Preliminary Results from a Spectroscopic Lyα Survey at Redshift 5.7 with IMACS

Crystal L. Martin\textsuperscript{1,4,5}, Marcin Sawicki\textsuperscript{1,3}, Alan Dressler\textsuperscript{2}, and Patrick J. McCarthy\textsuperscript{2}

\textsuperscript{1}UCSB, Department of Physics, Santa Barbara, California 93106
\textsuperscript{2}OCTW, 813 Santa Barbara Street, Pasadena, CA 91101-1292
\textsuperscript{3}HIA, 5071 West Saanich Rd., Victoria BC, V9A 7M7 Canada
\textsuperscript{4}Packard Fellow
\textsuperscript{5}Alfred P. Sloan Fellow
E-mail: cmartin@physics.ucsb.edu

Abstract

We describe preliminary results from an ultra-sensitive, spectroscopic emission-line survey and illustrate the challenges inherent in identifying high-redshift Lyα emitters. Our multi-slit windows technique complements other types of emission-line surveys. Narrowband imaging surveys cover large areas of sky but only detect much brighter objects. Longslit spectra taken along cluster caustics yield intrinsically fainter lensed Lyα emitters but probe small volumes of space. We have observed the COSMOS deep field and a field at 15h +00. To a line flux of a few $\sim 10^{-18}$ ergs s$^{-1}$ cm$^{-2}$, we found 150 emission-line sources (with no detectable continuum) among 4 masks. These candidates are being re-observed with broad spectral coverage to determine the line identity. To date, the interloper to Lyα ratio is about 8:1. The sky positions of the Lyα candidates generally do not coincide with those of foreground objects in ultra-deep $r$ band or $i'$ images – consistent with the presence of a strong Lyman break.

\textit{Key words:} reionization, starburst galaxies, cosmology

1 Introduction to the Multislit Windows Technique

Finding distant galaxies is a contrast problem. The night sky is much brighter than the galaxies. Since atmospheric OH emission lines dominate this background, ground-based observations are most sensitive at wavelengths falling between the molecular line complexes. Imaging through one of the larger windows at 8200 Å led to the first samples of Lyα-selected galaxies at redshift 5.7 ([3], [7], and [10]).
Table 1
Summary of Blind Lyα Searches with IMACS

| Date       | Field   | Integration Time (s) | Conditions          |
|------------|---------|----------------------|---------------------|
| 2004 April | 10h Field | 22,800               | clear; 0.8 to 2.5 seeing |
| 2005 March | 10h Field | 36,000               | clear; 0.6 to 0.8 seeing |
| 2005 May   | 15h Field | 24,300               | partly cloudy; 0.8 seeing |

In principle, the ∼ 150 Å of sky in this OH-free window can be dispersed with a spectrograph to improve the line-to-sky contrast by reducing the sky brightness by another factor of 50 (i.e. 150 Å / 3 Å FWHM). Although a number of high-redshift Lyα emitters have been serendipitously discovered during deep spectroscopic observations of other targets, the volume probed in a typical longslit observation is insignificant. Custom-designed, multi-slit masks can be employed, however, when spectroscopic observations are made with a band-limiting, OH-suppression filter. This multi-slit windows technique has been used previously to search for z=5.7 and z=6.5 Lyα emitters on the world’s largest telescopes ([1], [9], [6], and [11]). These surveys failed to produce bona-fide Lyα emitters because they did not probe large enough volumes of space.

Order of magnitude improvements in search volume (at z=5.7) were realized with the introduction of the IMACS short (f/2) camera on the Magellan telescope. We carried out blind Lyα searches at z=5.7 in 2004 April, 2005 March, and 2005 May with paired follow-up runs. The total detector area in spectroscopic mode is 737 square arcminutes; approximately 10% of the field is subtended by the 100 slits, each of width 1.5 arcseconds, on our masks. Table 1 summarizes the observations to date. Fields at 10h and 15h have each been observed twice with interlaced masks. The best data were obtained on the 2005 March run when 36,000 s were obtained on the 10h Field in 0.8 arcsecond, or better, seeing. Sensitivities are being computed individually for each run, but typical values are a few × 10^{−18} ergs s^{−1} cm^{−2}.

2 Results from Blind Emission-Line Search

The reduced, sky-subtracted data were searched for emission lines. If continuum emission was detected blueward of the discovery line, then the line was rejected from the list of Lyα candidates. Intergalactic absorption toward a redshift 6 galaxy effectively moves the Lyman break from 912 Å up to the Lyα line ([4]). Many Lyα candidates were found in each field, and a subset of these
Table 2
Emission-Line Objects Discovered in Blind Search

| Date       | Field       | N (Emission Lines) | N (Ly$\alpha$ Candidates) | N (Ly$\alpha$ Confirmed) |
|------------|-------------|--------------------|---------------------------|--------------------------|
| 2004 April | 10h Field   | 87                 | 52                        | 3                        |
| “          | 15h Field   | 86                 | 48                        | 5                        |
| 2005 March | 10h Field   | 67                 | 31                        | 6                        |
| 2005 May   | 15h Field   | 25                 | 22                        | TBD                      |

were selected for follow-up spectroscopy without the narrowband blocking filter. Table 2 shows the yield of total emission-line objects, Ly$\alpha$ candidates, and confirmed Ly$\alpha$ emitters to date.

3 Confirmation via Spectroscopic Follow-Up

3.1 10h Field

Follow-up spectra of the 10h Field were obtained 2005 May. Slits were placed on 43 targets from the 2004 April search and 48 targets from the 2005 March search. We re-detected all but 3 of the 2005 March objects. The positions for the 2004 April candidates are less accurate than those for the 2005 runs. The addition of the Magellan corrector lens in the middle of 2004 changed the focal length, and the scale changes in the mask plane have not been accurately modeled. Among the 2004 April targets, only 28 of 43 were recovered.

We identified about 8 interlopers per Ly$\alpha$ (and [OII]) emitter. The line was positively identified for about one-third of the interlopers. A Ly$\alpha$ identification was ruled out for the other two-thirds due to presence of continuum emission blueward of the discovery line and/or the presence emission-lines blueward of the discovery line.

Inspection of the spectra left 6 and 3 likely Ly$\alpha$ emitters from the 2005 March and 2004 April candidates, respectively. Figure 1 shows the spectra. Our follow-up spectra had to be taken at lower resolution than originally planned, and the [OII]3726,29 doublet is not resolved. Our sample of Ly$\alpha$ emitters may include several [OII] interlopers. The follow-up spectra are shown in Figure 1.
Fig. 1. Confirmation spectra of several Ly$\alpha$ emitters from the 10h Field. Spectra are aligned in wavelength, and the discovery lines can be seen in the low background window just the right of center at 8200 Å. The candidates are, from top to bottom, MSDM30.5-8.1, MSDM17.5+8.1, MSDM25.5+5.1, MSDM75.5-6.1, MSDM100.5-2.1, MSDM26.5+7.1, MSDM80.0+3.1, MSDM64.0-5.1, and MSDM52.0+8.1. (One object, MSDM52.0+8.1, is not shown due to resolution limits on the display.)

3.2 15h Field

Follow-up spectra were obtained in 2004 July for the 15h Field. Slits were assigned for 37 of 48 objects from the Ly$\alpha$-candidate list. (The others had overlapping spectra or discovery lines in the inter-chip gaps.) We detected 16 of these emission-line objects. The positions of candidates in the mask plane could not be modeled as accurately as desired because the corrector was installed between the discovery run and the follow-up run. The quality of the discovery line in the un-detected candidates was as high as that of the re-detected candidates. Apparently the model of the scale changes in the mask plane was not perfect.

We identified 8 of these 16 objects as foreground galaxies based on their spectra. One, MSDM94-8, was identified as foreground based on a positional coincidence with a foreground galaxy. Five objects were confirmed as Ly$\alpha$ (or [OII]) emitters, and these are shown in Figure 2. The two remaining objects have not been classified yet.
Fig. 2. Follow-up spectra of 15h Field Lyα candidates from 2004. Confirmed Lyα (or [OII]) emitters include MSDM79+8, MSDM98+1, MSDM94-4, MSDM99-1, and MSDM71-5.

4 Confirmation via Continuum Break

Any high-redshift Lyα emitter must present a strong continuum break shortward of the Lyα line (4). Faint, foreground galaxies with an interloping emission-line in the 8200 Å OH-window will normally have fairly blue colors. Broadband imaging shortward of the 8200 Å window therefore provides another check on the identity of the ~8200 Å line. True Lyα emitters will not be detected in this veto image.
We obtained an ultra-deep Subaru $r$ band image of the 10h field from the COSMOS team and an $i'$ band image from the CFHT Legacy Survey. The sky positions of our candidates were computed from a transformation calculated by Ken Clardy. For the 2005 data on the 10h field, our experiments show that the positional uncertainty along the slit is less than 0.5 arcseconds. Perpendicular to the slit, the error is assumed to be half the slit width, or 0.75 arcseconds. The uncertainty for the 2004 positions in both fields may be somewhat larger.

Figure 3 shows the positions of the Ly$\alpha$ candidates from the 10h field on the CFHT image. Only object MSDM26.5+7.1 is clearly associated with an object in the $i'$ image. We find more Ly$\alpha$ candidates within 2 arcseconds of foreground galaxies than expected. Some fraction of these are probably [OII] emission lines from HII regions in the outer parts of the foreground galaxy. Spectra of the foreground galaxies or higher-resolution spectra of the candidates should easily determine which objects are interlopers.

A deep $B$ band image of the 15h field was obtained previously with the NOAO mosaic camera. Positional errors should be similar to those for the 10h field. In the 15h field, only MSDM94-8 was rejected due to an exact positional coincidence with a foreground object.

5 Role of Ly$\alpha$ - Selected Galaxies in Reionzation

Measurement of the luminosity distribution of Ly$\alpha$ emitters is critical to understanding the role of emission-line selected galaxies in maintaining the ionization of the intergalactic medium at redshift 6 (6). A full analysis of the data presented here should provide the best constraints on the faint-end slope to date. Existing observations that probe slightly fainter emitters probe such small volumes that the uncertainties in the number density are large (2, 8). The strong clustering properties of the Ly$\alpha$ emitters have been emphasized by (3) in their estimate of the luminosity distribution. In addition, the evolution, or lack of evolution, in the Ly$\alpha$ luminosity function at this epoch is an important constraint on the epoch and progression of reionization (5).

At present, we are working to finish the data processing for the 15H Field follow-up. We can also investigate the proximity of the Ly$\alpha$ candidates to foreground galaxies three ways: spectra of the foreground objects, higher resolution spectroscopy, and Monte Carlo simulations. The effective survey volume is a function of object flux, and this function is being determined with simulations. With these results in hand, we will compute the faint-end slope of the Ly$\alpha$ luminosity function at $z = 5.7$. 

6
Fig. 3. Position of Ly$\alpha$ candidate on ultra-deep $i'$ band image of the 10H field. North is up and east is to the left. The circles are $1''$ in radius, which is about twice the positional uncertainty. Each image is $10''$ on a side; north is up and east is to the left.
The authors would like to thank Yoshi Taniguchi, Peter Capak, and Patrick Shopbell for making the Subaru r band image of the COSMOS field available and the CFHTLS team for the i’ image of the CFHTLS 10h field. Ken Clardy contributed enormously to modeling the transformation from the mask plane to the sky and back, and his thoughtful help is greatly appreciated.

References

[1] D. Crampton and S. Lilly, in ASP Conf. Ser. 191, Photometric Redshifts and High-Redshift Galaxies, ed. R. J. Weymann, L. J. Storrie-Lombardi, M. Sawicki, and R. J. Brunner (San Francisco: ASP), 229 (1999).
[2] R. Ellis, M. R. Santos, J. Kneib, and K. Kuijken, ApJ, 560, 119 (2001).
[3] E. M. Hu et al., AJ, 127, 563 (2004).
[4] P. Madau, ApJ, 441, 18 (1995).
[5] S. Malhotra and J. E. Rhoads, ApJ, 617, 5 (2004).
[6] C. L. Martin and M. Sawicki, ApJ, 603, 414 (2004).
[7] J. E. Rhoads et al., AJ, 125, 1006, (2003).
[8] M. R. Santos et al., ApJ, 606, 683. (2004).
[9] A. Stockton, Ap&SS, 269, 209 (1999).
[10] Y. Taniguchi et al., ApJ, 585, L97 (2003).
[11] K. H. Tran, S. J. Lilly, D. Crampton, and M. Brodwin ApJ, 612, 89 (2004).