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The Large Area Lyman Alpha Survey

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Abstract. The Lyman-α line is expected to be strong in the presence of active star formation and the absence of dust, making it a good tool for finding chemically primitive galaxies in the early universe. We report on a new survey for high redshift Lyman-α sources, the Large Area Lyman Alpha (LALA) survey. Our survey achieves an unprecedented combination of volume and sensitivity by using narrow-band filters on the new 8192\(^2\) pixel CCD Mosaic Camera at the 4 meter Mayall telescope of Kitt Peak National Observatory.

Well-detected sources with flux and equivalent width matching known high redshift Lyman-α galaxies have an observed surface density corresponding to 11000 ± 700 per square degree per unit redshift at \(z = 4.5\). Early spectroscopic followup from the Keck telescope suggests that \(\sim 1/3\) of these are actually at \(z \approx 4.5\), and has confirmed five \(z > 4\) Lyman-α emitters so far. Combining our photometric survey with spectroscopic results, we estimate a net density of \(\sim 4000\) Lyman-α emitters per square degree per unit redshift at \(z \approx 4.5\). The star formation rate density (estimated both from UV continuum and from line emission) is comparable to that of the Lyman break galaxy population within present uncertainties. The most extreme Lyman-α emitters in our sample have rest frame equivalent widths > 100\(\AA\), consistent with the expectations for the first burst of star formation in a primitive, dust-free galaxy.
1. Introduction

The first major burst of star formation in a young, high redshift galaxy is expected to produce copious numbers of ionizing photons thanks to an abundance of hot, massive main sequence stars. The interstellar medium that gave birth to the stars can then convert $2/3$ of these photons into Lyman-$\alpha$ photons as neutral hydrogen atoms are ionized and recombine. The strong Lyman-$\alpha$ line emission that can result was first proposed as a signpost of young galaxies in formation by Partridge & Peebles (1967; hereafter PP67).

However, searches for Lyman-$\alpha$ emission at high redshift failed to discover a field population of such galaxies for thirty years. (See review by Pritchet 1994 and references therein; and more recently, Thompson & Djorgovski 1995; Thommes et al. 1998.) These searches placed stringent upper limits on the abundance and brightness of the Lyman-$\alpha$ line at high redshift. More recent searches have finally found Lyman-$\alpha$ emitters in the field (Cowie & Hu 1998; Hu, Cowie & McMahon 1998; Pascarelle, Windhorst, & Keel 1998; Dey et al. 1998; Hu, McMahon, & Cowie 1999; Steidel et al. 2000; Manning et al. 2000), but at line luminosities $\sim 10^{-2}$ below the early predictions by PP67.

Several factors could be responsible for this paucity of bright Lyman-$\alpha$ sources, including dust effects, small star formation units, and long star formation time scales. (PP67 based their estimates on dust free, Milky Way-sized galaxies that form most of their stars in $3 \times 10^7$ years.)

Dust can quench this line very effectively: Lyman-$\alpha$ photons are resonantly scattered by neutral hydrogen atoms, and so traverse a much longer path than continuum photons do in order to escape the galaxy where they are emitted. This long path enhances the optical depth for line photons, reducing the line equivalent width. Quantitative estimates of this effect are however quite sensitive to the spatial distribution of the ISM (e.g. Neufeld 1991). In contrast, star formation in small units would yield small line and continuum luminosities while leaving equivalent widths unaffected. Under this scenario, the expected numbers of Lyman-$\alpha$ sources would rise in inverse proportion to their luminosity. Protracted star formation would also reduce both line and continuum luminosities. Additionally, a star formation event lasting longer than the lifetime of a massive star would allow metals and dust produced by the first generation of stars to pollute the galaxy’s ISM, resulting again in dust extinction and potential reductions in Lyman-$\alpha$ equivalent width.

Good statistical samples of Lyman-$\alpha$ emitters that yield distributions of luminosities and equivalent widths should allow us to distinguish among the above possibilities. We are conducting the Large Area Lyman Alpha (LALA) survey to obtain such a sample.

Whatever the reason for the faintness of Lyman-$\alpha$ sources, the effects of dust provide another strong reason for seeking these objects: Truly primordial galaxies, taken here to mean chemically unevolved systems, will have large Lyman-$\alpha$ equivalent widths because of their low dust content. Lyman-$\alpha$ surveys should therefore preferentially select for this most interesting class of high-redshift galaxy. This is not to say that all Lyman-$\alpha$-selected galaxies will be primordial, nor even that a large fraction will be. Dustier galaxies can have substantial Lyman-$\alpha$ equivalent widths if their ISM is patchy, or if it is in bulk
motion (Kunth et al 1998). However, if chemically primitive galaxies are to be found at all, the Lyman-α search is a good tool to discover them.

2. The Survey

The Large Area Lyman Alpha (LALA) survey is possible because of new wide field instrumentation. We exploit the $8192^2$ pixel CCD Mosaic camera at the Kitt Peak National Observatory’s 4m Mayall telescope to achieve a survey efficiency (measured in the product $A\Omega$ of collecting area and solid angle) some 6 times greater than comparably deep narrowband surveys at Keck. The “core” survey uses five overlapping 80Å bandpass filters ($\lambda_c = 6559$, 6611, 6650, 6692, and 6730Å) to look for Lyman-α line emission at $4.37 < z < 4.57$. The corresponding survey volume is about $8.5 \times 10^5$ comoving Mpc$^3$ per 36′ field for $H_0 = 70\text{ km s}^{-1}\text{ Mpc}^{-1}$, $\Omega = 0.2$, $\Lambda = 0$. We integrate for about 6 hours per filter per field, and achieve a limiting sensitivity $\sim 2 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ in the line. Further details, including a brief description of data reduction, are given in Rhoads et al (2000).

Additionally, we use supporting broad band images from the NOAO Deep Widefield Survey (B$_w$, R, and I filters; see Schommer, Jannuzi, & Dey 2001, this meeting) and from our own data (V and SDSS z’ filters), and have recently obtained 8200Å narrowband data to extend the LALA survey to $z \approx 5.7$.

Spectroscopic followup of some LALA candidates has been carried out using the Keck Observatory’s Low-Resolution Imaging Spectrograph. To date, we have confirmed five emission line galaxies at $z > 4$. Two representative spectra are shown in figures 1 and 2. One of these two is a galaxy with very little continuum that would have gone undetected in a broadband survey of even extreme depth, while the other is a less spectacular emission line source with a clearly detected continuum and Lyman break.

3. The Lyman-α Source Population

Based on our photometric results and on the statistics of our first spectroscopic followup, we inferred a source density of $\sim 4000$ Lyman-α emitters per square degree per unit redshift at $z = 4.5$, with an uncertainty dominated by small numbers of spectra (Rhoads et al 2000).

We can estimate the star formation rate density in the Lyman-α galaxies in two quasi-independent ways. First, we coadd the observed $z'$ band flux of all our good candidates and apply starburst models to convert this rest-frame UV continuum into a star formation rate. Correcting this rate for our estimate that 1/3 of the good candidates are actually $z = 4.5$ Lyman-α emitters, we obtain a rate of $13 \times 10^{-3}M_\odot\text{ yr}^{-1}\text{ Mpc}^{-3}$. Second, we coadd the continuum-corrected line fluxes of all our good candidates and apply a standard conversion factor to go from Lyman-α flux to ionizing luminosity and thence star formation rate. Applying again a 1/3 correction factor to account for foreground contamination, we find a lower value of $2.2 \times 10^{-3}M_\odot\text{ yr}^{-1}\text{ Mpc}^{-3}$. The difference in these two estimates may be due to the effects of dust, which would affect the Lyman-α based estimate more strongly than the UV continuum estimate. Alternatively,
Figure 1. Keck spectrum of a confirmed $z = 4.52$ Lyman-α source. This object has a line flux of $1.7 \times 10^{-17} \text{erg cm}^{-2} \text{s}^{-1}$ and a rest frame equivalent width of 15Å. The line is asymmetric (see inset) and has a strong continuum decrement from the red to the blue side, both of which are expected for high-redshift Lyman-α emitters (Stern & Spinrad 1999). In order to accentuate the well-sampled line and suppress noise, the spectrum of this source has been smoothed with a boxcar filter of width 9 pixels = 16.6Å [main panel] or 3 pixels = 5.5Å [inset panel].

our simple correction factors of $1/3$ for foreground contamination could be wrong if the $z \approx 4.5$ sources have a systematically stronger line to continuum ratio than the remaining candidates. While these star formation rates are still quite uncertain (pending further spectroscopy), they are comparable to the Lyman break galaxy rate at $z = 4$, which is $5 \times 10^{-3} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ (Madau et al 1996).

The spectra in figures 1 and 2 are representative of our spectroscopically confirmed $z > 4$ galaxies in the sense that about half have rest frame equivalent widths $> 100$Å, which is near the upper limit for star forming galaxies (100 to 200Å; Charlot & Fall 1993). This suggests that some of the LALA sources may indeed be dust-free and chemically primitive. Further spectroscopy to rule out weak narrow-lined AGNs and/or galactic winds (see Kunth et al 1998) will help confirm this possibility.

4. Future Directions

Photometric redshift constraints derived from our suite of broadband filters, combined with consistency checks from our growing spectroscopic sample, will enable us to use the entire LALA sample to study population properties of the Lyman-α emitters. These include the luminosity function, distribution of equivalent widths, and clustering properties. Planned near-infrared followup of selected sources will allow us to confirm the Lyman-α line identification through an [O II] $\lambda 3727$ line search and to look for older stellar populations through a study of rest-frame optical light. Finally, searches in new narrowband filters will allow us to study the evolution of the Lyman-α source population. Ultimately,
Figure 2. Keck spectrum of another confirmed Lyman-α source, this time at $z = 4.37$. This object has a line flux of $\sim 4 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ and a rest frame equivalent width $> 100\,$Å at the 2$\sigma$ level. The continuum emission from this source is undetected in our deep broadband images and at best marginally detected in the spectrum. In order to accentuate the well-sampled line and suppress noise, the spectrum of this source has been smoothed with a Gaussian filter with a 4 pixel $= 19.4\,$Å full width at half maximum. The lower panel shows 1$\sigma$ photon counting errors, suitably adjusted for the smoothing. The weak “line” to the left of Lyman-α is a residual from the subtraction of the 6300Å sky line.
we hope to identify statistical samples of primitive galaxies at a range of redshifts from $z = 4.5$ to $z > 6$.

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