Galaxies at $z > 5$: The View from Hawaii

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Abstract. We review the properties of $z > 5$ galaxies studied with HST and with the Keck telescopes, and discuss the detectability of Ly$\alpha$ emission-line galaxies out to $z \sim 6.5$ based on these data and ongoing narrowband imaging surveys. The brightest sources may show $(R - Z)$ color breaks, although the high sky background at $Z$ ($\lambda_{\text{eff}} \approx 9200 \, \text{Å}$), makes such observations challenging for typical faint sources. Keck LRIS observations of the $z = 5$ SDSS quasar and $z > 5$ galaxies observed with HST in the HDF show that the strength of the Lyman break is evolving more slowly than extrapolations from models at $z \sim 3$ would predict.

1. Introduction

Over the last year and a half, a number of very high redshift ($z > 5$) galaxies have been reported (Dey et al. 1998, Hu et al. 1998, Weymann et al. 1998, Spinrad et al. 1998, Chen et al. 1999, Hu et al. 1999), and our knowledge of the $z > 4$ galaxy population (e.g., Hu et al. 1996, Petitjean et al. 1996, Fontana et al. 1996, Hu & McMahon 1996, Trager et al. 1997, Franx et al. 1997, Hu et al. 1997, Frye & Broadhurst 1998, Hu et al. 1998, Soifer et al. 1998, Pelló et al. 1999, Steidel et al. 1999, Hu et al. 1999) has been substantially increased. These samples have recently been joined by radio galaxy identifications which reach $z > 5$ (van Breugel et al. 1999a, 1999b). At the highest redshifts now probed, identification of galaxies basically relies on two key diagnostics: the Lyman break across the continuum and the redshifted Ly$\alpha$ line. Both characteristics have been used to select and to verify high-$z$ galaxy candidates.

The extremely faint nature of the high-$z$ galaxy population in infrared continuum light and the increasing strength and frequency of nightsky emission lines at very long wavelengths makes it clear that the contrast and detection of high-redshift galaxies from the ground is challenging, even for the new generation of 8- to 10-m class telescopes. The discovery of very high equivalent width emitters at $z = 4.55$ (Hu & McMahon 1996) indicated the existence of a substantial population of strong Ly$\alpha$ emitters which could be observed to very high redshifts, beyond $z > 5$. In this paper we report on the status of ongoing Ly$\alpha$ emission-line searches combined with color-selection data and consider the prospects for future identifications at the very high redshift end.
2. Lyα Searches

The Lyα searches are designed to address issues of detectability of field galaxies at very high redshifts, using the increased contrast of the object against the background sky when viewed in the Lyα emission line. The contrast of emission features against the neighboring continuum is also enhanced by the \((1 + z)\) magnification of line widths, producing high equivalent width signatures. Through the use of spectral regions free of strong night sky lines (e.g., Fig. 1), these studies are also designed to address object statistics over a range of different redshift intervals, since our ability to detect and reliably confirm very high-redshift galaxies is otherwise highly dependent on the location of emission features with respect to background nightsky lines. Narrowband Lyα searches combined with deep multi-color data on the Hawaii Survey Fields and HDF have been used as a training set (Cowie & Hu 1998; Hu 1998) to test emission line identifications in terms of color and equivalent width diagnostics over an extensive spectroscopic database, starting at \(z \sim 3.4\), where color selection is robust, and working out to successively higher redshifts \((z \sim 4.6, 5.7, 6.5)\). This allows studying continuity in properties of genuine Lyα emitters and both color-selected galaxies and low-redshift foreground emitters at progressively longer wavelengths, where higher sky backgrounds from the increased density of strong nightsky lines and fainter continua for the more distant galaxies are issues. A variant approach is to use a Fabry-Perot (Calar Alto Deep Imaging Survey, Meisenheimer et al. 1998), which requires a high-level of precision in low-level light processing and flat-fielding.

The present Lyα surveys have reached \(z \sim 5.7\) (Hu et al. 1999), and \(z \sim 6.5\) narrowband studies have recently been started.

From the initial wide-field narrowband surveys for Lyα emitters at \(z \sim 3.4\) and 4.5, Hu et al. (1998) estimated a surface density of Lyα emitters of \(\sim 13,000/\text{unit } z/\angle^2\) down to an emission flux of \(\sim 10^{-17}\) ergs cm\(^{-2}\) sec\(^{-1}\). These estimates were found to be consistent with a complementary deep spectroscopic study, where the slit provided limited spatial sampling, but wide wavelength coverage at somewhat greater sensitivity, and recovered 4 Lyα emitters with redshifts from 3.05 \(\rightarrow 5.64\). Preliminary results from the \(z \sim 5.7\) searches suggest number densities perhaps a factor of 6 lower than the value for the lower redshift systems given by Hu et al. (1998).

3. Spectroscopic Searches

The surface number density estimates for Lyα emitters imply that sufficiently deep spectroscopic exposures may intercept some of these systems, at least over the lower redshift ranges. In fact, the first published \(z > 5\) galaxy, RD-1, was a serendipitously discovered Lyα emitter at \(z = 5.34\) reported by Dey et al. (1998) during deep long-slit observations of a neighboring object in the field, with both emission line and break identified in the spectra, and with the break confirmed by broad-band filter imaging. For RD-1, estimates of the continuum magnitude above the Lyman break are \(\sim 26.3\) AB mags using the broad-band imaging data, with emission-line flux = \(3.5 \times 10^{-17}\) ergs cm\(^{-2}\) s\(^{-1}\), \(W_\lambda = 600\) Å (Dey et al. 1998). The success of the spectroscopic searches depends on the surface number density at the redshifts and fluxes being probed. Equivalent width estimates,
and particularly continuum magnitudes for faint objects measured in dispersed modes have larger associated errors than estimates tied to standard broadband filter photometry. Higher sensitivities trade off against small area coverage, and for slit spectroscopy there is the additional issue of whether with chance superpositions sample objects fall only partly within the slit. The additional problem in using this method as a search technique is that it is difficult to assess the fraction of emitters missed because they lie in regions of strong nightsky lines, and that for such cases confirming observations can be extremely hard to make.

An interesting variant of this search technique is to use slitless spectroscopy (Chen et al. 1999). Incomplete object sampling by a slit is removed, but the general problem of overlapping galaxy spectra must be dealt with. Using extremely deep STIS parallel exposures from HST, Chen et al. (1999) identify a Lyα emitter at a probable redshift of 6.68. At $z = 6.68$ Lyα falls in regions of strong OH lines, which makes confirmation with ground-based observations extremely challenging.

4. Color Breaks

The strong depression of the continuum below the redshifted Lyman break caused by the numerous neutral hydrogen absorbers dubbed “the Lyα forest” is the most notable feature in the galaxy continuum light of very high redshift
systems, where the extreme faintness of these objects, typically > 26 mags (AB) above the break, precludes the use of detailed absorption features to estimate the redshift. This method has been most successfully applied (e.g., Fernández-Soto et al. 1999) in the Hubble Deep Field (HDF; Williams et al. 1996), where the high precision of the photometric measurements permits robust detection of a break signature, and where the availability of photometric data at longer wavelengths (NICMOS infrared observations) allows discrimination of Lyman break galaxies from red objects. HDF 4-473.0 (Weymann et al. 1998), shown to be a ‘V dropout’ by the absence of detectable flux in the WFPC2 F606W filter, combined with a roughly flat $f_\nu$ spectrum out through 1.6$\mu$m, was confirmed as a $z =$ 5.60 galaxy through deep LRIS spectra on Keck. An emission line with flux $\sim 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ and $W_\lambda = 300$ Å, identified as Ly$\alpha$, was used to establish the redshift. The magnitude above the break is $\sim 26.6$ AB mags.

A second color selected target, HDF 3-951.1 and 3-951.2, was identified by the color break, and placed at an estimated redshift $z =$ 5.34 (Spinrad et al. 1998) on the basis of the break location. For this close pair, no emission features are detected (Fig. 2 of Spinrad et al. 1998), with upper limits on possible Ly$\alpha$ more than a factor of 10 below the observed flux of HDF 4-473.0 Spinrad et al. (1998) consider the possibility that the absence of Ly$\alpha$ emission might be associated with its brighter continuum. Because studies at this depth and

Figure 2. Multicolor $B$, $V$, $R$, $I$, $Z$, and narrowband 8185/105 Å images taken with LRIS on Keck of the $z =$ 5.74 object, SSA22-HCM1. Each panel is 30$''$ on a side. The strong contrast of this object in the 8185 Å narrowband filter can be seen, in comparison with the $Z$ band, which samples the continuum in a region free of emission. SSA22-HCM1 is an $R$ ‘dropout’ and the object is absent at $B$, $V$, and $R$ in these extremely deep Keck LRIS images.
precision of color measurement are only available for a small region of sky (≈ 5 arcsec$^2$ each for the HDF and HDF South), key questions one would like to address from the HDF color-break selected galaxies are: (1) How typical are these properties of the high-redshift galaxies; what are the consequences for future detections? (2) Are the bright high-redshift galaxies devoid of Ly$\alpha$ emission?

5. Properties of the $z > 5$ Galaxies

Figs. 2 and 3 show images and a spectral energy distribution (SED) for the $z = 5.74$ galaxy, SSA22-HCM1 (Hu et al. 1999). This object is an ‘$R$’ dropout, and is notably absent in deep Keck LRIS images in $B$, $V$, and $R$, which reach 1σ limits of $B=28.3$, $V=28.2$, and $R = 27.8$ for a 2$''$ diameter aperture. The SED shows both the strong Lyman break and the Ly$\alpha$ emission feature (flux=1.75 x 10$^{-17}$ ergs cm$^{-2}$ s$^{-1}$; $W_{\lambda} = 175$ Å), which was confirmed with deep LRIS spectroscopy. The increased contrast in the appearance of the object as detected in the 8185 Å narrowband filter compared with the line-free $Z$ band filter around 9200 Å may be noted. For these measurements we use fluxes measured in the narrowband filter, instead of values recovered from spectroscopic extractions, for greater precision. Aperture 1σ errors are estimated from laying down random apertures
Figure 4. Theoretical models (Thommes & Meisenheimer 1999, in preparation) for the surface density of high-z Lyα emitters as a function of flux and redshift. The plotted points show the fits to the $z = 3.43$ emitters (Cowie & Hu 1998). Arrows show limits from non-detections by earlier long-slit surveys of Thompson & Djorgovski (1995) and of the current limits for the Fabry-Perot surveys by the CADIS group (Thommes et al. 1998). The main qualitative points to note are: (1) the surface density of emitters falls off dramatically as a function of limiting survey flux and (2) reaching the redshift $z > 6$ population critically requires getting down to below $10^{-17} \text{ erg cm}^{-2} \text{s}^{-1}$. At current sensitivities coverage of fairly wide areas is desired.

away from identified sources, since in the deep exposures magnitude limits are set by the background faint source population (Fig. 2). The measured continuum above the break, 25.5 mags (AB), is a magnitude higher than the Weymann et al. (1998) observed estimate for HDF 4-473.0, and lies between our estimated continuum magnitudes of 24.9 and 25.7 (based on our deep $Z$ band observations of the HDF) for the 3-951 pair. SSA22-HCM1 is the brightest of the $z = 5.7$ Lyα emitters surveyed to date, and in contrast to 3-951 has strong emission. However, it appears that more typical emitters at these redshifts have properties like 4-473.0 (Hu et al. 1999, in preparation). We can summarize the expected properties for Lyα-emitting galaxies above $z \sim 6$, based on the current $z \sim 5.7$ survey, as: Lyα fluxes $\sim 10^{-17} \text{ ergs cm}^{-2} \text{s}^{-1}$, equivalent widths of a few 100 Å, and continuum magnitudes fainter than $\sim 26.5$.

Efforts to model the high-redshift emitters have begun (e.g., Thommes 1998, Haiman & Spaans 1999), and we can use these as a starting point to estimate the
detection limits that will be required for working at higher redshifts. Fig. 4 from Thommes (1998) shows the expected surface number density of Lyα emitters for four redshift intervals \((z = 3.5, 4.5, 5.7, \text{and} 6.5)\) corresponding to spectral regions free of strong nightsky lines. Overplotted are the data from Cowie & Hu (1998) for \(z = 3.4\), and other upper limits. It can be seen that, in agreement with the properties summarized above, surveys will need to exceed 5σ detection limits of \(10^{-17} \text{ ergs cm}^{-2} \text{s}^{-1} (10^{-20} \text{ W m}^{-2})\), and preferably cover wide areas.

6. \((R - Z)\) Color Selection

Because SSA22-HCM1 is so bright in \(Z\) it is interesting to examine color statistics for objects in \((R - Z)\) vs. \(Z\). Fig. 5 shows the color distribution of objects in the HDF and SSA22 fields over a sample area of 75 arcmin\(^2\). Magnitudes are measured on the AB system using 2\(''\) diameter corrected apertures. The fiducial color boundary used here of \((R - Z) > 2.75\) lies marginally above the range of possible M star contaminants, which might be distinguished by compactness criteria. At faint magnitudes the depth of the \(R\) exposure dominates the errors in the \((R - Z)\) color measurement, which can be quite large. Filled symbols indicate known \(z > 5\) galaxies (or in the case of HDF 3-395.1 and 3-395.2, the summed magnitudes of the object pair). In the case of HDF 4-473.0, the colors are estimated from deep WFPC2 and NICMOS photometry (Weymann et al. 1998). The 5σ \(Z\) band criterion is not sufficiently deep to include SSA22-HCM1, the \(z = 5.60\) galaxy HDF 4-473.0, or the \(z = 5.34\) emission-line galaxy RD1 (based on the estimated \(I(AB) = 26.1\)), but the threshold is only a few tenths of a magnitude from reaching the brighter two objects. Thus, it appears that the use of deep \(Z\)-band filter imaging and \(R - Z\) color selection on the large telescopes may be a possible way to extend methods for selecting candidates to higher \((z > 5.7)\) redshifts for ground-based studies, although the background sky brightness near 9200 Å is high. This could be used in combination with a near-IR color measurement to distinguish break objects from highly reddened galaxies.

7. Evolution of the Continuum Break

The new \(z \sim 5\) quasars discovered by the Sloan Survey (Fan et al. 1999) provide a means of evaluating the expected continuum depression below the Lyα line at high redshifts. Because of the rapid increase in the gas density with redshift, it is expected that, at the higher redshifts, there will be a sizable break. In Fig. we show a spectrum of the newly discovered \(z = 5\) quasar, J033829.31+002156.3, for which we determine a factor of 4 break across the emission line. By comparison, Zhang et al. (1997) find, at \(z = 5\), for \(H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_0 = 0.06\) and a Haardt-Madau (1996) spectrum and ionizing flux, that the spectrum of a \(z = 5\) quasar will have an average flux in the region between 1050 Å and 1170 Å that is 10% of the continuum value which would be present in the absence of Lyman alpha scattering. A plot of the continuum break across Lyα for various \(z > 4\) quasars (Schneider et al. 1991; Kennefick et al. 1995) and galaxies is shown in
Figure 5. \((R−Z)\) colors of galaxies in the HDF and SSA22 fields. The dashed vertical line shows the 5\(\sigma\) magnitude limit in \(Z\). The filled squares show the colors of (both components of) HDF 3-395 and HDF 4-473.0, and the filled diamond shows the measured \((R−Z)\) color for SSA22-HCM1. The solid line at \((R−Z) = 2.75\) provides an arbitrary divider for very red objects. Known stars (indicated with asterisks) can lie in the region above the line. Galaxies populating the upper part of the plot include both dust-reddened objects and high-\(z\) continuum break objects.

Fig. 5. \(D_A\) is the index (Oke & Korycanski 1982)

\[
D_A = \left(1 - \frac{f_\nu(\text{observed})}{f_\nu(\text{continuum})}\right)
\]

in the rest-frame wavelength range 1050 Å to 1170 Å.

8. Future Investigations

It is useful to consider possible directions for future studies. A number of \(z > 4\) galaxies have been found using cluster lens systems (e.g., Trager et al. 1997, Franx et al. 1997, Frye & Broadhurst 1998, Pelló et al. 1999), where amplification of the source has increased its detectability. In general, such discoveries do not provide information on the statistics, continuum magnitudes, and base emission-line fluxes of the high-redshift galaxies found, but for very well-studied cluster lens systems (e.g., Bézecourt et al. 1999) it may be possible to recover such information. Typical magnification is about 1 magnitude (Smail et al. 1999), and this may be a fruitful way to extend high-redshift searches.

The availability of new IR spectrographs for the 8–10-m. class telescopes will make it possible to study \([\text{O}

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The Lyman break strength at high redshift is estimated to be a factor of 4 from LRIS spectra (Songaila et al. 1999) of the $z = 5.00$ Sloan Survey quasar (Fan et al. 1999). Such observations may provide more information on the degree of dust extinction in the high-redshift galaxies detected by their Lyα. However, for $z > 5$ systems $[\text{O} \text{II}]$ lies in the thermal IR and cannot be readily studied from the ground.

For redshifts $z > 5$, high equivalent width Hα emission from high ionization foreground extragalactic HII regions is a possible contaminant which can mimic Lyα. Such systems may have no detectable continuum, and $[\text{N} \text{II}]$ suppressed to less than 2% of Hα (Stockton & Ridgway 1998). The incidence of these systems is not known, but a few cases have been encountered in our $z \sim 5.7$ and $z \sim 6.5$ surveys — and identified by wide wavelength spectra covering the corresponding $[\text{O} \text{II}]$ and $[\text{O} \text{III}]$. Extensive wavelength coverage is required to verify sources as Lyα emitters.

Searches for yet higher $z$ galaxies are of necessity forced into the near IR since the light below $1216(1+z)$ Å will be essentially extinguished by the strong Lyα forest blanketing or by H I Gunn-Peterson (Miralda-Escudé & Rees 1998) at the redshifts where the IGM was neutral. We can look forward to detecting these objects with the Next Generation Space Telescope.

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Figure 7. The measured Lyman break strength \((1-D_A)\) at high redshifts for quasars ([filled squares] Schneider et al. 1991; Kennefick et al. 1995; Songaila et al. 1999) and high-redshift galaxies HDF 4-473.0 and 3-395 ([open diamonds]). Upper limits are indicated for the \(z = 4.92\) lensed galaxy (Franx et al. 1997) and for SSA22-HCM1 at \(z = 5.74\) (Hu et al. 1999). The solid curve shows Zhang et al.’s (1997) extrapolation using a Haardt-Madau (1996) spectrum.

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