barkana (2001), Barkana & Loeb (2001), and Miralda-Escudé (2003) for recent reviews. Several theorists have argued that the hydrogen in the IGM could have been reionized twice (e.g., Wyithe & Loeb 2003; Cen 2003; Haiman & Holder 2003; Somerville et al. 2003). A first reionization occurs at $z \sim 20$, driven by the formation of massive, zero-metallicity Population III stars (e.g., Bromm 2004). However, their radiative and mechanical feedback may have disrupted the subsequent star formation, possibly leading to a partial recombination until an increasing Population II massive star population and declining IGM density allow the second reionization to occur at $z \sim 6$, as indicated by the high-redshift quasar spectroscopic measurements. How and when reionization(s) happened, and the details of the reionization process, have been among the most pressing questions in astrophysical cosmology, holding many clues about the first generation of light sources.

High-redshift Lyα emitters offer a complementary approach to studying the early reionization history of the IGM. It has long been suggested that the first sources of ultraviolet radiation, responsible for the reionization of the universe, should be strong Lyα emitters (Partridge & Peebles 1967). After several decades of largely unsuccessful searches (for a review, see Pritchet 1994), numerous Lyα emitters are finally being discovered at high redshifts (e.g., Dey et al. 1998; Hu et al. 1998, 2004; Weymann et al. 1998; Rhoads et al. 2000, 2003; Ellis et al. 2001; Dawson et al. 2002; Kodaira et al. 2003; Dickinson et al. 2004; Stanway et al. 2004). These discoveries demonstrate that Lyα-emitting galaxies do exist in significant numbers out to the current horizon of their detectability. The most distant sources, confirmed out to $z = 6.578 \pm 0.002$ (Kodaira et al. 2003), are seen *prior* to the quasar-derived reionization redshift of the IGM. Since Lyα photons injected into a neutral IGM are strongly scattered, the red damping wing of the Gunn-Peterson trough should strongly suppress, or even completely eliminate, detectable Lyα emission (Miralda-Escudé & Rees 1998;

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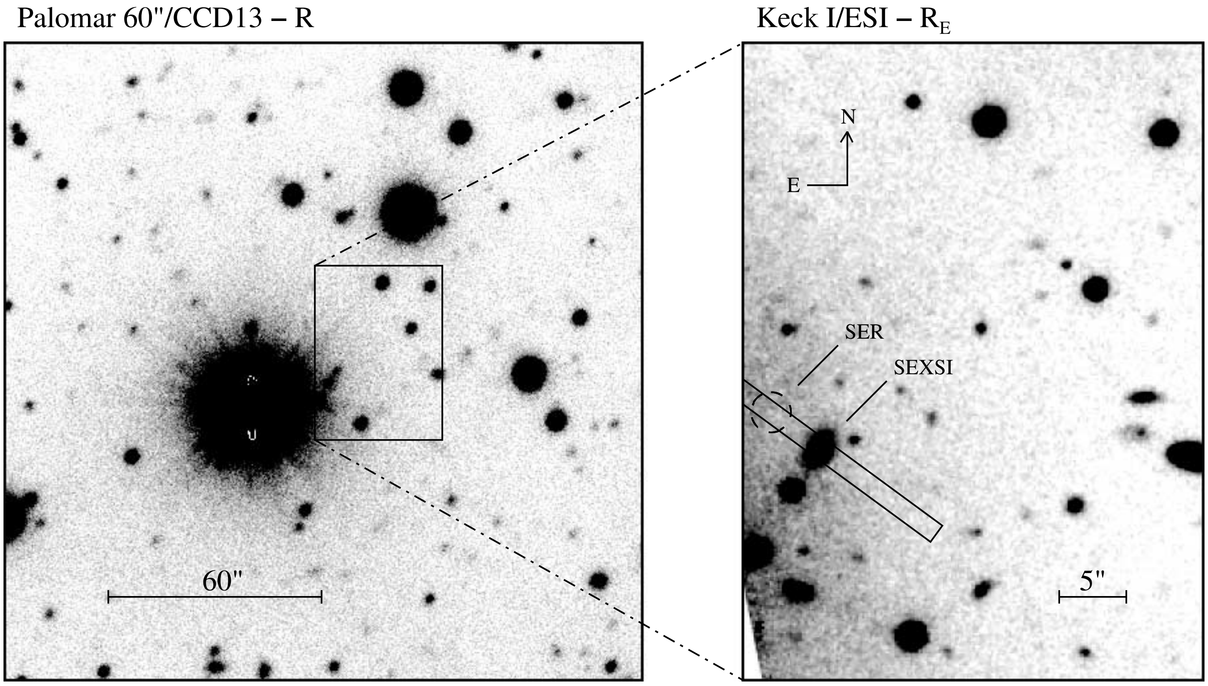

FIG. 1.—Optical, R-band images of SEXSI-SER in the MS 1621.5+2640 field. Orientation and scales are indicated. The left panel presents shallow, wide-area R-band imaging from Palomar Observatory. The right panel highlights the area around SEXSI-SER and was obtained with the Keck II telescope through an Ellis R_E-band filter. The Keck imaging was oriented so as to avoid the bright star east-southeast of SEXSI-SER. The target of the slitlet that serendipitously covered SEXSI-SER was CXOSEXSI J162256.7+264103 (labeled "SEXSI"); the orientation (position angle of 53°.7) and size (1″.0 × 27″) of the slitlet is indicated. We find no optical source at or near the location of SEXSI-SER (labeled "SER"), consistent with the z = 6.5 interpretation of the spectrum.

Miralda-Escudé 1998; Loeb & Rybicki 1999; Barkana & Loeb 2004; Gnedin & Prada 2004; Furlanetto et al. 2004). Initially it was thought that small Lyα-emitting galaxies embedded in a neutral IGM would be incapable of ionizing enough of their surroundings to prevent this effect, thus implying that the detection of even a *single* Lyα-emitting galaxy requires that the reionization epoch occurs at a higher redshift. Subsequent calculations (Haiman 2002), however, show that even for faint sources with little ionizing continuum, a sufficiently broad ($\Delta v \gtrsim 300$ km s^{-1}) emission line can remain observable. The transmitted fraction depends upon the size of the local cosmological H II region surrounding a source and therefore on the ionizing luminosity and age of the source (e.g., Santos 2004) as well as on contributions from associated, clustered sources (e.g., Wyithe & Loeb 2004b). Nevertheless, we expect a rapid decline in the observed space density of Lyα emitters as the reionization epoch is approached; a statistical sample of Lyα emitters spanning the reionization redshift should still be a useful probe of reionization (Haiman & Spaans 1999; Rhoads & Malhotra 2001; Haiman 2002). However, such an effect may be detectable only for the fainter sources, and it depends on many as-yet unknown details about the geometry of reionization, intrinsic evolution of the Lyα luminosity function, as well as the winds and environment of high-redshift Lyα emitters.

Here we report the discovery of a Lyα-emitting galaxy at $z = 6.545$, hereafter referred to as SEXSI-SER, serendipitously identified in the course of spectroscopic follow-up of hard (2–10 keV) X-ray sources from the Serendipitous Extragalactic X-ray Source Identification program (SEXSI; Harrison et al. 2003; Eckart et al. 2004). The SEXSI survey, whose scientific goal is to understand the sources contributing to the cosmic X-ray background, has obtained spectroscopic redshifts for $\gtrsim$450 hard X-ray sources selected from 27 archival *Chandra* fields (M. Eckart et al. 2005, in preparation). By the nature of this extensive spectroscopic campaign of faint, modest surface density sources, the SEXSI survey is also particularly well suited to serendipitous searches for high-redshift Lyα-emitting galaxies.

SEXSI-SER marks the sixth Lyα-emitting galaxy identified at $z \approx 6.5$. This redshift corresponds to a clean window in the night sky, relatively free of telluric emission lines, and has thus been a preferred redshift for narrowband imaging surveys. Four $z \approx 6.5$ Lyα emitters have been confirmed from such surveys to date (Hu et al. 2002; Kodaira et al. 2003; Rhoads et al. 2004). A fifth $z \approx 6.5$ Lyα emitter has recently been reported from a slitless spectroscopy program with the VLT (Kurk et al. 2004), while Tran et al. (2004) report on an unsuccessful narrowband *spectroscopic* search with the same telescope.

We describe our imaging and spectroscopic observations in § 2 and discuss the inferred physical properties of SEXSI-SER in § 3.1. The implications of this discovery with respect to the early star formation density and the epoch of reionization comprise § 3.2 and § 3.3, respectively. A coordinated paper, Malhotra & Rhoads (2004), provides a more detailed analysis of the luminosity function of Lyα emitters at $z \approx 5.7$ and $z \approx 6.5$. Throughout this paper we adopt a Λ-cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}. At $z = 6.545$, such a universe is 0.82 Gyr old, the look-back time is 93.9% of the total age of the universe, and an angular size of 1″.0 corresponds to 5.4 kpc.

2. OBSERVATIONS

2.1. *Optical Imaging*

SEXSI-SER was identified in the outskirts of MS 1621.5+2640 (Ellingson et al. 1997), a $z = 0.428$ galaxy cluster that was the target of a 30 ks exposure with *Chandra* and is one of the 27 SEXSI survey fields. To support spectroscopic follow-up

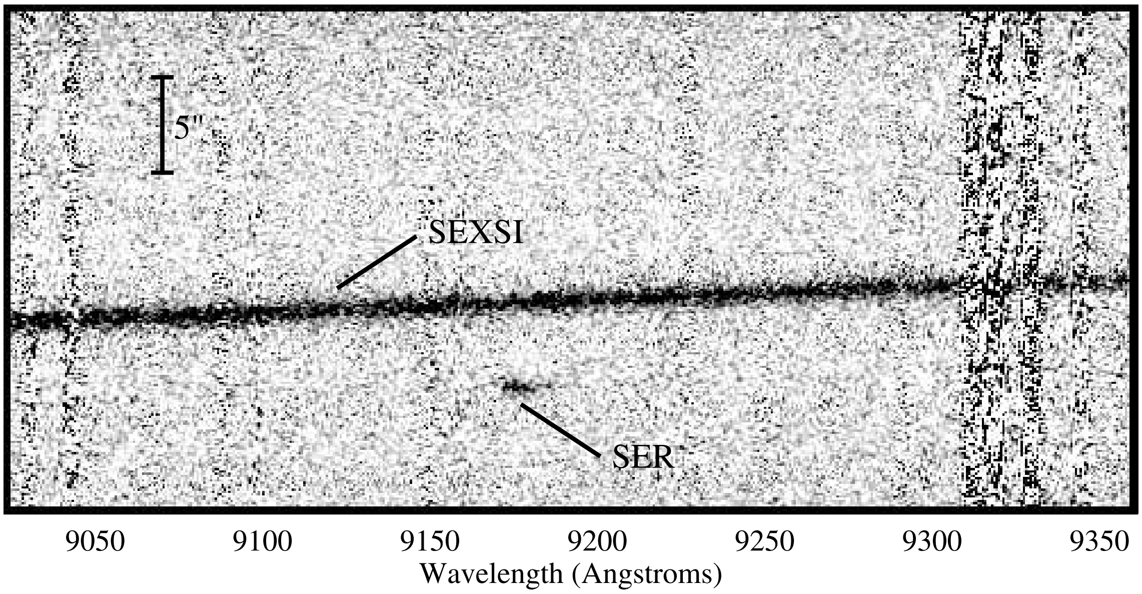

FIG. 2.—Two-dimensional, processed spectrum of SEXSI-SER at $z = 6.545$ obtained with DEIMOS on the Keck II telescope. The total exposure time is 1 hr.

of X-ray sources in the MS 1621.5+2640 field, we obtained shallow, wide-field images with the CCD13 camera on the Palomar 60 inch (1.524 m) telescope on UT 2001 May 18. Eckart et al. (2004) presents these observations, obtained through a Kron-Cousins R-band filter ($\lambda_c = 6450$ Å; $\Delta\lambda = 1500$ Å). On UT 2004 April 25, we used the Echelle Spectrograph and Imager (ESI; Sheinis et al. 2002) on the Keck II telescope to obtain a deep, 1200 s image through an Ellis $R_{\rm E}$-band filter ($\lambda_c = 6657$ Å; $\Delta\lambda = 1200$ Å) in photometric conditions with 0.″7 seeing. Figure 1 displays these optical images.

2.2. *Keck Spectroscopy*

We identified SEXSI-SER in spectra obtained with the Deep Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) on the Keck II telescope. These observations, taken on UT 2003 August 24, roughly contemporaneous with the launch of the *Spitzer Space Telescope*, were on the final night of a three-night run studying SEXSI sources over multiple fields. During this observing run we observed 19 slit masks, each of which used 1.″0 wide slitlets, the 600ZD grating ($\lambda_{\rm blaze} = 7500$ Å; $\Delta\lambda_{\rm FWHM} = 3.7$ Å), and a GG455 order-blocking filter. Typical exposure times were 1 hr, split into three 1200 s exposures for effective cosmic-ray removal. We used IRAF to process the data using standard techniques. Flux calibration relied upon observations of G191B2B obtained during the same observing run. Because of contamination of second-order light longward of 9100 Å from the blue standard star, the flux calibration at long wavelengths is extrapolated; this estimate should be accurate to better than 10% at 9200 Å.

We identified SEXSI-SER in a slitlet targeting CXOSEXSI J162256.7+264103, an $f_{2-10\ \rm keV} = 1.85 \times 10^{-14}$ ergs cm^{-2} s^{-1} hard X-ray source hosted by an $R \sim 21.7$ galaxy. Figure 1 illustrates the orientation and size of the slitlet. The wavelength coverage for this slitlet is 5650 Å -1 μm, with a 20 Å chip gap centered at 8235 Å. Approximately 4.″5 from the bright target, an asymmetric, isolated emission line at 9172 Å is evident in the spectrum. Figure 2 shows the processed, sky-subtracted, two-dimensional spectrum, and Figure 3 presents the extracted, fluxed spectrum of SEXSI-SER. We note that since SEXSI-SER is 11.′4 from the core of MS 1621.5+2640, gravitational lensing from the galaxy cluster is negligible. The extracted spectrum has been corrected for the Galactic extinction of $E(B-V) = 0.039$, determined from the dust maps of Schlegel et al. (1998). The asymmetric emission line is present in all three 1200 s DEIMOS exposures as well as a follow-up spectrum obtained with ESI on UT 2004 April 25. We therefore consider it unlikely that the line is spurious and due to scattered light from the 12th magnitude star approximately 30″ east-southeast of SEXSI-SER.

3. RESULTS AND DISCUSSION

3.1. *Spectroscopic Results and Inferred Physical Properties*

SEXSI-SER shows a single, strong, asymmetric emission line. In principle, strong emission lines may be associated with several species, e.g., Lyα, [O II] λ3727, [O III] λ5007, or Hα. Stern et al. (2000a) provide a detailed discussion of one-line redshifts and searches for high-redshift Lyα emission,

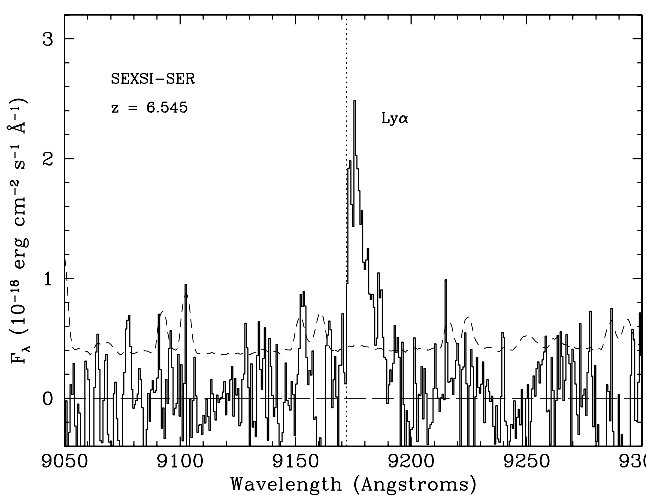

FIG. 3.—Spectrum of SEXSI-SER at $z = 6.545$ obtained with DEIMOS on the Keck II telescope. The total exposure time is 1 hr, and the spectrum was extracted using a 1.″0 × 1.″2 aperture. The vertical dotted line indicates the assumed observed wavelength of Lyα. The dashed line illustrates the error spectrum, assuming Poisson statistics from sky plus object.

discussing at length tests to distinguish Lyα emission from foreground interlopers. In the case of SEXSI-SER, we identify three lines of evidence that lead us to associate the line with highly redshifted Lyα.

First, the line is isolated. [O II] λ3727, the principal doppelgänger of high-redshift Lyα emission, can be ruled out as an identification for SEXSI-SER, since this doublet would have been resolved at the resolution of our observations. In addition, [O III] λ5007 and Hα are unlikely interpretations because of the lack of neighboring emission lines (Hβ and [O III] λ4959 for [O III] λ5007; [N II] $\lambda\lambda$6548, 6584; and [S II] $\lambda\lambda$6716, 6731 for Hα).

Second, the SEXSI-SER emission line has an extremely large equivalent width. We detect no continuum from SEXSI-SER. Averaging the flux in the 9200–9300 Å range, which is relatively clear of telluric emission, we measure a continuum flux of $-(0.03 \pm 0.04) \times 10^{-18}$ ergs cm^{-2} s^{-1} Å^{-1}. The implied equivalent width of SEXSI-SER, based on a Monte Carlo simulation subject to the constraint that both the line flux and continuum level are positive, is $W_\lambda^{\rm obs} > 410$ Å at the 67% confidence limit. As detailed in Stern et al. (2000a), isolated emission lines in the optical with measured equivalent widths larger than ≈300 Å should be almost exclusively identified with Lyα. The Kennicutt (1992) spectral atlas of nearby galaxies shows that the rest-frame equivalent width of the Hα+ [N II] complex rarely exceeds 200 Å, that of [O III] λ5007 rarely exceeds 100 Å, Hβ rarely exceeds 30 Å, and [O II] λ3727 rarely exceeds 100 Å. Lyα, however, can have rest-frame equivalent widths as large as 200 Å (Charlot & Fall 1993), which is further boosted by the $1 + z$ cosmological amplification of observed equivalent widths. The measured equivalent width for SEXSI-SER corresponds to a rest-frame equivalent width $W_\lambda^{\rm rest} > 54$ Å. For comparison, Dawson et al. (2004) find a consistent median $W_\lambda^{\rm rest} \approx$ 90 Å from a sample of 17 confirmed Lyα-emitting galaxies at $z \approx 4.5$.

Finally, the asymmetric profile of the emission line of SEXSI-SER leads us to confidently identify it with Lyα. While low-metallicity systems can have extreme Hα to [N II] $\lambda\lambda$6548, 6584 and [S II] $\lambda\lambda$6716, 6731 ratios, and both active galactic nuclei (AGNs) and high-ionization H II dwarf galaxies can have high equivalent width emission lines, the asymmetric profile characteristic of high-redshift Lyα emission is difficult to mimic from other emission features. Asymmetric Lyα emission is created by outflowing winds causing a broad red wing, while foreground neutral hydrogen absorption causes a sharp blue cutoff (e.g., Stern & Spinrad 1999; Dawson et al. 2002; Hu et al. 2004). Following the definitions of Rhoads et al. (2003), we find asymmetry parameters of $a_\lambda = 3.7^{+0.6}_{-2.3}$ and $a_f = 2.4^{+1.9}_{-0.7}$ for SEXSI-SER, values that are typical of high-redshift Lyα emission and are strongly atypical of low-redshift [O II] λ3727 emission (cf. Fig. 3 of Dawson et al. 2004). Specifically, [O II] λ3727 emission lines have typical values of ≈0.8 for both a_λ and a_f. Identifying the SEXSI-SER emission line at 9172 Å with Lyα, the implied redshift is $z = 6.545 \pm 0.001$, where the redshift has been measured from the break in the emission line and the quoted error solely reflects uncertainty in the wavelength calibration; systematic errors on the redshift due to kinematics and absorption are likely larger.

The spectrum of the slitlet target, CXOSEXSI J162256.7+264103, shows a composite galaxy spectrum at $z = 0.689$ with several absorption line features characteristic of early-type galaxies (e.g., CaHK, a strong 4000 Å break, G-band) as well as narrow emission from [O II] λ3727 and [O III] $\lambda\lambda$4959, 5007. The emission line of SEXSI-SER would correspond to a rest-frame wavelength of 5430 Å if it were associated with this galaxy, a wavelength that does not correspond to any strong features in typical galaxy spectra. We conclude that the two systems are unrelated. No continuum source is evident at the inferred location of SEXSI-SER in the Keck imaging, implying a 3 σ limit of $R_{\rm E} > 26.8$ in a 1.″5 diameter aperture. Since the $R_{\rm E}$ band corresponds to a rest-frame wavelength of 880 Å for $z =$ 6.545, shortward of the Lyman continuum break, this is consistent with the high-redshift interpretation of SEXSI-SER. Furthermore, no optical sources are evident in our deep ESI image near (<4″) from the location of SEXSI-SER, suggesting that the observed emission line is unlikely associated with extended [O II] λ3727 or [O III] λ5007 emission from a foreground system. Such situations are regularly the culprits of serendipitously identified, isolated emission lines with more symmetric profiles (e.g., H. Spinrad 2004, private communication; Stern et al. 2000a). Finally, we note that since SEXSI-SER lacks an identification in imaging, we cannot be certain of its location relative to the discovery slitlet, and thus the measured flux suffers some uncertainty from unknown slit losses.

Since the SEXSI-SER Lyα emission line is asymmetric, we calculate the line flux by summing the pixels in the range 9170–9190 Å, finding a Lyα flux of $(2.13 \pm 0.15) \times 10^{-17}$ ergs cm^{-2} s^{-1}. For $z = 6.545$ and our adopted cosmology, this corresponds to a line luminosity of $L_{{\rm Ly}\alpha} = (10.39 \pm 0.73) \times 10^{42}$ ergs s^{-1}. Determined directly from the pixel flux values, we derive an observed-frame line FWHM of 6.6 Å. Correcting for the instrument resolution and assuming SEXSI-SER filled the 1.″0 wide slitlet, this corresponds to $\Delta v = 180$ km s^{-1}. For Lyα emission powered by star formation, Hu et al. (1999) give a conversion rate of 1 $M_\odot$ yr^{-1} = 10^{42} ergs s^{-1} to relate Lyα luminosities to star formation rates (but see caveats in Rhoads et al. 2003; Loeb et al. 2005), implying a star formation rate of ≥10 $M_\odot$ yr^{-1} for SEXSI-SER. The inequality derives from the unknown fraction of the line flux that has been absorbed by foreground and associated neutral hydrogen. We note that studies of Lyα-emitting galaxies of similar luminosity but at lower redshift find no evidence of an AGN contribution to the Lyα luminosity. In particular, Dawson et al. (2004) find no C IV λ1549 emission in a composite spectrum derived from 11 Lyα emitters at $z \approx 4.5$, while deep (∼170 ks) exposures with *Chandra* of narrowband-selected $z \approx 4.5$ candidates in the Large Area Lyman Alpha (LALA) Boötes field (Malhotra et al. 2003) and Cetus field (Wang et al. 2004) detect no X-ray emission, even in stacked X-ray images.

3.2. *The Surface Density of z ≈ 6.5 Lyα Emitters*

The useful sky areal coverage from our three-night DEIMOS observing run was approximately 5.2 arcmin^2, calculated from 1.″0 wide slits covering most of the 16.′3 available on each of 19 slit masks observed. Although in principle we are sensitive to emission lines over a very broad wavelength range (e.g., Lyα emitter at $z = 6.17$ identified by Cuby et al. 2003), we are most sensitive in the atmospheric line free range $9050 \lesssim \lambda \lesssim 9310$ Å, corresponding to Lyα at $6.44 < z < 6.66$. The implied surface density of Lyα emitters at $z \approx 6.5$, based on this single source, is 7.5×10^{-4} arcmin^{-2} Å^{-1}, about 5 times the surface density derived by Kodaira et al. (2003) from their deep, narrowband imaging survey. The comoving volume of our survey is approximately 2600 Mpc^3, implying a star formation density of 4×10^{-3} $M_\odot$ yr^{-1} Mpc^{-3} at $z \approx 6.5$. Since no attempt to account for sources below our detection threshold has been made, this might be considered a lower limit, though we caution against parameters derived from a single source identified in an apparently unusually fortuitous observation. For comparison,

TABLE 1
Surface Density of Lyα Emitters

z	Survey Area (arcmin^2 Å)	Flux Limit (ergs cm^{-2} s^{-1})	No. of Candidates	Spectroscopic Success	Σ(Lyα) (deg^{-2} unit$-z^{-1}$)	References
3.4	75×77	1.5×10^{-17}	19	15/15	14,400	1
4.5	25×78	1.5×10^{-17}	3	2/3	4490	1
	1116×85	2.6×10^{-17}	225	1/3	3460	2
5.7	710×150	$\sim 2 \times 10^{-17}$	18	3/4	560	2
	$\sim 400 \times 110$	3×10^{-17}	11	1/3	365	3
	702×120	2×10^{-17}	26	19/23	1120	1
	5×150	6×10^{-18}	0	0/0	<5840	4
6.5	814×132	$\sim 1 \times 10^{-17}$	73	2/9	660	5
	1200×84	2×10^{-17}	4	1/4	40	2
	18×190	5×10^{-18}	0	0/0	<1280	6
	43×190	$\sim 2 \times 10^{-17}$	1	1/1	540	7
	5×260	$\sim 2 \times 10^{-17}$	1	1/1	3370	8

Notes.—We omit Lyα surveys behind galaxy clusters, for which the effects of gravitational lensing complicate the derived surface densities. We also omit imaging surveys that have not yet reported on spectroscopic success rates.

References.—(1) Hu et al. 1998; (2) Rhoads et al. 2000; (3) Maier et al. 2003; (4) Martin & Sawicki 2004; (5) Kodaira et al. 2003; (6) Tran et al. 2004; (7) Kurk et al. 2004; (8) this paper.

our estimated star formation density at $z \approx 6.5$ is approximately an order of magnitude greater than that derived by Kodaira et al. (2003) and Kurk et al. (2004). Table 1 summarizes the results of several recent surveys for high-redshift Lyα emission.

3.3. *Implications for Reionization*

Although it has now been shown that the existence of a *single* Lyα-emitting galaxy at a high redshift does not imply that reionization must have occurred at a yet higher redshift, we do expect that the epoch of reionization should be accompanied by a rapid decline in the observed space density of faint Lyα emitters (e.g., Haiman & Spaans 1999; Rhoads & Malhotra 2001; Haiman 2002). This is simply due to the time it takes a young protogalaxy to create and maintain a sufficiently large H ii, or Strömgren, sphere to allow Lyman photons to escape. We now consider the luminosity functions of Lyα emitters at high redshift. For simplicity, we omit Lyα surveys behind galaxy clusters, for which the effects of gravitational lensing complicate the derived surface densities.

$z \approx 5.7$.—There are two recent reports on spectroscopic confirmation of $z \approx 5.7$ Lyα-emitting galaxies. Rhoads et al. (2003) report on 18 candidate $5.67 < z < 5.80$ Lyα emitters in a 710 arcmin^2 survey region, out of which four sources were attempted spectroscopically and three were confirmed. Hu et al. (2004) present results on 26 narrowband-selected candidate $5.653 < z < 5.752$ Lyα emitters in a 702 arcmin^2 region, out of which 23 sources were attempted spectroscopically and 19 were confirmed. Hu et al. (2004) do not provide the spectroscopically derived Lyα fluxes, instead giving the fluxes of the sources in a narrowband filter ($f_\nu^{\rm NB}$; $\lambda_c = 8150$ Å, $\Delta\lambda_{\rm FWHM} = 120$ Å) and in a long-pass z filter (f_ν^z). We model the narrowband filter as a top-hat function, the Lyα-emitter galaxy spectra as a Lyα emission line of flux $f_{{\rm Ly}\alpha}$ superimposed upon a flat (in f_ν) continuum longward of Lyα, and we assume an opaque Lyα forest at this redshift, implying negligible flux blueward of Lyα. In this approximation, the Lyα flux of a source at redshift z is given by

$$f_{{\rm Ly}\alpha} = \frac{c}{\lambda_{{\rm Ly}\alpha}^2}\left[(120\ \text{Å})f_\nu^{\rm NB} - (8210\ \text{Å} - \lambda_{{\rm Ly}\alpha})f_\nu^z\right],$$

where $\lambda_{{\rm Ly}\alpha} \equiv 1216(1+z)$ Å.

$z \approx 6.5$.—Several Lyα emitters at this redshift have been reported in the literature from a variety of different surveys. We attempt to combine these disparate results into a single cumulative luminosity function. Kodaira et al. (2003) report on 73 candidate $6.508 < z < 6.617$ Lyα emitters in an 814 arcmin^2 survey region, out of which nine sources were attempted spectroscopically and two were confirmed. For our adopted cosmology, this survey samples a comoving volume of 2.02×10^5 Mpc^3, although when correcting for spectroscopic incompleteness, the effective volume is 9/73 of this. Kurk et al. (2004) report on a single source at $z = 6.518$ in a slitless survey over 43 arcmin^2 that was sensitive to Lyα emission at $6.4 < z < 6.6$. Rhoads et al. (2004) report on four candidate $6.52 < z < 6.55$ Lyα emitters in a 1200 arcmin^2 survey region. All four sources have been followed up spectroscopically, and only one is confirmed at high redshift. Finally, the relevant parameters for the survey that identified SEXSI-SER are provided in § 3.2.

Figure 4 presents the empirical cumulative luminosity function of Lyα emitters in these two redshift windows along with a fiducial nonevolving Schechter luminosity function intended for comparison purposes. Only minimal attempts to account for incompleteness have been attempted here; we therefore expect large errors both at the bright end, from small number statistics, and at the faint end, from incompleteness. Restricting the analysis, therefore, to moderate luminosity sources, we find no strong evolution in the cumulative luminosity function of Lyα emitters between $z \approx 5.7$ and $z \approx 6.5$. A more detailed analysis of the luminosity function of Lyα emitters in these two redshift windows is provided by Malhotra & Rhoads (2004); they also find a lack of evolution. If the reionization epoch represented a very large *and* rapid change in the neutral fraction of the IGM, this event should produce an associated change in the observable properties of Lyα emitters (e.g., Gnedin 2000). For example, in the dynamic IGM models of Santos (2004), as $x_{\rm H\,I}^{\rm IGM}$ increases from 0.05 to 0.95, the observed Lyα line flux drops by nearly an order of magnitude. In this picture, the high surface density of Lyα emitters at $z \approx 6.5$ therefore suggests that the IGM does not evolve rapidly between $z \approx 5.7$ and $z \approx 6.5$. However, if the reionization transition was more gradual, depending on the luminosity and density evolution of ionizing sources, or if there were some geometric complexities, e.g., due to a bias-driven clustering of sources, the observable changes in

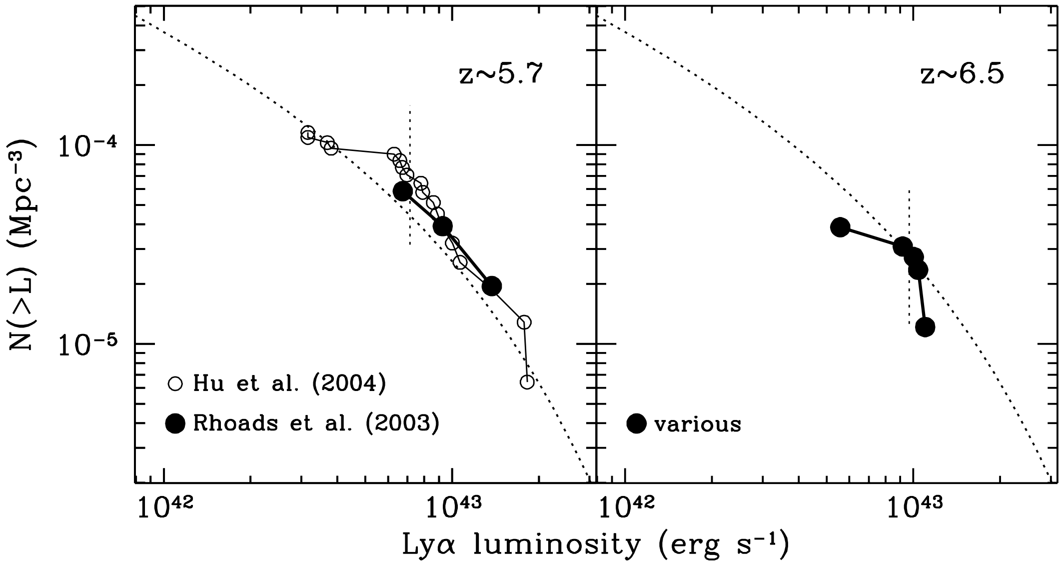

FIG. 4.—Empirical cumulative luminosity functions for Lyα emitters at $z \approx 5.7$ and $z \approx 6.5$. All points are from surveys with spectroscopic follow-up. The dotted curve in each panel illustrates a nonevolving Schechter luminosity function with $L^* = 1.4 \times 10^{43}$ ergs s^{-1}, $\alpha = -1.6$, and $\phi^* = 1.0 \times 10^{-4}$ Mpc^{-3} and is meant as only a fiducial line for comparing the panels. The vertical dotted lines illustrate the line luminosity corresponding to a line flux of 2×10^{-17} ergs cm^{-2} s^{-1} for each redshift range. This corresponds to the rough limit of most of the surveys.

the apparent luminosity function of Lyα emitters could have been more gradual.

4. CONCLUSIONS

We report the discovery of a Lyα-emitting galaxy at $z = 6.545$ serendipitously identified with the Keck II telescope. The galaxy resides within 30″ of a bright ($R = 12$) Galactic star and may provide a useful target for adaptive optics imaging. Our discovery marks the sixth Lyα-emitting galaxy identified at $z \approx 6.5$. This redshift lies beyond the putative epoch of reionization as inferred from the spectra of high-redshift quasars, when the damping wings of the neutral IGM should severely attenuate Lyα emission. Models predict that Lyα emission from individual sources of sufficient age and luminosity to create H II regions in a neutral IGM might still be visible beyond the epoch of reionization. However, the expectation is that the luminosity function of Lyα emitters, at least at the faint end, should drastically change as this threshold is crossed.

We combine results from the literature to compare the cumulative luminosity function of Lyα emitters at $z \approx 5.7$ and $z \approx 6.5$, finding no evidence of dramatic change, at least in the luminosity range probed here. Similar conclusions are reached in the more detailed analysis of Malhotra & Rhoads (2004), a coordinated paper that derives the luminosity functions in these two redshift windows. These results suggest that the universe remains largely ionized to $z \approx 6.5$.

This does not necessarily contradict the quasar results. The observed Gunn-Peterson troughs can be caused by partly reionized regions of the IGM with neutral hydrogen fractions as low as $x_{\rm H\,I}^{\rm IGM} \sim 10^{-3}$, whereas the counts of Lyα sources can probably easily accommodate $x_{\rm H\,I}^{\rm IGM} \sim 10^{-1}$, which also may be consistent with the results by Wyithe & Loeb (2004a) and Mesinger & Haiman (2004). Also, whereas some observers find a qualitative change in the absorption properties of the IGM at $z \approx 6$ (e.g., Fan et al. 2002; Cen & McDonald 2002; White et al. 2003), others do not (Songaila 2004). The nature, extent, and geometry of the reionization transition from $x_{\rm H\,I}^{\rm IGM} = 1$ to $x_{\rm H\,I}^{\rm IGM} < 10^{-3}$ remain highly uncertain.

We caution that these results on the luminosity function of Lyα emitters at $z \approx 6.5$ rely somewhat on the serendipitous discovery of SEXSI-SER described herein. As the surface density of $z \approx 6.5$ Lyα emitters inferred by SEXSI-SER is somewhat (a factor of 5) larger than that derived from other surveys, the results described here might instead be interpreted to imply that at least a subset of the authors of this manuscript are lucky, a result that has been hinted at in previous work (e.g., Becker et al. 1992; Dey et al. 1998; Stern et al. 2000b, 2004; Dawson et al. 2002).

We emphasize that the surface density of Lyα emitters offers an independent tool for studying the ionization state of the IGM, sensitive to ionization fractions $0.1 \lesssim x_{\rm H\,I}^{\rm IGM} \lesssim 1$ expected near the epoch of reionization, ionization fractions that are difficult to probe with quasar absorption studies. As more Lyα emitters are confirmed at high redshift, the statistical weight of the results hinted at here will be tested. We note, however, that models of protogalaxies suggest winds might compromise the ability of Lyα emission to constrain strongly the neutral fraction of the IGM without rest-frame optical observations to constrain the systemic redshift, age, and luminosity of the young galaxies (Santos 2004). Furthermore, biased clustering around Lyα emitters likely contributes significantly to the ionizing photon budget for the more massive protogalaxies (e.g., Wyithe & Loeb 2004b); changes in the Lyα emitter luminosity function prior to the epoch of reionization are potentially only significant at the lowest luminosities. Speculatively, we conclude by noting that only one source has been identified beyond $z \approx 6.5$ to date, a lensed source at $z \approx 7$ found by Kneib et al. (2004).[6] The Kneib et al. (2004) source lacks Lyα emission, making the exact redshift identification extremely difficult. This is suggestive of a source identified beyond the epoch of reionization and may be the first example of the challenges of observational

[6] The lensed $z = 10.0$ source identified by Pelló et al. (2004) has recently come into question on the basis of a reanalysis of the discovery spectroscopic data by Weatherley et al. (2004) and deep near-infrared imaging by Bremer et al. (2004), which fails to detect the source.

astronomy as we attempt to identify and study sources embedded in a neutral universe.

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