FIRST RESULTS FROM THE LARGE-AREA LYMAN ALPHA SURVEY

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ABSTRACT

We report on a new survey for $z \approx 4.5$ Ly$\alpha$ sources, the Large-Area Lyman Alpha (LALA) survey. Our survey achieves an unprecedented combination of volume and sensitivity by using narrowband filters on the new 81922 pixel CCD Mosaic camera at the 4 m Mayall telescope of Kitt Peak National Observatory. Well-detected sources with flux and equivalent width matching previously known high-redshift Ly$\alpha$ galaxies (i.e., observed equivalent width EW > 80 Å; $2.6 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ < line + continuum flux < $5.2 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$, and a small uncertainty on the equivalent width, $\delta$EW < EW/4) have an observed surface density corresponding to 11,000 ± 700 deg$^{-2}$ per unit redshift at $z = 4.5$. Variations in this surface density are apparent on comparison between counts in 6561 ± 40 and 6730 ± 40 Å filters. Early spectroscopic followup results from the Keck telescope included three sources meeting our criteria for good Ly$\alpha$ candidates. Of these, one is confirmed as a $z = 4.52$ source, another remains consistent with either $z = 4.55$ or $z = 0.81$, and the third is an [O III] $\lambda$5007 emitter at $z = 0.34$. These pilot spectroscopic results suggest that approximately one-third of our good candidates are bona fide Ly$\alpha$ emitters, implying a net density of ~4000 Ly$\alpha$ emitters per square degree per unit redshift.

Subject heading: galaxies: general

1. INTRODUCTION

More than three decades ago Partridge & Peebles (1967) predicted that galaxies in their first throes of star formation should be strong emitters in the Ly$\alpha$ line. Their predictions were optimistic, based on converting roughly 2% of the hydrogen in Milky Way–sized galaxies into heavier elements in yr$^{-1}$. This translates into a line luminosity of $\sim 10^{40}$ ergs s$^{-1}$.

These Ly$\alpha$ emitters are also expected to be common—if all the $L^*$ galaxies have undergone a phase of rapid star formation, one should see a surface density of about $10^2$ galaxies per square degree per unit redshift. Searches based on these expectations did not detect field Ly$\alpha$ emitters (see reviews by Pritchet 1994; Koo & Kron 1980; Pritchet & Hartwick 1987, 1990; Cowie 1988; Rhee, Webb, & Katgert 1989; Smith et al. 1989; Lowenthal et al. 1990; Wolfe et al. 1992; de Propris et al. 1993; Macchetto et al. 1993; Möller & Warren 1993; Djorgovski & Thompson 1992; Djorgovski, Thompson, & Smith 1993; Thompson, Djorgovski, & Trauger 1992; Thompson et al. 1993; Thompson, Djorgovski, & Beckwith 1994; Thompson & Djorgovski 1995; Thomes et al. 1998).

Only recently have Ly$\alpha$ emitters been observed, albeit at luminosity levels roughly 100 times lower than the original prediction. These Ly$\alpha$ emitters have been found from both deep narrowband imaging surveys (Cowie & Hu 1998; Hu, Cowie, & McMahon 1998; Pascale, Windhorst, & Keel 1998; Hu, McMahon, & Cowie 1999; Steidel et al. 2000; Kudritzki et al. 2000) and deep spectroscopic surveys (Dey et al. 1998; Manning et al. 2000; but see Stern et al. 2000). Weak Ly$\alpha$ emitters have also been found through targeted spectroscopy of Lyman break objects (e.g., Steidel et al. 1996; Lowenthal et al. 1997). The lower luminosity in the Ly$\alpha$ line may be because of attenuation by dust if chemical enrichment is prompt, or because the star-forming phase is more protracted, or because the star formation happens in smaller units that later merge. The first two scenarios will give a smaller equivalent width than early predictions, while the last scenario results in low luminosities but high equivalent width.

Dust effects are expected to be severe—even a small amount of dust can greatly attenuate this line, because it is resonantly scattered. However, two factors can help the Ly$\alpha$ photons escape. First, if Ly$\alpha$ photons are produced in diffuse regions of a clumpy interstellar medium, they can simply scatter off the dense clumps and escape (Neufeld 1991), and some geometries can even lead to an increase in the equivalent width of the line. Second, energetic winds are seen in low-z Ly$\alpha$ emitters (Kunth et al. 1998). These can displace the neutral gas and Doppler shift the peak wavelength of the resonant scattering, thereby reducing the amount of scattering and the path length for interaction with dust.

Detailed predictions for luminosities and surface densities of Ly$\alpha$ emitters using a Press-Schechter formalism and a range of dust obscuration and star formation timescales have been explored by Haiman & Spaans (1999), who are able to reproduce the surface densities of Ly$\alpha$ emitters reported by Hu et al. (1998) with a wide range of models. In order to narrow down the range of possibilities and characterize the high-redshift Ly$\alpha$ population,
better statistics over a wide range of flux and source density are needed.

2. NARROWBAND IMAGING SURVEY

An efficient search for Lyα emitters (and other emission-line galaxies) was started in 1998 using the CCD Mosaic camera at the Kitt Peak National Observatory’s 4 m Mayall telescope. The Mosaic camera has eight 2048 × 4096 chips in a 4 × 2 array comprising a 36′ × 36′ field of view. The final area covered by the Large-Area Lyman Alpha (LALA) survey is 0.72 deg² in two mosaic fields centered at 14h25m57s, +35°32′ (2000.0) and 02h05m20s, −04°55′ (2000.0). Five overlapping narrowband filters with FWHM ≈ 80 Å are used. The central wavelengths are λ6559, 6611, 6650, 6692, and 6730, giving a total redshift coverage 4.37 < z < 4.57. This translates into a surveyed comoving volume of 8.5 × 10¹⁶ comoving Mpc³ per field for \( h_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega = 0.2, \text{ and } \Lambda = 0 \). About 70% of the imaging at z ≈ 4.5 is complete, and an extension of the survey to z > 5 is planned. In about 6 hr per filter per field we are able to achieve line detections of about 2 × 10⁻¹⁷ ergs cm⁻² s⁻¹. The survey sensitivity varies with seeing. Broadband images of these fields in a custom B₁ filter (λ₀ = 4135 Å, FWHM = 1278 Å) and the Johnson-Cousins R, I, and K bands are being taken as part of the NOAO Deep Wide-Field Survey (Jannuzi & Dey 1999).

The images were reduced using the MSCRED package (Valdes & Tody 1998; Valdes 1998) in the IRAF environment (Tody 1986, 1993) together with assorted custom IRAF scripts. In addition to standard CCD data reduction steps (overscan subtraction, bias frame subtraction, and flat-fielding), it was necessary to remove cross talk between pairs of CCDs sharing readout electronics and to remove a ghost image of the telescope pupil. Astrometry of USNO-A catalog stars was used to interpolate all chips and exposures onto a single coordinate grid prior to combining final images. Cosmic-ray rejection is of particular importance in a narrowband search for emission-line objects. We therefore identified cosmic rays in individual images using a digital filtering method (Rhoads 2000) and in addition applied a sigma clipping algorithm at the image stacking stage. Weights for each exposure were determined using the method of Fischer & Kochanski (1994), which accounts for sky level, transparency, and seeing to optimize the signal-to-noise ratio level for compact sources in the final image.

Catalogs were generated using the SExtractor package (Bertin & Arnouts 1996). Fluxes were measured in 2′32 (9 pixel) diameter apertures, and colors were obtained using matched 2′32 apertures in registered images that had been convolved to yield matched point-spread functions.

3. SPECTROSCOPIC OBSERVATIONS

Spectroscopic followup of a cross section of emission-line candidates was obtained with the low-resolution imaging spectrograph (LRIS) instrument (Oke et al. 1995) at the Keck 10 m telescope on 1999 June 13 (UT). Two dithered exposures of 1800 s each were obtained through a single multislit mask in good weather. We used the 400 line mm⁻¹ grating (λslit ≈ 8500 Å) and a position angle of 139°6′ (east of north). These data were reduced using a combination of standard IRAF ONEDSPEC and TWODSPEC tasks together with the homegrown slit mask reduction IRAF task “BOGUS” (D. Stern, A. Bunker, & S. A. Stanford 2000, private communication) for reducing LRIS data.

4. THE EMISSION-LINE SOURCE POPULATION

Our imaging data yield numbers of sources as a function of their fluxes in several filters, from which we can construct number densities as a function of magnitudes, colors, and equivalent widths. In order to gracefully handle sources that are not detected in all filters, we have chosen to use “a sin h magnitudes” (Lupton, Gunn, & Szalay 1999), which are a logarithmic function of flux for well-detected sources but approach a linear function of flux for weak or undetected sources. Figure 1 shows the color-magnitude diagram for the 6559 Å (± 40 Å) and R filters. The color scatter achieved for bright sources (R < 22) is 0.10 mag (semi-interquartile range). This includes the true scatter in object colors and is therefore a firm upper limit on the scatter introduced by any residual systematic error sources, which we expect to be a few percent at worst.

To sharpen our focus on the high-redshift Lyα population, we identify the range of parameter space occupied by known z > 3 Lyα emitters. These sources have typical observed equivalent widths \( \geq 80 \) Å and line + continuum fluxes \( \geq 5 \times 10^{-17} \) ergs cm⁻² s⁻¹ (adjusted to \( z = 4.5 \) and measured in an 80 Å filter). We further want to restrict attention to sources with sufficiently reliable detections that the number of false emission-line candidates is a small fraction of the total candidate sample. The data set includes many continuum sources (\( \sim 1.4 \times 10^4 \) in the flux range above). It is expected to contain a few hundred emission-line sources, based on earlier source counts from smaller samples (Hu et al. 1998) and on our own findings (below). The fraction of continuum sources with measured equivalent widths above some threshold \( \text{EW}_0 \) can be calculated as a function of signal-to-noise ratio level \( n \) and filter width \( \Delta \lambda \). The measured equivalent width for a source with no line emission or absorption in the narrowband filter will be \( 0 \pm \Delta \lambda / n \). Thus, a false positive becomes an \( m \) event, where \( m = n \text{EW}_0 / \Delta \lambda \). Our sample would be reasonably safe from contamination with \( m = 3 \), which would correspond to about 20 false positives in a sample of 14,000 sources, and very safe for \( m \approx 4 \), corresponding to less...
than one false positive in 14,000 sources. We have conservatively chosen detection thresholds $n = 5$ and $\text{EW}_{0} = \Delta \lambda = 80 \, \AA$, which gives $m = 5$. This keeps the number of false positives small even when the foregoing analysis is expanded to include errors in the continuum flux (which increase photometric error in the color by a factor $\sim \sqrt{2}$) and a realistic distribution of equivalent widths for the low-$z$ galaxy populations. As a further check on our sample, we use the photometric color error estimates from SExtractor to demand that the source be an emission-line source at the $4 \sigma$ level.

Combining all of these requirements, the final criteria for good candidates in our survey become $\text{EW} > 80 \, \AA$, $\delta(\text{EW})/\text{EW} \leq 0.25$, and $2.6 < f_{17} < 5.2$, where $f_{17} \equiv f/(10^{-17} \, \text{ergs cm}^{-2} \, \text{s}^{-1})$. There are 225 such sources detected in the 6559 Å filter in a solid angle of 0.31 deg$^2$ and redshift range $\delta z = 0.07$. This corresponds to 11,000 good candidate Ly$\alpha$ emitters per square degree per unit redshift. The precise upper flux cutoff used is somewhat arbitrary, but including sources with larger fluxes in our list of good candidates has little effect on the total source counts.

The final 6730 Å image had a broader point-spread function (1.31 FWHM) than the 6559 Å image (0.98 FWHM), which was partially compensated by lower sky noise. Its net point-source sensitivity in a 9 pixel aperture was reduced by 0.23 mag relative to the 6559 Å catalog. In addition, 6730 Å samples a slightly higher redshift, resulting in an 0.08 mag increase in distance modulus ($q_0 = 0.1$, $\Lambda = 0$). Accounting for both effects, the matched flux range that falls between the $5 \sigma$ detection limit and the bright luminosity limit for good candidates in both filters is $3.45 < f_{17} < 5.2$ at 6559 Å and $3.2 < f_{17} < 4.8$ at 6730 Å (where both ranges are adjusted to the flux in a 9 pixel aperture under 0.98 seeing). The corresponding counts are 70 candidates at 6730 Å and 104 candidates at 6559 Å. Thus, the source density in directly comparable luminosity bins varies by a factor of 1.5, a difference that is significant at about the $3 \sigma$ level. Some of this difference could be due to flux calibration errors, since most of the candidates lie near either the flux or equivalent width thresholds. More interestingly, it could be a signature of large-scale structure at one of the emission-line redshifts $z \approx 0.33, 0.78, 4.5$. For sources at $z \approx 4.5$, the comoving distance between the centers of the two redshift slices is 72 Mpc, while the thickness of each slice is 36 Mpc and the transverse comoving size is 89 Mpc (again assuming $H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, $\Omega = 0.2$, and $\Lambda = 0$). Comparable or larger density variations have been observed in galaxy populations at $z \approx 3.1$ (Steidel et al. 1998) and $0.2 \leq z \leq 0.9$ (Cohen et al. 1996).

5. SPECTROSCOPIC RESULTS

Our spectroscopic follow-up consisted of a single Keck LRIS slit mask, placed to include the most spectacular emission-line source from the imaging data. The mask was further optimized to contain a large number of additional emission-line candidates spanning a wide range of flux and equivalent width in order to characterize the different populations of sources with extreme narrowband colors and to thereby tune candidate selection criteria for future spectroscopic observations. Those sources with $5 \sigma$ narrowband detections and photometrically measured $\text{EW} > 65 \, \AA$ were all confirmed as emission-line objects at the narrowband wavelength. In total, we detected two [O iii] $\lambda 5007$ emitters at $z = 0.34$, three [O iii] $\lambda 3727$ emitters at $z = 0.77$ and $z = 0.81$, one confirmed Ly$\alpha$ ($\lambda 1215.7$) emitter at $z = 4.52$, and one source that could either be Ly$\alpha$ at $z = 4.55$ or [O ii] $\lambda 3727$ at $z = 0.81$. Among these seven sources, two fell below the 80 Å observer-frame equivalent width threshold for good Ly$\alpha$ candidates (with $\text{EW} = 71$ and 59 Å, and both with $z \approx 0.766$) and were brighter than the upper flux limit expected for known high-redshift Ly$\alpha$ sources (one each at $z = 0.34$ and $z = 0.81$). We also found a $z = 2.57$ galaxy with emission lines of C iv $\lambda 1549$, He ii $\lambda 1640$, and O iii $\lambda 1663$. This source may have been included in the narrowband candidate list (with $\text{EW} = 36 \, \AA$) because of a weak spectral break around 6560 Å. Finally, we found a few serendipitous emission-line sources in the slit spectra. One of these is a single-line source with large equivalent width, possibly Ly$\alpha$ at $z = 3.99$. Spectra of two interesting sources are shown in Figure 2.

6. DISCUSSION: THE Ly$\alpha$ SOURCE POPULATION

By combining our imaging survey with these spectroscopic results, we can estimate the source density of Ly$\alpha$ emitters passing our selection cut. Our spectra included three sources fulfilling the criteria given above for good candidates. Of these,
one was confirmed as a $z = 4.52$ Ly$\alpha$ source, with $EW = 84$ Å and a continuum flux $R = 25.0$. The second is a clear $z = 0.34$ [O III] emitter, with $EW = 108$ Å and $R = 24.75$. The third remains a candidate $z = 4.55$ source, with $EW = 235$ Å and $R = 25.7$ but is more conservatively interpreted as a $z = 0.81$ [O III] emitter on the basis of a rather strong continuum on the blue side of the line. Final broadband images of the field will shortly be available from the NOAO Deep Wide-Field Survey, and in the future we will use this data to help discriminate between star-forming galaxies at $z < 1$ (which should be blue in $B_R - R$) and $z \approx 4.5$ objects (which should be red “dropouts” in $B_R - R$).

From these statistics, we estimate that roughly one-third to one-half of the good candidates will be confirmed as Ly$\alpha$ sources, yielding ~4000 emitters per square degree per unit redshift. This is compatible with earlier measurements from smaller volumes (Hu et al. 1998) after accounting for differences in flux thresholds.

Our measurement is distinct from previous efforts in the field for its basis in a large number of candidate emitters. Poisson errors in our source counts are of order ±7%. This is smaller than the variations observed in the comparison of two filters (of order ±40%). By combining observations in multiple fields, we will be able to average over local fluctuations in number densities effectively. When completed, the LALA survey will yield co-moving volume of ~2 × 10$^8$ Mpc$^3$ (§ 2) and a sample of several hundred Ly$\alpha$ emitters and will allow the luminosity function, equivalent width distribution, and correlation function of this population to be determined for the first time.

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