Searching for $z = 6.5$ Galaxies with Multislit Windows

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Abstract. A method for searching for emission-line objects in “windows” between atmospheric emission lines using multislits is described. A search for Ly $\alpha$ emitters at $z = 6.5$ in the 9130 Å window using this technique is being carried out with the multi-object spectrograph on CFHT. This technique could be extended to similar windows at longer wavelengths, aided by the $(1 + z)$ factor in observed equivalent widths. In the $J$ band there are windows corresponding to Ly $\alpha$ at $z = 7.7, 8.7$ and $9.3$; in the $H$ band, there are two at $z = 11.9$ and $13.4$. Multislit window observations in these bands coupled with photometric redshift information offer perhaps the best method of the detecting extremely high redshift galaxies.

1. Introduction

Questions of how galaxies and quasars formed in the early Universe and when and how the intergalactic medium became ionized continue to occupy a central place in observational cosmology. As quasars and galaxies are discovered at higher and higher redshifts, the questions posed by these primordial objects become more pressing, offering the strongest constraints on cosmogonic theory (e.g., Silk & Rees 1997, Haehnelt et al. 1998). The detection of several galaxies with $z > 5$ have recently been reported (e.g., Cowie & Hu 1998; Dey et al. 1998; Hu, Spinrad and Lanzetta in these proceedings) indicating that searches for objects at even higher redshift are essential. Most of the highest redshift galaxies have been detected as a result of their emission lines, either through targeted narrow band filter surveys (e.g., Cowie & Hu 1998, Hu, Cowie & McMahon 1998), as a result of being lensed by a foreground cluster (e.g., Franx et al. 1997), or serendipitously in deep, long slit exposures (e.g., Hu, Cowie & McMahon 1998, Dey et al. 1998).

Unfortunately, as Ly $\alpha$ moves to higher and higher wavelengths the atmospheric emission lines imposed on the object spectra become stronger and stronger and hence harder to remove. Increased fringing and decreasing detective quantum efficiency in CCD detectors considerably exacerbates this problem. Hence, despite the fact that very strong Ly $\alpha$ emission is frequently observed in
high redshift galaxies, such lines are usually only detected in line-free regions. There are not many such “windows” that are very wide, but there is nice one between ~8965Å – 9290Å which is the subject of this investigation. These wavelengths correspond to redshifted Ly α at 6.38 < z < 6.64, but also to redshifted [OII] at z ~ 1.45, [OIII] at z ~ 0.82, and H α at z ~ 0.39. Fortunately, most of the latter typically have substantially lower equivalent widths than Ly α and, according to Cowie & Hu (1998) most observed emission lines with W >> 100Å are Ly α. Fortuitously, atmospheric water vapour absorption is low in this window.

Apparently, the density of high redshift Ly α emitters is very high. Hu et al. (1998) estimate that there are 15,000 per square degree per unit z with V < 25.25, based on narrow band emission line surveys at z = 3.4 and z = 4.6. These galaxies are very faint, of course, but, in general, they are very compact and have narrow emission lines, both of which aid in their detectability by spectroscopic means.

2. Observations

2.1. Strategy

To search for strong Ly α emitters, we decided to use a grism giving 10.5Å per pixel on the CFHT multi-object spectrograph in multi-slit mode in conjunction with a custom filter 300Å wide centered at 9130Å. To survey a reasonably large area yet maintain a low sky brightness, 2″ wide slits (corresponding to five 0″4 pixels) were used (it should be noted, however, that the small size of very high redshift galaxies means that the spectra are essentially slitless and, with typical seeing at CFHT of < 1″, the effective resolution is about 25Å). The 300Å long spectra occupy about 29 pixels at our chosen resolution. However, the wings of the filter transmission curve are not square and so an additional 10 pixels were allocated to avoid any overlapping of spectra. Since the total height covered by the slit mask corresponds to 1150 pixels, 30 spectra (from 30 long slits) can be fitted into the available area. The precise slit separation was chosen so that the zero orders from slits at the top of the mask would fall within the 10 pixel “interspectral” gaps which were allowed for the filter wings. Two small “bridges” were left in the slits to ensure the integrity of the mask after all the slits were cut. An image of the mask is shown in Figure 1a.

The total area covered by the slits is 2″ * 9′ long * 30 slits or 9 square arcmin. This is only about 1/8 the total area of the focal plane which would be available if instead a narrow band filter (say 50Å wide) were used for such a survey. However, with the multislit technique a six-fold multiplex gain is realized since 300Å are searched simultaneously and, as mentioned above, the resolution is better, about 25Å for seeing-limited sources. The resulting higher sensitivity, albeit over a smaller area, is an attractive trade given the expected high density of sources. Based on the density estimated by Hu et al. (1998), approximately 10 Ly α emitters per field might be expected with V < 25.25 in our redshift interval, although their estimate was based on lower redshift objects.
2.2. Observations and Reduction Procedure

Observations of two CFRS fields were carried out with the CFHT in 1998 August. The bandpass of the 300Å filter was not optimal, being centered somewhat blueward of the desired wavelength. Figure 1b shows the transmission of the filter as a function of wavelength, superimposed on a spectrum of the night sky. The filter has an average peak transmission of about 90%, the bandpass is relatively rectangular in shape, and it has good rejection outside of the transmissive bandpass. However, as the figure demonstrates, it ideally should have been centered redward by ∼40Å. The filter characteristics were within specifications, but these had been somewhat relaxed to ensure quick delivery.

Since the precise filter characteristics and precise offsets of the zero order spectra relative to the first order spectra (in order to place the zero orders within inter-spectral strips) were not known in advance of the observations, the slit mask had to be fabricated immediately prior to the target observations. In order to cut thirty 2″ × 9′ slits at normal cutting speeds at CFHT, four hours are required. Since this was impractical, the cutting speed was doubled with the result that the edges of the slits were much rougher than usual or optimal. Consequently, the slit mask was far from ideal. However, our observational technique minimized the associated problems: the objects were dithered along the slits from one observation to the next, resulting in excellent flat-field correction.

Series of one hour exposures were obtained of the CFRS1415+52 and 2215+00 fields during three nights for a total of 4h and 16h respectively. A part of one such exposure is shown in Figure 2a. Short, 300Å long, spectra of a few brighter objects can be seen superimposed on the background which increases significantly towards the blue, as expected from the sky background illustrated in Figure 1b. During observations, a few bright objects were recentered vertically in the
slits before each subsequent exposure and the fields were offset horizontally by \( \sim 2'' \) between exposures.

Individual exposures were first divided by a superflat which was formed from all the dithered data. The sky background was then subtracted along the slits in a more or less conventional way with IRAF. These background-subtracted images were shifted and combined using a badpixel mask to reject regions of the slit bridges and bad CCD columns. A portion of the resulting, co-added, spectral image is shown in Figure 2b. As mentioned above, despite the relatively poor slits and the omnipresent CCD fringing at such wavelengths, the images flat-fielded extremely well as a consequence of our dithering procedure. Emission line spectra are clearly visible on these images in addition to the more common short continuum spectra.

In principle, recognition software such as Sextractor (Bertin & Arnouts 1996) could now be used to detect the emission-line objects in an unbiased way to a given flux threshold. However, the presence of more or less point-like zero-order images in the bottom third of the field (from bright objects in the top third) introduces a considerable number of spurious images. These can, of course, be identified and removed \textit{post facto}. However, in addition, emission lines superimposed on continua may also not be recognizable by standard detection software (although these are unlikely to be the Ly \( \alpha \) emitters). Hence, two further steps were taken to alleviate these problems: the (known) inter-spectral strips where the zero orders lay were replaced with strips of uniform background which have appropriate noise characteristics, and background subtraction was performed.
Figure 3. (a) (left) The same image as in Figure 2b but with the continua subtracted to improve detection of emission lines superimposed on continua. This image was gaussian smoothed to enhance the visibility of sources for display purposes. Residuals from the brighter continuum sources are evident but easily rejected. Some potential fainter sources are visible in this figure in addition to the three obvious ones. (b) Wavelength and flux calibrated spectrum of the three-emission-line object at the upper left of Figure 2b and 3a. H$\beta$ (plus noise on the violet side) and the [OIII] lines are visible.

along the spectral slices in order to subtract the continua. This process works well for all spectra but those of the brightest objects (which are not of interest for this investigation) for which residuals frequently remain at the ends of the spectra. A portion of a continuum-subtracted image is shown in Figure 3a (this image was gaussian smoothed with the resolution expected for point sources to further enhance such features). Several faint sources in addition to the three obvious ones (and noise spikes!) are visible. The spurious residuals from bright stars are disconcerting but easily rejected. With such images, conventional software can be used to detect the emission lines in an unbiased manner.

3. Emission-line Objects

Examples of obvious emission-line objects are shown in Figure 3a. Since this technique produces actual spectra, albeit over a small wavelength range, actual wavelengths, equivalent widths, and fluxes can also be extracted and reduced by conventional means. A fluxed spectrum of the emission-line galaxy shown at the upper left in Figures 2b & 3a is reproduced in Figure 3b. This object is clearly a galaxy at $z = 0.86$ since it shows H$\beta$ and the [OIII] lines. This galaxy is CFRS22.0184 with $I_{AB} \sim 22.4$. The two most obvious single emission line galaxies in Figures 2b & 3a (lower right) have $I_{AB} \sim 25$ and have $W >> 100$A, but it is not obvious without further evidence (e.g., a photometric redshift) whether they are at $z \sim 1.4$ or $\sim 6.5$. Approximately 50 such objects, most of which are much fainter, are present on our deep exposure of the 22h field.
Analyses of their colors and further spectroscopic observations are currently underway to establish their redshifts.

4. Summary

A combination of multislits and intermediate band filters appears to be an excellent method for the detection of faint emission-line objects. This method has been used to explore the window between the strong atmospheric emission lines near 9130Å. Several dozen emission-line objects have been detected, some of which have equivalent widths $>\!>100\AA$ and hence may be galaxies with redshifted $\text{Ly}\alpha$ emission at $z \sim 6.5$. Obviously, this technique could be extended to similar “windows” at longer wavelengths, aided by the $(1 + z)$ factor in observed equivalent widths. In the $J$ band there are windows corresponding to $\text{Ly}\alpha$ at $z \sim 7.7, 8.7$ and 9.3. There appear to be only two in the $H$ band, corresponding to $z \sim 11.9$ and 13.4. Multislit observations in these windows when coupled with photometric redshift information offer perhaps the best method of the detection of extremely high redshift galaxies.

Although our initial observations using this technique were successful, they could be improved upon in several ways. The detective quantum efficiency of the CCD was reasonable, being about 50% at this wavelength, but it could be higher. Similarly, the peak efficiency of the grating occurs at 7500Å and so a grating with a more appropriate blaze could be obtained. Finally, as mentioned above, neither the filter nor the actual slit mask used were optimal. Taken all together, a factor of at least two improvement in depth could easily be achieved.

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