A VLT/FORS2 MULTI-SLIT SEARCH FOR LY-α EMITTING GALAXIES AT Z ∼ 6.5\textsuperscript{1}

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ABSTRACT

We present results from a deep spectroscopic search in the 9150Å atmospheric window for z ∼ 6.5 Lyα emitting galaxies using the VLT/FORS2. Our multi-slit+narrow-band filter survey covers a total spatial area of 17.6 arcmin\textsuperscript{2} in four different fields and reaches fluxes down to 5 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2} (7σ detection). Our detection limit is significantly fainter than narrow-band searches at this redshift and fainter also than the unlensed brightness of Hu et al.’s HCM6A at z = 6.56, and thus provides better overlap with surveys at much lower redshifts. Eighty secure emission line galaxies are detected. However, based on their clear continuum emission shortward of the line or the presence of multiple lines, none of these can be Lyα emission at z ∼ 6.5. Our null result of finding no z ∼ 6.5 Lyα emitters suggests that the number density of Lyα emitters with L ≥ 2 \times 10^{42} \text{erg s}^{-1} declines by ≥ 2 between z ∼ 3 and z ∼ 6.5.

Subject headings: cosmology: observations – early universe – galaxies: evolution – galaxies: formation

1. INTRODUCTION

Great progress has been made over the last five years in the search for high redshift (z > 5) galaxies. Several groups have successfully detected galaxies beyond z ∼ 5 using both the continuum-based “drop-out” approach and searches for strong emission lines using either narrow-band filter imaging or dispersed long-slit spectroscopy (Rhoads et al. 2003; Kodaira et al. 2003; Stanway et al. 2004; Dickinson et al. 2004; Lehnert & Bremer 2003; Maier et al. 2003; Hu et al. 2004). A few surveys also have targeted the caustics in lensing galaxy clusters to take advantage of the associated flux amplification (Ellis et al. 2001; Santos et al. 2004; Kneib et al. 2004).

The relative advantages of these different survey approaches are fairly clear. Continuum selection is most closely tied to star-formation rate but is in practice limited to relatively luminous objects. Furthermore, the establishment of a true continuum “break” or “drop-out” requires two filters longward of Lyα, limiting the applicability of the method to z ≤ 5.5 unless deep wide-field infrared imaging data is available. In comparison, narrow-band Lyα based searches avoid this difficulty but obviously only pick out objects with strong Lyα emission. For galaxies with high equivalent widths, Lyα surveys can reach to fainter continuum levels than the continuum based techniques. Relative to narrow-band imaging, longslits dispersed spectroscopic surveys achieve a large increase in sensitivity due to the reduced background, but at the cost of severely reduced sky coverage. The use of cluster lensing amplification also enables much fainter objects to be detected, but involves only a small survey area in the source plane (≤ 0.5 arcmin\textsuperscript{2}). Lensed samples also require careful analysis to avoid biases introduced by the peculiarities of the lensing (Porciani et al, in preparation).

An alternative approach developed by Crampton & Lilly (1999, hereafter CL99) is to combine multiple parallel longslits with a narrow-band filter that limits the observed spectral range to a few hundred angstroms. This technique is optimal for a targeted redshift survey because we achieve the full sensitivity gain of a high resolution spectrum and increase the spatial coverage by the number of longslits. The redshift range is the same as that of a narrow-band survey, but this allows optimum use of narrow atmospheric windows such as that at 9000 – 9300Å. However, unlike a narrow-band imaging survey, there is no significant selection in emission line equivalent width. Furthermore, spectral line identification diagnostics such as line asymmetries, line doublets etc., as well as precise redshifts are obtained in the first pass. In principle, this eliminates the need for follow-up spectroscopy to confirm the reality and characteristics of emission lines. The multi-slit/filter approach has been used on CFHT by CL99, and on Keck/LRIS by Stockton (1999) and Martin & Sawicki (2004, hereafter MS04) to search for Lyα emitters (LAE). However, none of these surveys detected any LAEs at z > 5.

In this paper, we present the results from a search for z ∼ 6.5 galaxies using the multi-slit/filter approach in the 9150 Å window on the VLT/FORS2. The program was initially motivated by the first galaxy at z > 6 found by Hu et al. (2002) within an 0.4 arcmin\textsuperscript{2} area behind the lensing cluster A370. Our own observations were designed to reach below the de-amplified brightness of HCM6A and to sample an area 50 times larger. Compared to the initial

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multi-slit/filter study by CL99, the current survey is about five times deeper and covers twice the spatial area. It also surveys a volume five times larger than that of Stockton (1999) and MS04. Our study is the first to survey a relatively large volume at $z \sim 6.5$ to the low luminosities comparable to that of most galaxies in $z \sim 3$ surveys.

Figure 1 illustrates some of the features of these different approaches by comparing emission line searches at $z > 3$ with the large continuum selected sample at $< z > 3$ of Shapley et al. (2003). Many of the Ly$\alpha$ selected objects have continuum luminosities overlapping those of the continuum selected “drop-out” objects, but the continuum levels can also extend well below this level for high equivalent width galaxies, especially when the line flux detection limit is itself reduced, as in the present work. The dispersed surveys have a much lower equivalent width limit than the narrow-band imaging surveys. However, as can be seen on the figure, to fully exploit this would require an even lower line flux limit because of the apparent max-

600: VPH grism gave 1.6Å per $2 \times 2$ binned pixel, each of which covered $0.25 \times 0.25$ arcsec$^2$. The FORS2 slit-mask had nine parallel longslits, each 2′′ wide and 415″ long, spaced 42″ apart; the same mask was used for all observations. Each of the four fields were observed with two or three adjacent mask pointings that were displaced from each other by 1.5″ perpendicular to the slit direction. The total spatial area covered by our FORS2 observations is thus 17.6 arcmin$^2$. The total exposure times for each pointing was 8100 – 10800 seconds.

The seeing varied between 0.5 – 1.0 arcsec with an average of $\sim 0.7''$, leading to a spectral resolution for point sources of about 5Å, sufficient to identify the [OII]3727 doublet at $z \sim 1.4$ and to detect the line asymmetry associated with Ly$\alpha$ emission. Wavelength and flux calibration were achieved with an Argon arc and observations of the standard star LTT6248. The data were reduced using a combination of IRAF and D. Kelson’s Python package.

2.3. Detection of Emission Lines

The variable response of the grism over the CCD was removed using a domeflat, and the data were flat-fielded using a master flat created from all the science images where bright objects had been masked. The sky emission was removed by subtracting a running median through the data at constant wavelength. A global continuum subtraction was then made by fitting a linear function of wavelength along each spatial pixel along the slit. For optimal emission line detection, the final image was normalized by a noise-map that had been derived from the statistics of the coadded frames (averaged over 25'' along the slit). This noise-map reflected the effects of the varying sky brightness across the spectral window due to OH emission lines, the effects of the filter transmission in wavelength and of the blaze angle of the volume-phase holographic grating from slit to slit, as well as the different exposure times both along the slit and from observation to observation. To exclude regions with unacceptably high noise levels, we truncate the wavelength range to 9035 $\lambda < 9225$Å. Apart from the residuals from particularly bright objects, this procedure resulted in a two-dimensional image of very uniform appearance in which emission lines appeared as point sources.

Emission lines were detected using SExtractor v2.2 (Bertin & Arnouts 1996). Subsequent measurement of the line fluxes and uncertainties as well as the equivalent widths of the lines were measured from the original data using aperture (3′′ diameter) photometry. From visual inspection of detected emission lines, we concluded that emission lines with formal $S/N > 7$ were robust.

The noise-map was used to determine the survey volume as a function of the line flux detection limit. The deepest part of the survey reaches $5 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, approximately a half reaches a depth of $6 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, and the whole survey volume of $6130 h^{-3}_7$ Mpc$^{-3}$ is covered at $1.8 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$; these values correspond to $7\sigma$ detection limits.

2.4. Identification of Emission Lines

A necessary condition for identification of an emission line as Ly$\alpha$ at $z \sim 6.5$ is that there be no detected continu-

2. SUMMARY OF OBSERVATIONS AND DATA

2.1. Re-analysis of the CFHT Data (CL99)

As part of the main VLT program, we have re-analyzed our 1999 CFHT data (CL99). A total of 11 emission line objects with line fluxes of $f \geq 2 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ at wavelengths of $9000 \leq \lambda \leq 9250$Å were detected. One emission line object was identified as a candidate galaxy at $z \sim 6.43$ because of its high observed equivalent width ($W_{\text{obs}} \sim 200$ Å), absence of detected continuum shortward of the line, and the absence of an identifiable counterpart in deep $UBVRI$ imaging. However, follow-up spectroscopy taken with the VLT/FORS2 in July 2003 showed that the emission was in fact H$\alpha$ at $z \sim 0.4$ associated with a relatively bright galaxy that lay outside of the longslit aperture. The most important lesson from this was the need to map contiguous areas of the sky by stepping observations perpendicular to the longslits, thus minimizing the confusing effects of neighboring objects, and to obtain accurate astrometry along the slit. In addition, it emphasized that high observed equivalent widths ($W_{\text{obs}} \sim 200$ Å) can not be reliably associated with Ly$\alpha$, as also stressed by Stern et al. (2000) and Rhoads et al. (2004).

The CFHT survey thus resulted in no Ly$\alpha$ galaxies above $f \geq 2 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (i.e. $L > 3L^*$, assuming $L^* = 3.2 \times 10^{42}$ erg s$^{-1}$) in an area of 9 arcmin$^2$ with $\Delta z = 0.2$ (equivalent to a volume of $4170 h^{-3}_7$ Mpc$^3$).

2.2. New VLT/FORS2 Observations

To extend this program, further observations were made with the VLT/FORS2 spectrograph during 23-26 July 2003 of four fields: the HDF-South (Williams et al. 2000), the Chandra Deep Field South/GOODS-S/UDF region (Giavalisco et al. 2004), the CFRS-22 hour field (CFRS22), and one of the CTIO Deep Lens Survey fields (DLS-F5). In each of these four widely spaced areas, our observations sparsely sample a 6 × 7 arcmin$^2$ area, thus minimizing the effects of cosmic variance on the survey statistics. The
um shortward of the line. To search for such emission, we used our own spectra as well as the publicly available $bviz$ imaging of GOODS-S, the existing public imaging of HDFS (both HST and ground-based) supplemented with a new 3hr $R$-band image obtained with FORS2 during our own observing run, our own $UBVRIZ$ for the CFRS22 field Brodwin (2004), and imaging in $BV Rz$ for the DLS-F5 field kindly made available by the DLS team.

The final SExtractor catalog of emission lines from all ten pointings contained $\sim 80$ objects. Most objects were in fact easily identified as lower redshift galaxies from their FORS2 spectra alone, e.g. the [SII]$\lambda 6717, 6731$ pair, the [OIII]$\lambda 4959, 5007$ pair, and the resolved [OII]$\lambda 3727$ doublet. In all but one case the Ly$\alpha$ identification is securely excluded based on continuum emission extending to much shorter wavelengths in the deep imaging data. The final object in which no continuum was detected is identified as [OIII]$\lambda 5007$ based on a second weaker emission line at the correct wavelength for [OII]$\lambda 4959$.

We thus have a secure null result: There are no Ly$\alpha$ emitting galaxies within the volume and flux limits of our current survey. Using Poisson statistics (Gehrels 1986), we can place a limit of less than 1.84 objects at the 84% (one-sided) confidence level.

3. DISCUSSION

Our multi-slit/filter survey probes flux levels several times fainter than the narrow-band imaging surveys at $z \sim 6.5$ and slightly fainter than the de-amplified brightness of the lensed HCM6A. Although we do not reach the flux levels of the ($z < 6$) lensed objects found by Ellis et al. (2001) and Santos et al. (2004), we still expected to find several LAE's at $z \sim 6.5$ brighter than $L = 2 \times 10^{42}$ ergs $s^{-1}$, as shown in Fig. 2.

Our first robust conclusion, as already suggested by the brighter, wide-angle, narrow-band imaging surveys of Kodaira et al. (2003) and LALA (Rhoads et al. 2004), is that the number density of LAE's must be significantly lower than suggested by the discovery of the lensed HCM6A; Hu et al. (2002) were very fortunate to find this one object.

Our null result also suggests that the number density of LAE's with $L \geq 2 \times 10^{42}$ ergs $s^{-1}$ is lower at $z \sim 6.5$ than at $z \sim 3$. We stress that compared to narrow-band imaging searches at $z \sim 6.5$, our survey reaches lower flux densities (without lensing) and thus provides better overlap with $z \sim 3$ surveys at fainter luminosities ($L < 5 \times 10^{42}$ erg $s^{-1}$; see Fig. 1). For $z \sim 3$ surveys with flux sensitivities comparable to ours and spectroscopic confirmation, we use the properties of the individual objects to determine the number of LAE's we expected in our own survey, i.e.

$$N_{\text{pred}} = \sum_i \frac{1}{V_i} \times V(L_i)$$

(1)

where $V_i$ is the volume occupied by the $i$th object, with luminosity $L_i$, in the given survey, and $V(L_i)$ is the volume available to luminosity $L_i$ in our own survey. The values for $N_{\text{pred}}$ using the properties of the individual LAE's from Cowie & Hu (1998) and Kudritzki et al. (2000) are shown in Table 1 and Fig. 3. We also include the same estimate using Hu et al. (2002)'s HCM6A, as this is the only $z > 5$ survey with flux sensitivities comparable to ours.

In addition, we have computed the number of LAE's that we expected to find based on the major LAE surveys at $3 \lesssim z \lesssim 6.5$. In this case, we adopt a procedure similar to MS04 and assume a Schechter function with a non-evolving $L^* = 3.2 \times 10^{42}$ and $\alpha = 1.5$. We determine $\Phi^*$ for each survey, and for these $\Phi^*$ we then compute the expected number of LAE's ($N_{\text{pred}}$) in our own survey. These results also are listed in Table 1 and shown in Fig. 3.

Relative to surveys at $z \sim 3$, we can exclude with $\geq 95\%$ confidence that the number density stays constant between $z \sim 3$ and $z \sim 6.5$.

Taken as a whole, the various surveys indicate that the luminosity function of Ly$\alpha$ emitters is declining in number density around $L \sim 3 \times 10^{42}$ erg $s^{-1}$ ($\sim L^*$; see Fig. 2). We estimate the number density of LAE's declines by $\sim 2$ between $z \sim 3$ and $z \sim 6.5$ (Fig. 3). This is less than the factor of six observed in Lyman-break galaxy surveys at $z \sim 6$ (e.g. Stanway et al. 2004). However, we note that our assumed shape for the luminosity function does not fit the LAE surveys at $z > 5$ very well, and that incompleteness in the narrow-band surveys may become particularly problematic at $L < 2L^*$ (see Fig. 2).

Finally, our experience with this survey in both phases emphasizes the difficulty of identifying Ly$\alpha$ from a single emission line. As noted by Stern et al. (2000) and found in this survey, isolated emission lines with very large observed equivalent widths ($> 200\AA$) are not exclusively Ly$\alpha$ emission.

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Table 1

| Source                | z     | $L_{\text{min}}$ $(10^{42})^b$ | $\Phi^c$  | $N_{\text{pred}}^d$ |
|-----------------------|-------|--------------------------------|-----------|----------------------|
| Kudritzki et al. (2000) | 3.13  | 1.7                            | ⋯         | 4.8                  |
| Cowie & Hu (1998)     | 3.4   | 2.0                            | ⋯         | 5.0                  |
| Hu et al. (2002)      | 6.56  | 2.8                            | ⋯         | 25.3                 |
| Kudritzki et al. (2000) | 3.13  | 1.7                            | 0.0031    | 4.1                  |
| Cowie & Hu (1998)     | 3.4   | 2.0                            | 0.0030    | 4.0                  |
| Hu et al. (1998)      | 4.52  | 4.9                            | 0.0035    | 4.7                  |
| Shimasaki et al. (2004) | 4.79  | 2.6                            | 0.0009    | 1.2                  |
| Ouchi et al. (2003)   | 4.86  | 2.0                            | 0.0023    | 3.1                  |
| Hu et al. (2004)      | 5.7   | 7.1                            | 0.0051    | 6.8                  |
| Ajiki et al. (2003)   | 5.7   | 5.1                            | 0.0019    | 2.6                  |
| Rhoads et al. (2003)  | 5.7   | 6.3                            | 0.0015    | 2.1                  |
| Rhoads et al. (2004)  | 6.5   | 11.1                           | 0.0021    | 2.8                  |
| Kodaira et al. (2003) | 6.5   | 5.4                            | 0.0016    | 2.2                  |
| Hu et al. (2002)      | 6.56  | 2.8                            | 0.0437    | 58.8                 |

\(^a\)The expected number $N_{\text{pred}}$ for the first three entries is determined using the properties of the individual Ly$\alpha$ emitters from the given survey (see text). These are the only three surveys with flux sensitivities comparable to ours and spectroscopic confirmation. For the remaining entries, we assume a luminosity function with $L^* = 3.2 \times 10^{42}$ erg s$^{-1}$ and $\alpha = -1.5$.

\(^b\)The value we adopted for the minimum luminosity (in units of erg s$^{-1}$) of a given survey to determine $\Phi^*$. The value we adopted for the minimum luminosity (in units of erg s$^{-1}$) of a given survey to determine $\Phi^*$. The value we adopted for the minimum luminosity (in units of erg s$^{-1}$) of a given survey to determine $\Phi^*$. The value we adopted for the minimum luminosity (in units of erg s$^{-1}$) of a given survey to determine $\Phi^*$.

\(^c\)Number density $\Phi^*$ in units of Mpc$^{-3}$ ($\Omega_M = 0.3$, $\Omega_A = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$).

\(^d\)Using the $\Phi^*$ of the given survey and our volume, the number of Ly$\alpha$ emitters ($L \geq 2 \times 10^{42}$) we expected to find from assuming a luminosity function (lower entries). Values for the three top entries are determined from Eq. 1.
Fig. 1.— Rest Ly$\alpha$ equivalent width versus the flux of the Ly$\alpha$ line for the Lyman-break galaxy (LBG) sample at $< z > = 3$ (small circles; Shapley et al. 2003) as well as spectroscopically confirmed Ly$\alpha$ emitters at $z \sim 5.7$ (solid triangles; Rhoads et al. 2003; Hu et al. 2004) and at $z \sim 6.5$ (large solid circles; Kodaira et al. 2003; Rhoads et al. 2004); Hu et al. (2002)'s de-amplified $z = 6.56$ LAE is also shown (large solid square). All the fluxes have been redshifted to $z = 6.5$. The long-dashed lines denote the nominal limits of narrow-band searches such as LALA while the dot-dashed lines denote our FORS2 limits. The diagonal short-dashed line corresponds to a continuum flux of $I_{AB} = 25$; the deficit of LBG's above the dashed line is purely due to this selection effect. Here we clearly see the difference between a line-selected sample (e.g. vertical and horizontal limits of our FORS2 survey) and a continuum selected sample (diagonal dashed line). LAE's fainter than a given continuum luminosity can still be detected in a line-selected sample such as ours. Note that although dispersed surveys reach much lower equivalent widths than narrow-band imaging surveys, they would require even lower flux limits to fully exploit this sensitivity given the apparent maximum continuum luminosity shown by high redshift galaxies.
Fig. 2.—The cumulative luminosity functions of Lyman-α emitters at $3 < z < 5$ (left), $z \sim 5.7$ (middle), and $z \sim 6.5$ (right). Open symbols denote photometrically selected LAE samples (Ouchi et al. 2003; Maier et al. 2003; Ajiki et al. 2003) and filled symbols surveys with spectroscopic follow-up (Cowie & Hu 1998; Kudritzki et al. 2000; Hu et al. 2002, 2004; Kodaira et al. 2003; Rhoads et al. 2003, 2004). The dashed curve in all three panels represents a non-evolving luminosity function with $L^* = 3.2 \times 10^{42}$ erg s$^{-1}$ and $\alpha = -1.5$. The solid curve in the right panel represents the number densities probed by our VLT/FORS2 survey; the hatched line is our corresponding 1σ (one-sided) upper limit on the LAE number density. The solid and hatched lines in the middle panel represents the same from MS04. Compared to narrow-band imaging searches at $z \sim 6.5$, our survey provides better overlap with $z \sim 3$ surveys at fainter luminosities ($L < 5 \times 10^{42}$ erg s$^{-1}$). The number density of LAE’s at $z \sim 6.5$ is significantly lower than the value suggested by Hu et al. (2002)’s lensed object, and it seems to be lower than that from the unevolved $z \sim 3$ luminosity function.
Fig. 3.—Observed number density of Lyα emitters as a function of redshift. The solid horizontal line with an arrow denotes our own 84% (one-sided) confidence level for the number density of LAE’s at $z \sim 6.5$. The solid points for Cowie & Hu (1998), Kudritzki et al. (2000), and Hu et al. (2002) correspond to the predicted number of LAE’s in our survey volume based on the properties of their individual objects (see Table 1 for minimum luminosities). The open symbols correspond to the predicted number of LAE’s from a given survey estimated by assuming a non-evolving luminosity function with $L^* = 3.2 \times 10^{42}$ erg s$^{-1}$ and $\alpha = -1.5$ (see Table 1). The errorbars are estimated from Poisson statistics using the number of LAE candidates in a given survey, and values for $N_{pred}$ at a similar redshift are randomly shifted in $z$ for clarity. Our results suggest that the number density of LAE’s declines by about a factor of two between $z \sim 3$ and $z \sim 6.5$. 