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The Most Distant Galaxies

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Abstract

I review selected current observations of distant galaxies and our interpretation of the fragile (and occasionally contradictory) data. Galaxies at the “contemporary limit” of technology and redshift ($z \sim 6$) are difficult to locate in the first place. Moreover, the large redshift may push some critical confirming and/or interpretative analysis toward unfamiliar IR wavelengths. I will concentrate on observational means and results to explore the early evolution of galaxies. We also note the biases that intrude on plans for the interpretative aspects of distant galaxy photometry and spectroscopy. We discuss the best methods of selection for those very distant systems; these methods include utilizing strong sub-mm emission from dust, photometry indicating a UV “spectral break,” and finally the signal of a strong Ly α emission line. This feature has now carried us to a galaxy redshift in excess of $z = 6.57!$

1.1 Introduction, Motivations, and Questions

The study of distant galaxies is empirically demanding – not surprisingly, as these galaxies are very faint.

Of course there are a variety of motivations to observe and perhaps understand distant “units of the Universe”. We would like to detail the present-day “lumpiness” of the Cosmos and its evolution from a very smooth “sea” at decoupling. At the nominal redshift of the Cosmic Microwave Background the key fluctuations on reasonable scales are only of order 10^{-5} . Of course at $z \sim 0$ we have a very inhomogeneous distribution of baryons we call galaxies and the Intergalactic Medium (IGM hereafter).

Noting the obvious, studying distant galaxies is synonymous with traveling far back in cosmic time towards the birth of massive sub-structures and large

galaxies. Can we now see directly the development of single galaxies of Milky Way dimensions?

We now believe that most galaxies form and accumulate either (1) by the infall of gas (and dark matter) as “monolithic” entities, self-gravitating by the time we can observe them, or (2) by a series of major and/or minor mergers. This is the now-popular “bottom-up” scenario. Here it is presumably difficult to catch the small and immature systems in the act of merging, depending perhaps on the appropriate dynamical time scales. Thus for scenario (2) we would anticipate young galaxies to illustrate complex morphologies, quite different from those of the mature galactic systems we study readily here and now, at zero redshift. There is indeed some evidence for “recent” mergers from the fine images of distant galaxies observed with the Hubble Space Telescope (HST) - see Stern & Spinrad (1999) for some plausible early merger examples (Fig. 1). And we’d like to push these examples back in cosmic time to even “younger” galaxy growth - but the first problem is, quite naturally, the location of small and dismally faint candidates for galaxies in formation

Another important contemporary research area emerging is the study of intergalactic (gaseous) matter usually seen in silhouette against a bright background source like a QSO or an unusually bright and distant galaxy . And now, new observational techniques are beginning to tell us about the interaction history of galaxies and the IGM (*cf.* Adelberger *et al.* , 2003).

One of this paper’s topics, directly or indirectly stated, is just how early in cosmic epoch (parameterized by redshift) we can study individual galaxies or their “pre-galactic” fragments. There is only a short time interval between the early epochs beyond $z = 3$ (see Figure 2). How can the galaxies evolve so quickly?

The historical view of our empirical and theoretical march outward toward higher redshift has shown a fairly rapid expansion. By 1976 a few radio galaxies had been located and studied at $z > 0.5$. The $z = 1.0$ threshold (for galaxies) was crossed in 1981. Of course Quasars and QSOs had been actively observed and known earlier at large distances - redshifts in the 1960s and 1970s taking us to $z = 2.01$ (Schmidt 1965) and then 2.88, and then to $z = 3.5$ (OQ 172; Baldwin *et al.* , 1974). Finally, $z = 4$ for QSOs was surpassed by the Palomar two-color-based searches (Schneider, Schmidt & Gunn 1991), and searches for Ly α on low-resolution grism spectra (Osmer 1999) were equally successful. Almost all the recent stages of the “QSO- z race” have emphasized red-IR photometry and unusual colors, since the $z \sim 5$ QSOs are heavily depressed by the Ly α forest of the IGM (see Fan *et al.* 2001). The largest published QSO redshift to date is $z = 6.28$ (Fan *et al.* , 2002; Pentericci *et al.* , 2002a).

Now we are witness to the era of a friendly race toward higher and record-breaking galaxy redshifts. The current limit for galaxies, which we shall detail later in this publication, is near $z = 6.5$. Is this redshift close to the end of the “dark ages”, where re-ionization by massive stars and/or early QSOs play as vital sources of ionizing radiation? We return to this topic, with empirical evidence, toward the conclusion of this review.

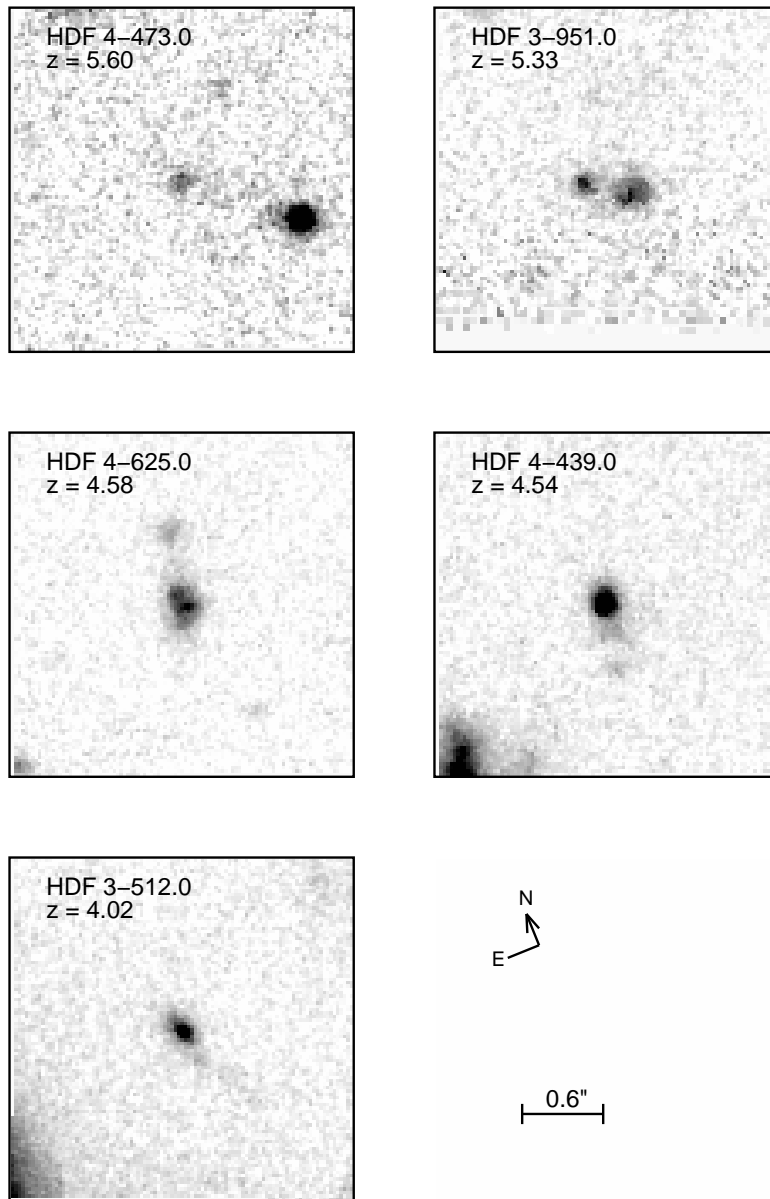


FIGURE 1: HST images of five spectroscopically confirmed galaxies located in the HDF(N). Note the distortions, small tails, and multiple central components - presumably due to mergers. Overall the galaxies are obviously quite small at this stage of their evolution. From Stern & Spinrad (1999)

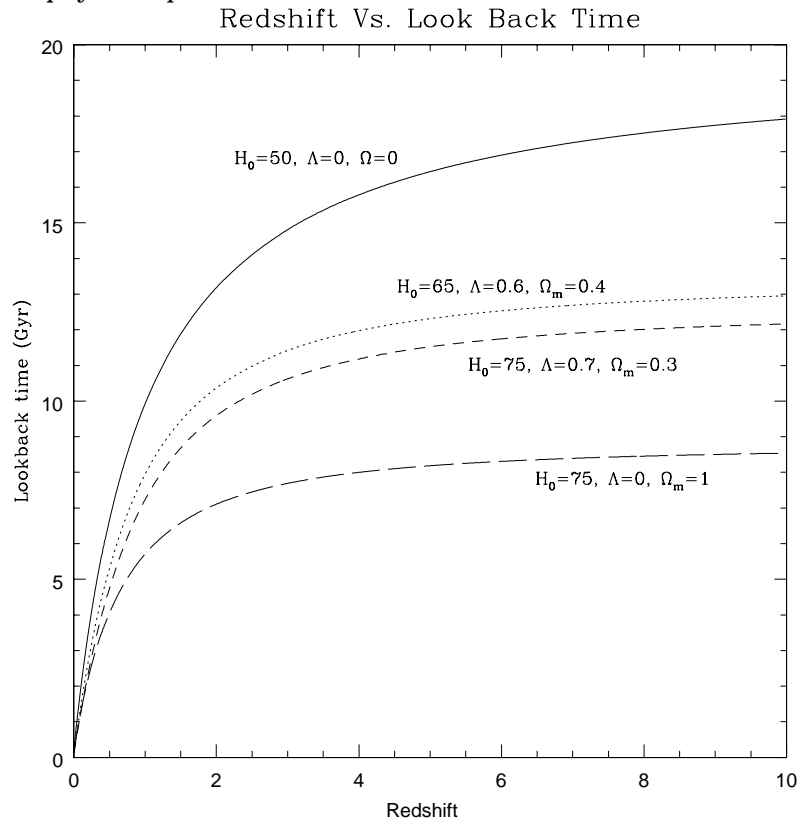


FIGURE 2: A plot of look back time (in Gyrs) versus redshift for three cosmological models. Most might now prefer the short-dashed curve. Note that at high z ($z \gtrsim 3$) the time intervals become quite short. Figure by Curtis Manning

1.2 Some Issues In The Contemporary Theory Of Early Galaxy Evolution

Over the last three or four years, the thoughts of theorists have narrowed on the birth and evolution of galaxies - including dark matter halos, plus the baryons we observe more directly. These adventuresome researchers have bi-modally attacked the problems with a pair of model types. Most contemporary modeling assumes, *ab initio*, the Lambda Cold Dark Matter cosmology (LCDM).

Following Weinberg *et al.*, (1999), we note that the current (broad) theory of galaxy formation and early evolution follows White & Rees (1978) and their “successors” - gravitational collapse of a dark matter halo, gas falling into the potential well so defined, and then gas astrophysics (cooling, contracting, and eventually forming stars in a dense baryonic core). Now we often add inflationary cosmological parameters and thus demand $\Omega_m + \Omega_\Lambda = 1$.

The “technology” for modeling often takes one of two paths. The first is hierar-

chical numerical simulations (with a realistic treatment of the collapse) including additional gas-phase physics and plenty of computational effort to cover the wide size range of non-spherical assemblies (the “roots” of the assembly “tree”) that appear.

The second tool, deemed the semi-analytical approach, assumes again LCDM halos. The proto-galaxies contract within, and then we find small sub-galactic systems (or fragments?) with the specific physically-motivated “stories” given by the strengths of their star-burst mergers. The mergers obviously increase the model masses, and also modify the relative numbers of luminous stars and the amount of residual gas. Even before that step, the semi-analytic models utilize the Press-Schechter (Press & Schechter 1974) formalism to describe the number of halos as a function of their mass. This approach allows conventional and mature use of population synthesis and even chemical evolution schemes in conjunction with the mergers demanded to build up galaxies of reasonable mass with moderate star-formation rates.

One of the strengths of the direct numerical simulations is to utilize the non-spherical distribution of dark matter and baryons to produce a more realistic treatment of the model’s gravitation. Then the more “astrophysical” computations can proceed; Weinberg *et al.*, (1999) predict the surface densities of galaxies as a function of their star-formation rate (SFR) over a relevant range of redshifts.

The semi-analytic models (*cf.* Baugh *et al.* 1999; Somerville & Primak 1999) have now been amplified to include a range of interesting physical processes, hopefully relevant to early galaxy evolution. For example, the central baryons and the outer dark matter (DM) halo interact to change the halo structure and foster further contraction of the model galaxy. Baugh *et al.* (1998) mention that the main constraining property of local galaxies they favor for comparison with semi-analytic modeling is the field galaxy luminosity function. The agreement is good; one can then easily visualize the effect of omitting or including various individual physical processes, like star-formation (SF) feedback.

The SFR in the early Universe (say, to $z = 3$ or 4) of these models is also well-matched by observations of the SFR per unit volume. (Madau *et al.* 1999).

Weinberg *et al.* (1999) also show the numerical simulation’s cumulative distribution of galaxies (with the parameter = surface density/ \square' /unit z) as a function of their SF rate from $z = 10$ to $z = 0.5$. At the moderately large galaxian $\text{SFR} = 10 \text{ M}_{\odot} \text{ yr}^{-1}$ for $z = 5$, the predicted surface density of galaxies is nearly $5/\square'$. This surface density is rather higher (by a factor of ~ 3) than observed by Spinrad and collaborators (although some of this observational statistic is derived from the $\text{Ly}\alpha$ - SFR correlation, which may be suspect). The best unpublished observational estimate for the SFR surface density at $z \sim 5$ is now $2 \pm 1/\square'$. However, this surface density for $\text{Ly}\alpha$ emitters is uncertain because their continua are often very weak and thus not necessarily sampled consistently in terms of galaxy luminosity. The theoretical simulations and follow-up astrophysical scaling may, of course, be systematically over-efficient in, for example, converting cooling gas to massive star births.

The numerical simulations with LCDM may have one flaw: they over-predict

the number of small galaxies near larger ones (which are countable) and thus the number of stars at low redshifts. We are not positive that a real problem exists; it may be that dark halos with coupled non-stellar baryons (*e.g.*, high velocity clouds (Klypin *et al.*, 1999) are being “counted” as observable systems.

The potential problems of early galaxy evolution from the theoretical side may well change, increasing or decreasing as their confrontations with empirical “facts” or new understandings go forward. The general outlines of the theory and relevant observations are probably fairly firm.

1.3 A Race For The Maximum Redshift

It is a very human tendency to climb a celestial mountain. So it stands for any race, including that of finding individual objects at greater and greater distances, abbreviated usually as at larger redshift, or “bigger z ” (where $1+z = \lambda_{\text{observed}}/\lambda_{\text{emitted}}$).

As Stern & Spinrad (1999) pointed out in their Table 1, there has been a fairly rapid increase in “ z_{max} ” for galaxies; we went from $z = 0.20$ in 1956 to $z = 1$ by 1982, but then to $z = 5.3$ in 1998 and $z = 5.7$ in 1999. The record-breaking progress since 1998 has been due to observations of the strong Ly α (from rest $\lambda 1216 \text{ \AA}$) emission line, shifted to the visible and red by the Universal expansion. Over the past year the “LALA” (Large Area Lyman Alpha survey) team (Rhoads *et al.* 2003) have selected Ly α emitters to $z = 5.75$. They are currently taking images for the $z = 6.6$ airglow window. Also in 2002 Hu *et al.* have located a cluster-lensed galaxy at the outstanding redshift of $z = 6.56$! And as these pages are completed, a Subaru group has found a faint Ly α galaxy at $z = 6.578$.

Modern research on quasars (QSOs, to be more precise), has also progressed; Osmer (1999) reviewed the situation 3 years ago, with QSOs located up to $z = 5.0$. Since then, the Sloan Digital Sky Survey has been successfully pushed QSO redshifts to and beyond $z = 6$! The key here is to obtain good red and near IR photometry, in particular looking for objects with very red (I-z) colors. The Sloan results are very current; Fan *et al.* (2002) found SDSS J103027.1 at $z = 6.28$, and a preprint on another Sloan QSO at $z \sim 6.43$ is just available as this section is being written. So the most distant QSO to date still trails the most distant, much fainter normal galaxy by a modest margin!

The distant QSOs are likely buried in a host galaxy which itself is well-hidden in the glare of the Active Galactic Nucleus (AGN). We now assume the presence of the underlying galaxy of stars and gas, in part confirmed indirectly by the normal abundances of the elements inferred from the emission lines in the QSO spectra.

1.4 The Identification Of Very Distant Galaxies

How do we go about locating the faint and distant galaxies at the heart of our exploration and this review?

We found several successful (or partly successful) methods to locate the faint targets at high redshift: none are without “flaws”. For example, some methods are

weakened by “contaminants”, be they intrinsically faint M, L, or T dwarf stars in the galactic disk, or a mis-identified (longer wavelength, smaller redshift) emission line.

Following the theme in the Stern & Spinrad (1999) review, we shall discuss several of the more successful search techniques; initially we’ll review the finding of distant galaxies utilizing non-optical wavelengths. Often these techniques turn out to be “safe” and productive.

1.4.1 Radio-Loud Galaxies

Radio galaxies at high redshift are rare but interesting guides to the location of large, mature galaxies and correlated structures - sometimes actual (rich) clusters (van Breugel *et al.* 1999; Lilly & Longair 1984). For some specific cases, like 4C 41.17 ($z = 3.798$), and also radio sources resembling it, we note that steep radio spectral indices and moderate flux densities correlate with high redshift and great luminosity. Such objects are visible across much of the presently observable Universe.

The stronger radio galaxies, those with fluxes $S_{408} \geq 100$ mJy, tend to follow a good Hubble relationship in the observer’s near-IR bands; that is, their (K,z) magnitude–redshift correlation is linear with only a moderate scatter.

This result shows that the powerful radio galaxies, E systems in morphological appearance, have a fairly strong resemblance to a luminous “standard candle” (van Breugel *et al.* 1999; Best *et al.* 1999). The history of the steep radio spectral index “angle” is reviewed by de Breuck *et al.* (2000). Going for the steepest radio spectral counterparts also tends to minimize the “contamination” by Quasars (radio spectral indices < -1.3).

We then may inquire: are all steep radio sources luminous galaxies and Quasar candidates? The answer here is mainly negative; it is the medium strength (so as not to exceed some limiting intrinsic luminosity) steep spectrum sources, identified at long wavelengths in the optical and IR that have the greatest promise in pointing out very distant spectrographic targets. These may be radio-loud stellar systems at a large redshift, say $z \geq 4$.

Somewhat tangential to our central motivation, we note that at both small and large distances, radio galaxies possess some/many of the characteristics of giant E galaxies (or luminous cluster Es). Since these E galaxies here and now have a strong correlation amplitude at small separations, we can anticipate many of the distant radio Es to also have smaller companions - perhaps in a group population. These earmarks of early structure are going to be valuable; the recent paper of Venemans *et al.* (2002) illustrates a large (2Mpc) overdense region at a redshift $z = 4.1$ located “around” the radio galaxy TNJ1338-1942. So the radio galaxy becomes a valuable marker in such a case. We note another, less well-documented case in the HDF(N) is currently being explored by Stern, Dey, Dawson, and Spinrad. Here the redshift is even greater; the first observed galaxies have $z \simeq 5.2$. No radio source takes part in that overdensity region, however. Stern *et al.* (2003) show a group surrounding the radio galaxy MG0442+0202 at

$z = 1.11$.

The record redshift for a radio galaxy is still $z = 5.19$ (van Breugel *et al.* 1999), with TNJ0924-2201. Several observing groups are concentrating on the identification of deep samples showing a steep spectrum, with the expectation that some are ultra-luminous and located at $z > 5$. These are rare systems; one problem in interpretation is that it should be a fairly slow process to “build” a large and luminous galaxy. Perhaps it requires a cosmic interval in excess of a billion years to do so, either in the model described as a “monolithic collapse” (Eggen, Lynden-Bell & Sandage 1962), or by the accumulation of smaller structures (Searle & Zinn 1978) - a hierarchical model. With the currently popular cosmology [$H_0 = 65$, $\Omega_\lambda = 0.7$, $\Omega_m = 0.3$], the look-back interval between $z = 4$ and (an arbitrary) $z = 20$ is only ~ 1.2 Gyr (see Fig. 2 again). That might be sufficient time to build a large galaxy; the implication is then a SFR of $\sim 80 M_\odot \text{yr}^{-1}$. That is a rarely observed and atypically high SFR. So it is a clue that massive radio galaxies are unlikely to be found at $z > 5$. But the near-IR Hubble Diagram of the highest- z radio galaxies plotted by van Breugel *et al.* (1999) continues to suggest a continuity in galaxy luminosity which we may still extrapolate to stellar (and gaseous) mass similarities.

Under standard CDM-based models of galaxy evolution, we expect the giant elliptical galaxies, which are the hosts of today’s radio galaxies, to form late (at $z \sim 1$) through a process of merging of smaller sub-units. Although these models seem to be consistent with what is known so far about field galaxy evolution (e.g. Barger *et al.* 1999), and indeed with observations of the hosts of the radio-quiet quasar population (Ridgway 2000), it is clear that radio galaxies are an exception. They seem to only show significant evolution at $z > 2$, and still appear to be luminous galaxies at $z \sim 3$ and perhaps beyond. One possible solution is that the most massive galaxies formed first in so-called anti-hierarchical baryonic collapse. In this model (Granato *et al.* 2001) the high baryon densities in the centers of the most massive dark matter halos cause them to start forming stars early. Thus, the fate of simplistic theoretical analyses suggest the need for a sharper observational analysis.

1.4.2 Galaxies With Strong X-ray Emission (Hidden AGNs)

To date many new X-ray galaxies have been located, using modern X-ray satellites such as Chandra and XMM-Newton. However, there are few X-ray-selected very distant galaxies, or AGN. To my knowledge there is one at a redshift in excess of 5; it is #174 in Barger *et al.* (2002) at $z = 5.186$, in the Chandra Deep-Field, North. We will return to this galaxy a bit later. There are, however, a considerable number of QSOs and other clearly noticed AGN at $z > 4$ (cf. Brandt 2002). Why are we physically interested in X-ray galaxies, anyway? As Barger *et al.* (2001) affirm, X-ray surveys, especially at hard (2-7keV) energies, provide a direct indication of an AGN, presumably due to an ultra-massive black hole at the galaxy nucleus. At $\gtrsim 5$ keV, absorption will play less of an obscuring role than seen for some “hidden” AGNs at optical frequencies and soft X-ray energies.

Complete samples of hard X-ray energies are now possible with the Chandra X-ray Observatory; the 1'' X-ray positions produce robust optical identifications of the counterparts. And about half of the sources can be identified with optically bright and “quiet” galaxies; they are at small redshifts.

With the longest integrations (say, one mega-second integrations) we begin to locate the faint X-ray population. Some of these sources are quite distant, $z > 4$ (cf. Barger *et al.* 2002). Their survey of the Chandra Deep-Field, North (equivalent to the HDF(N)) yielded a fair number of more-distant X-ray identifications; Table 1, below, puts them in $\Delta z = 0.5$ bins, and includes both narrow and broad-line (AGN) X-ray sources.

TABLE 1: Large Redshifts in the Chandra X-ray Sources (CDFN)

Δz	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	> 4.5
n	4	4	1	1	1

A quick inspection of Table 1 and 2, and Fig. 3 suggests no dramatic physical change in the co-moving density of X-ray emitting galaxies compared to all field galaxies.

TABLE 2: Photometry of Narrow-Line Sources at High Redshift

Barger (2002) #	z	R	I	Note
174	5.186	24.5	23.1	Ly α , optically luminous
285	4.137	25.7	25.0	Ly α emission
287	2.638	24.4	23.9	weak Ly α
294	2.240	24.1	23.5	weak Ly α

The largest redshift in the securely-identified group we discuss is B174 at $z = 5.186$. This source is associated with a moderately faint optical identification - a bit too faint to classify morphologically. The near-IR I and z band photometry of this $z \sim 5.2$ source suggest its intrinsic luminosity may lie between that of luminous QSOs and an \mathcal{L}^* galaxy; the AGN may be partly hidden, as the spectra of B174 does not display a broad component to its strong Ly α emission line. The other three X-ray galaxies at $z > 2$ appear to be residents in normal-luminosity host galaxies, based upon their photometry. The rough field galaxy correlation between I mag and the galaxy redshift can be seen in Fig. 3.

With the present generation of X-ray satellites and plausible integration times (Mega-secs), we cannot anticipate a large identification content of X-ray (AGN, or even “star-burst”) galaxies beyond $z = 5$. Eventually I would speculate that some sources with fluxes in the 2-8 keV range below $10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ may yield a few very large redshift objects.

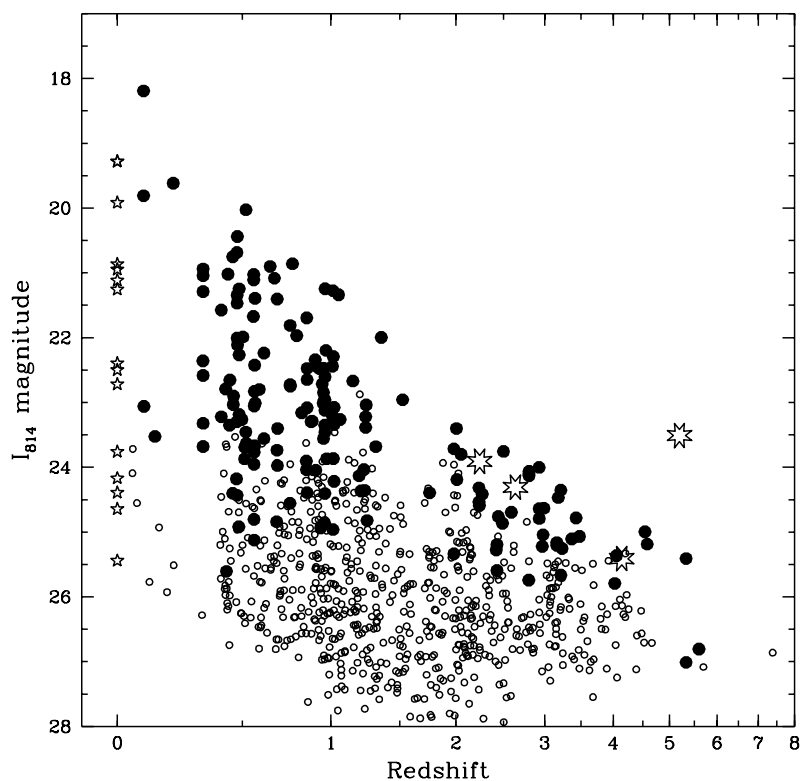


FIGURE 3: I-band (I₈₁₄) AB magnitudes versus redshift in the HDF(N), diagram by Mark Dickinson. The star-symbols at $z = 0$ are Galactic stars; filled circle symbols have spectroscopic redshifts, while the small open circles have photometric redshifts. When spectroscopic redshifts are found, the photometric point is removed. We note that three of the four distant X-ray sources (the large star-symbols) have rather normal (non-AGN?) magnitudes - like the field in general.

1.4.3 Dusty Sub-mm (IR) Galaxies

In recent years it has become evident that a modest number of fairly high redshift galaxies ($z \gtrsim 2$) are most readily recognized as unusual at far-IR or sub-mm wavelengths. Our Earth's atmosphere is a substantial barrier to sub-mm research on galaxies likely to be both very dusty and also have a rapid pace of star formation. That recipe augurs for reddened high IR emission, which we can most readily discover at sub-mm wavelengths. It follows that the most-secure continuum detections are at a wavelength of $850 \mu\text{m}$ (where receivers are fairly efficient, and our atmosphere fairly transparent). The detection system of choice at the moment is called SCUBA, for Submillimeter Common User Bolometer Array. This camera, utilized on the JCMT (James Clerk Maxwell Telescope), has enabled, for the first time, deep and relatively unbiased surveys which may identify the distant dusty galaxies (and/or AGN).

It is important to clarify which galaxies (or AGN) radiate so profusely at IR and sub-mm wavelengths. They *may* be largely responsible for the Far-IR extragalactic background. With the presently available redshifts for securely identified IR/sub-mm galaxies, their integrated energy density may be quite comparable to the integrated optical (emitted UV galaxy light measured in the HDFs) energy (*e.g.*, Genzel *et al.* 2002).

To deal with this global question, and also to understand the limit of SFR in a huge star-burst, reddened or not, the crying need is a reliable set of redshifts.

Blain *et al.* (1999) comment on the reason why many galaxies detected in the sub-mm spectral window are likely to be at high redshift. This is because the long wavelength side of the canonical sub-mm source spectrum has a very steep slope (cf. Blain *et al.* 2002). The steepness of the long-wave side leads to substantial negative K-corrections. That is, the observer's band (850 μm) benefits from a larger redshift moving the emitted and then redshifted peak distribution into that atmospheric window. This effect compensates for the usual geometric dimming of increasing luminosity-distance at higher z . Thus comparing the sub-mm (850 μm) flux with the VLA radio flux (say, near 1.4 GHz) can yield approximate redshifts without an optical spectrum. But they are not individually robust.

Another method of deriving a more precise redshift for a sub-mm galaxy detection is to make good use of the fact that dusty systems occasionally also show strong molecular lines of CO in emission. The transitions in CO are (3-2) or (4-3) for the redshift domain of $z \sim 2.6$ -2.8 (Frayser *et al.* 1998). But only a small minority have yielded CO molecular redshifts to date.

Very recently Chapman *et al.* (2003) have succeeded in obtaining good numbers of optical spectroscopic redshifts for sub-mm galaxies and AGN with precise radio positions. 16 redshifts of quality were obtained; probably one is a quasar. A few others may have some weaker AGN signal. The median redshift for the galaxies is $z = 2.4$, with a maximum redshift of $z = 3.699$. Thus one must extrapolate the 850 μm fluxes down to 1-2mJy in anticipation of future achievements in the $z \geq 5$ domain for sub-mm galaxies. That will surely require new hardware.

One sort of instrument planned for the near future is the APEX antenna (the Atacama [Chile] Pathfinder Experiment). It is a planned 12-m diameter sub-mm telescope at a high, dry site in northern Chile.

Surveys with the APEX should go deeper than the present SCUBA system. And that will be just a taste of what is to come with ALMA (the Atacama Large Millimeter Array). ALMA will be the mm/sub-mm counterpart of the VLT with 64 times the collecting area of APEX! It should make possible IR galaxy detections 100 times fainter than we now do with SCUBA and with good spatial acuity. This great array should lead to many redshifts with molecular CO lines and the [CII]158 μm line.

We end this section with an astrophysical speculation: with the Chapman *et al.* (2003) data we suggest a relatively high space density of very luminous and distant sub-mm ($z > 2$) galaxies. They may be 1000 times the density of similarly IR-luminous local star-bursts found here and now. Hence the detailed study of a few of the powerful IR galaxies will tell us much about young galaxy SF and dust

interactions.

1.4.4 **Gamma-Ray-Bursters**

A new and exciting demonstration of extragalactic “power” has recently emerged with the realization that Gamma-Ray-Bursters (GRBs) are apparently the most powerful cosmic explosions; observing their optical or radio afterglows can give us an indirect glimpse of a distant host galaxy. Not all bursters are successfully tracked for days or weeks after the outburst, but a reasonable fraction do point to distant ($z \gtrsim 1$) star-burst galaxy hosts. So, for this review we note that occasional luminous afterglows may signal the locations of star-forming young galaxies at $z > 4$.

The detailed physics of the situation is unclear, but there are now believable scenarios suggesting that the GRBs originate from the collapse of a massive star or even a stellar merger. So sites of active SF may be one of the “usual suspects”, much as Type II SNe may be sited in young-star-rich locations. With the improved ability to locate GRBs we do find several annual opportunities to follow the afterglows as they decay; occasionally a redshift from an afterglow spectrum rich in UV interstellar lines (shifted to the visible) is obtained. The highest conventional spectroscopic redshift measured to date is $z = 3.42$ (Kulkarni *et al.* 1998).

Because many GRBs are very luminous (for a short time interval) we note that the possibility exists to derive “photo- z ’s” or obtain low-resolution spectra of even more distant GRBs - perhaps with a little help from their galaxy hosts. Indeed Andersen *et al.* (2000) suggest a GRB at $z \sim 4.5$ from the afterglow’s broad-band colors. At higher redshifts we will need photometry and/or spectroscopy in the near-IR. The J-band at $\lambda \sim 1.2 \mu\text{m}$ will take the strong spectral discontinuity anticipated at Ly α (1216 Å, rest) to $z \sim 9!$ Of course our present abilities to obtain good S/N infrared spectra would be taxed by all but the earliest bright GRB afterglows; spectroscopy in the first minutes may be needed!

1.4.5 **Optical Selections of Distant Galaxies: “Photo- z ’s” and Ly α Emission Lines**

The case for the use of photometric redshifts – that is, redshifts based upon colors in 2 or (likely) more wave bands – has gradually strengthened since the mid-1990s. Most critically, we now expect fair precision from photometric redshifts and few catastrophic failures.

Stern & Spinrad (1999) compare spectroscopic and photometric redshifts in the HDF. The photometric redshifts are from the Stony Brook group (Fernandez-Soto, Lanzetta & Yahil 1999), and are determined by fitting the observed galaxy colors (long wavelengths only for really distant candidates) with redshifted spectral templates. These templates may be empirical, synthetic, or a hybrid. A second approach (Connolly *et al.* 1995) is purely empirical - having already a relationship between previously-observed galaxy redshifts and the observed total magnitudes (m) with color information (C) to boot. Then a derived redshift can be found from the multi-dimensional (m,C) pairs, used for training. More detail on these “tem-

plate fits” can be found in the Stern and Spinrad review. Comparisons between photometric and spectroscopic determination in the HDF yield residuals typically around 0.1 for Δz at almost all redshifts.

Naturally the most important usage of such photometric redshifts is at very faint levels ($m > 26.5$). These numerous faint galaxies are well beyond the capabilities of 10-m class telescopes for spectroscopic redshifts. The danger here is that galaxies marginally detected in the red-optical I,z bands and perhaps also in J, H, K [1.2, 1.6, 2.2 μ m] can feign very large redshifts if their signal is just a noise incursion at I or z bands, slightly below the 1 μ m observational limit of silicon-based CCDs. Since this topic is close to the kernel of this review, we note that Lanzetta *et al.* (1999) give some examples of faint, red photometric-z cases of difficult S/N. Their redshifts could exceed 6. Almost all of these ambiguous but potentially exciting cases have yet to be resolved. I speculate that better IR photometry (perhaps using the rejuvenated NICMOS camera on HST) would help in resolving that situation and perhaps suggest targets for future generations of near-IR spectrographs.

There is also a systematic problem at some level with color/redshift degeneracies; blue galaxies in general may show similar colors over a substantial intermediate z range. Prior information like the galaxy apparent magnitude can help decisively. This “Bayesian” procedure is illustrated by Benitez & Broadhurst (1999) for the HDF(N).

My personal recent experience with “I-drops” (implying a galaxy with only detectable flux at wavelengths above the I band, $\lambda \geq 8500 \text{ \AA}$ at the red edge) is that many of the spectroscopic candidates (15 to 20 targets per slitmask) are very difficult due to their faintness ($z \sim 25$ -26 mag) at longer wavelengths. A few also turn out to be low-luminosity galactic stars; these late M, L, and T class dwarfs turn up rather frequently. Since many of the candidates come from ground-based imaging, their image structure is not a very discriminating way to separate stars from QSOs from galaxies.

Most of the I-drops show a marginally detected red-color continuum, and thus add little to our initial appraisal. It turns out that approximately a quarter of the I-drops do eventually yield a redshift; about a third of these with the continuum discontinuity at Ly α (λ_0 1216 - the Ly α “forest”). Two-thirds of the spectroscopically detected I-drop systems (with eventual redshifts) have a noticeable to strong Ly α emission line. That usually yields an unambiguous redshift, as the reader can see with the illustrations in Weymann *et al.* (1998) and Fig. 4, here, by Spinrad, Stern, Dawson, Filippenko, and the GOODS team ($z = 5.83$).

The pairing of a red continuum color, a continuum discontinuity, and a fairly strong emission line usually signifies a robust Ly α redshift. The multiple-criteria spectroscopic technique has been successful to at least $z = 5.8$ and probably to $z = 6.57$. It should eventually be pushed to $z \sim 9$ with the Ly α line at (rest) 1216 \AA , right in the middle of the conventional near-IR J-band. Right now that is too technically difficult.

As these pages were being written, two preprints crossed our desk. In the first, Lehnert & Bremer (2003) discovered 6 galaxies at $4.8 \leq z \leq 5.8$. These

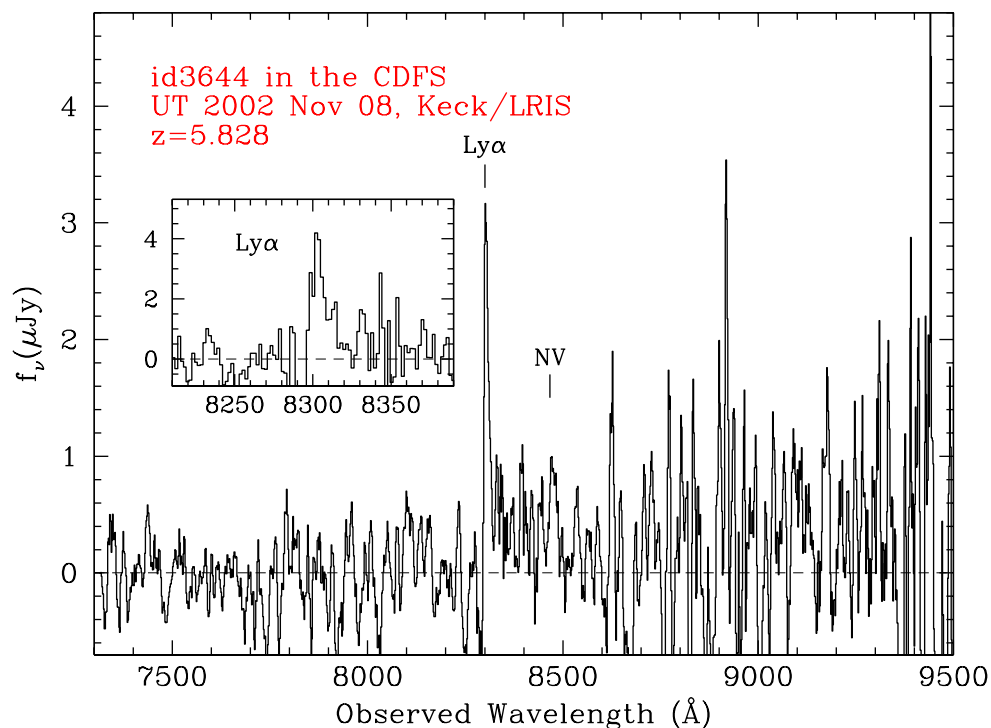


FIGURE 4: A recent Keck spectrogram of a color-selected (I-drop) faint galaxy. The strong Ly α emission line indicates a redshift $z = 5.83$. Also note the continuum discontinuity. The “spectral teams” were led by Spinrad and Filippenko, with reductions by Daniel Stern and Steve Dawson. This galaxy was originally selected by Mark Dickinson and the GOODS team.

galaxies were selected as photometric “R-drops”- that is, with little flux in the R-band and a flat spectrum at longer wavelengths. Follow-up spectroscopy with the VLT yielded accurate redshifts for these 6, with fairly strong Ly α emission. Their largest redshift was $z = 5.869$ (see Table 3 in §1.4.7).

The second very timely contribution, by Kodaira *et al.* (2003) (a Subaru telescope team), used deep narrow-band near-IR images to locate potentially very distant Ly α galaxies. The group also obtained a few spectra which lead to two fairly certain identifications. One line, with a symmetric line shape, is assumed to be Ly α and in the other case it appears to be satisfactorily asymmetric, hence reliably Ly α (see §1.4.6 for discussion of this point). The best spectrum is of SDFJ 132418.3 at $z = 6.578$. That would make this Ly α galaxy the largest redshift of any individual system measured to date. The redshift is only slightly greater than that of HCM 6 A ($z = 6.56$) by Hu *et al.* (2002), and Hu, Cowie & McMahon (2002).

These very contemporary detections of galaxies beyond the “QSO-limit” of

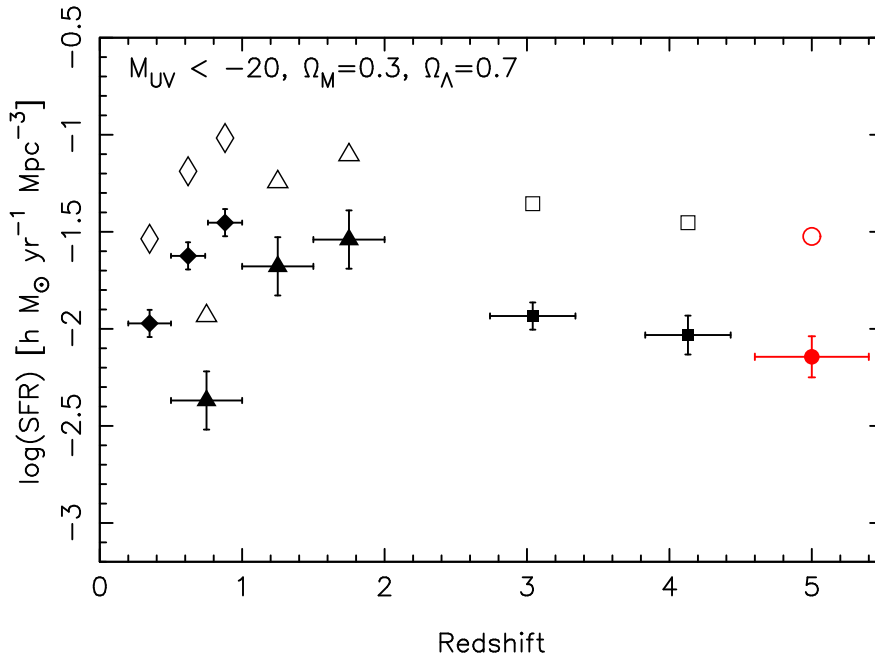


FIGURE 5: Star-formation rate density as a function of redshift based on the UV-luminosity function with a magnitude limit $M_{UV} < -20$. Triangles and diamonds are from Connolly *et al.* (1997) and Lilly *et al.* (1996), respectively. Squares represent data from Steidel *et al.* (1999) at $\langle z \rangle \sim 3$ and 4. The circle is the data of Iwata *et al.* (2003) at $z = 5$. Filled symbols indicate values without correction for dust extinction. Dust extinction was corrected following the prescription of Calzetti *et al.* (2000) with $E(B - V) = 0.15$ for all data points. Dust-corrected values are denoted by open symbols. Plot courtesy of I. Iwata.

$z = 6.4$ show us that UV emission from galaxies is still present at the “tail” of the “dark ages”. A future space-desideratum will be the galaxy morphology *in* the $\text{Ly}\alpha$ line. We are interested in any extended neutral gas about the galaxy – via the scattered $\text{Ly}\alpha$ emission from the central ionizing region (Haiman 2002 and references therein).

When the luminosity function of $\text{Ly}\alpha$ emitters is extended to $z \sim 6.5$ (fainter galaxies have to be included) we should be able to extend the SFR density to that great distance. A sample of the near-constancy of the SFR density from $z \sim 2$ to $z \sim 5$ is illustrated in Fig 5 (from Iwata *et al.* 2003). The galaxies going into the computation of the SFR density are photometrically selected, using the top of the UV-luminosity function ($M_{UV} - 5 \log h < -20$). Interestingly, an attempt by D. Stern and the author to utilize serendipitously discovered $\text{Ly}\alpha$ emitters at $z \sim 5$ yields a SFR density slightly higher than that of the $z \sim 5$ Iwata point in Fig. 5 (with considerable uncertainty). We view this as a possible coincidence, as these two methodologies may be sampling different populations. It is somewhat

surprising that the relatively slight decline of the SFR density, noted by Iwata *et al.* (2003) should be maintained to $z \sim 5$. At that redshift the detected objects are effectively sub-galactic in size and probably rather modest in mass. At least temporarily, their M/L ratios must be quite low. Will that be true of most small sub-galactic systems?

1.4.6 Details on the Ly α Emission Line in Very Distant Galaxies

The classic proposal by Partridge & Peebles (1967) that the Ly α emission line might carry a fair fraction of the escaping bolometric luminosity of a young-star-rich galaxy is now testable. The review by Pritchett (1994) is also strongly recommended. Of course these early predictions did not reflect the possible presence of dust. Since the 1990s various searches have been initiated for Ly α -emitting galaxies at large redshifts. Initially all of these searches led to negative results (eg, Thompson & Djorgovski 1995).

However, deeper photometric and spectroscopic searches of the last 6-7 years have yielded a modest number of “safe” Ly α emitters - often (at the largest z 's) the line being the only measurable spectral feature. The peak flux from a distant Ly α emission line galaxy can often exceed the (redward) continuum level by a factor greater than 10! Of course the line from a faint system still has to compete with the strong telluric sky emission bands of OH and O₂. Space-spectra won't deal with such a bright near-IR sky, and that will be advantageous.

Successful Ly α searches include Cowie *et al.* (1998); Hu *et al.* (1998), Pascarelle *et al.* (1998), Hu *et al.* (1999), Steidel *et al.* (2000), Kudritski *et al.* (2000), Fynbo, Möller, and Thomsen, (2001).

There are three modes of Ly α detection used with success in the past few years. They are narrow-band photometric excesses at fixed wavelengths (redshifts), a Ly α forest (Lyman breaks in the continua) plus emission at the line, and serendipitous or fortuitous detections on multi-slit spectrograms. The issues we may face for each/all of the sub-types include the emission line strength and shape, the luminosity function of Ly α emitters (and their surface densities), the effect of widespread neutral gas and dust, and the termination of the “dark ages” before or during the re-ionization epoch. Many of these topics have been addressed recently by Stern & Spinrad (1999); Rhoads *et al.* (2003); Ellis *et al.* (2001); Hu *et al.* (1999); Hu *et al.* (2002a), and in a predictive manner by Stiavelli (2002).

I suggest a few specific points where new observations and interpretations may be of substantial interest. For example, we'd like to confirm or deny that strong emission line Ly α galaxies ($z \geq 4$) obey the same luminosity function distribution as do photometrically selected Lyman break systems at $z = 3$ and $z = 4$ (*cf.* Steidel *et al.* 1999; Giavalisco 2002).

The difficulty in a present-sample comparison between Lyman break galaxies and Ly α emitters is that (at high luminosities, at least) only a modest fraction of Lyman break (continuum selected) galaxies have strong Ly α emission lines ($W_0 > 20 \text{ \AA}$, say). Among the Ly α -emitting systems (narrow-band or serendipitous detections) many candidates have very faint continua and would be missed in

normal broad-band photometry. This latter bias is stressed by Fynbo *et al.* (2001). Indeed, Rhoads *et al.* (2003) found that if they summarized the line/continuum ratio in Ly α galaxies, the equivalent widths occasionally “rose” to $W_\lambda^0 \geq 1000$ Å but more frequently to 190 Å. 60% of the Ly α emitters studied by Malhotra & Rhoads (2002) had observed equivalent widths (hereafter EW) > 240 Å. For Ly-break systems, Shapley *et al.* (2001) find their 60th-percentile line to be a marginally-detectable 20 Å EW. The Shapley galaxies are at a slightly lower redshift; that difference is not critical.

If the above trend of lower-continuum-luminosity galaxies ($z > 4$) having stronger Ly α -emission were to continue, we might diagnose this systematic as a trend toward lower metallicities for lower masses. But there are other possibilities; the Ly α -emission line may as easily depend upon physical outflows (galactic winds), which in turn could have some total mass-dependence (or merger timing).

To get some idea as to the evolution of the luminosity function of young galaxies, we can compare the surface densities of distant galaxies. Pritchet (1994) made a first approximation to this. We utilize the Steidel *et al.* (1999) luminosity function zero point, and the “predictions” by Lanzetta *et al.* (1999) and Stern & Spinrad (1999) for a constant (with z) luminosity function. The cumulative surface density of identified $z \geq 4.5$ galaxies in the HDF(N) is about $1.5/\square'$. These galaxies constitute a sample of continuum galaxies (photo-zs) and emission line galaxies with $I_{814} \leq 26.5$. This is very close to the “prediction” of the Lanzetta (unevolved) surface density (also see Ouchi *et al.* 2002).

The Lanzetta (1999) surface density curves do suggest a drop in the faint galaxy surface densities for the extreme case, $z \geq 6$; that is not surprising at about $I_{814} = 26$. Still at slightly fainter magnitude levels a measure of the $z \geq 6.0$ density by broad-band/narrow-band photometry may be a viable check on the luminosity function zero point and its shape (Lehnert & Bremer 2003).

What is the best physical interpretation of the very large EWs of Ly α often measured for galaxies at $z > 3$?

The Ly α -emitting galaxies with line EW in excess of 200 Å (rest-frame) (Malhotra & Rhoads 2002) are difficult to explain with a conventional O-B star mass function and ionizing spectra that are similar to those anticipated in extant solar-abundance models. The models rarely (and temporally) exhibit $W_\lambda^0 \geq 150$ Å (*e.g.*, Charlot & Fall 1993). To decrease the observed Ly α EW would be easy; as the dominant resonance line it is scattered frequently, and the resulting “random spatial walk” at the center of this line, coupled by small amounts of dust, can easily and drastically reduce the emission measure. It would, of course, also depend on the geometry.

To obtain a higher EW and/or higher flux in Ly α , one can call upon three scenarios:

(a) A “tilted” mass function, with more O stars than found in local HII regions, as an *ad hoc* premise.

(b) We can also reduce the heavy element abundances in our models, and this allows an increase in the number of ionizing photons per O star. A recent paper by Schaerer (2003) considers the temporal evolution of the Ly α line from

model stellar populations ranging down from solar metal-abundances to very low metallicities (below the abundance level of the most metal-poor stars and gas in relatively nearby star-forming systems). We amplify this discussion below.

(c) Finally, sometimes a strong Ly α emission line is the signature of an AGN. However, “real” AGN spectra, from QSOs down to modest-luminosity accretions, usually produce a broader Ly α emission line ($\Delta v \geq 1000 \text{ km s}^{-1}$) than seen in normal galaxies ($\Delta v \sim 500 \text{ km s}^{-1}$). They usually, but not always, also show C IV (moderately broad) 1549 Å. So most of the narrow-line Ly α galaxies must have a line powered by the UV flux from OB stars. This is confirmed by the lack of hard X-ray flux in LALA galaxies at $z \simeq 4.5$ (Malhotra *et al.* 2003), indicating they are not obscured AGN.

The previously-mentioned Schaerer paper (Schaerer 2003) predicts EW of $\sim 240\text{-}350 \text{ \AA}$ for metallicities down to $Z = 4 \times 10^{-4}$ (down from solar by a factor of ~ 50 times). Stiavelli (2002) shows even larger EW for Ly α in metal-poor OB stars. Conceivably the initial stellar mass function (IMF) could also vary and be itself slanted toward higher masses because of the lower abundances. So the pairing of low abundance and a structure favoring massive O stars might allow EW to match most of the Ly α galaxies selected by Malhotra & Rhoads (2002) and by Rhoads *et al.* (2003). An almost-practical spectroscopic test of this idea can be made by examining the UV HeII transition at $\lambda_0 1640 \text{ \AA}$. This line is much weaker than Ly α in star-forming populations - with EW $\sim 5 \text{ \AA}$ anticipated at low abundances of the metals. At higher abundances (near solar) it will be even weaker. Thus higher S/N spectrograms will be required in practice to use this He II feature in Ly α “test galaxies”.

The shape of the Ly α emission line in distant star-forming galaxies is peculiar and may turn out to be an interesting guide to the circumgalactic medium as well as to galaxian winds or sporadic outflows.

The asymmetry of the Ly α line has been noted by Kunth *et al.* (1998) and Pettini *et al.* (2001); it is also mentioned by Stern & Spinrad (1999). We have utilized the broad red wing of the Ly α line and its sharp ISM/IGM cutoff on the blue side as a secondary criterion for assuming a single strong emission line is to be identified as Ly α . This is opposed to the profile of the [O II]]3727 doublet – unresolved in most lower-spectral-purity observations of faint objects. Recent work by E. Landes, S. Dawson, and the author has compared a spectral asymmetry index (a lambda-space ratio) for ten strong Ly α emission lines; this particular index is small for a symmetric line and large for a red winged emission. Out of a sample of seven medium-resolution spectra of galaxies with a “solid” [O II] identification ($z = 1.0$) the asymmetry index averages 0.9 ± 0.1 , while the 10 bonafide Ly α galaxies, with $\langle z \rangle \approx 4$ display a larger range of index, from 1.0 to 2.3, with none less than unity. Seven of the Ly α systems are clearly asymmetric with a noticeable red wing (see Fig. 6).

The Ly α line is usually steeply declining on its blue side; we’ll soon come back to this observation. So deciding whether an emission line is [O II] at a modest z or Ly α at a large z , can often be helped by measuring the asymmetry. Of course a Ly α (bigger redshift) decision based upon a large line asymmetry index becomes

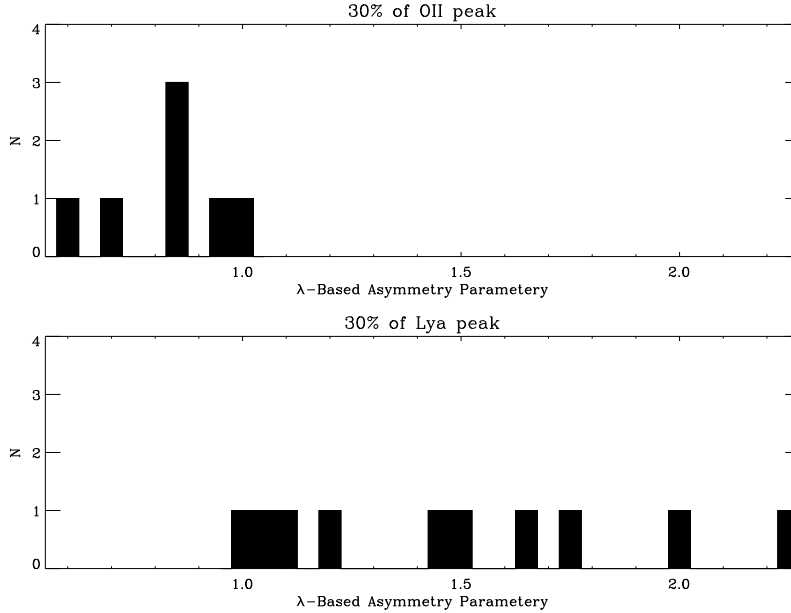


FIGURE 6: The $\text{Ly}\alpha$ emission line asymmetry index, applied to [O II] emitters (upper panel) and to $\text{Ly}\alpha$ lines (lower panel). The line wavelength asymmetry is defined at 30% of the line peak; an index over unity implies a stronger red wing to the line profile. Most but not all of the strong $\text{Ly}\alpha$ line emitters show an asymmetric red wing, with an index ≥ 1.5 . The $\text{Ly}\alpha$ galaxies range in redshift from $z = 3$ to $z = 5.3$. Figure and reductions by Emily Landes.

a sufficient, but not necessary condition for claiming the $\text{Ly}\alpha$ identification.

The astrophysics behind the red wing of $\text{Ly}\alpha$ has been well expounded by Tenorio-Tagle *et al.* (1999), Ahn, Lee & Lee (2002), and Dawson *et al.* (2002). The scenario here is a mini-galaxy scale outflow of neutral and partly ionized matter; the blueward velocity component being absorbed by external and expanding neutral H gas between us and the outflow. The backscattered component can be sufficiently redshifted off of the receding wind, and hence avoid immediate absorption. This will impose a broadened red wing to the $\text{Ly}\alpha$ line.

On the blue side of $\text{Ly}\alpha$ we have a rapid decrease in intensity, a very sharp cutoff to the galaxy emission line at a slightly smaller redshift. The actual galaxy systemic velocity is likely to be near but blueward of the line peak, rather than its bisector at about half of maximum intensity.

In any case the $\text{Ly}\alpha$ H absorption can take place in neutral circumgalactic gas, and in putative cluster gas, and also, at slightly lower redshift, neutral H clouds in the IGM - the well-studied $\text{Ly}\alpha$ forest.

One interesting semi-quantitative aspect of the blue side cutoff is the difference we have noticed between the blue edge of Ly α in QSO spectra and that of the normal distant galaxies, highlighted in this review (see Fig. 7). A new type of “proximity effect” seems in place, in the sense that the galaxy Ly α profile on the short wavelength side is extremely steep, going from the line peak to near zero intensity in $\Delta v_1 = 100 \text{ km s}^{-1}$, on our few echelle (higher spectral resolution) observations of the brightest distant systems (in their Ly α line). The profile on the blue side of the strong emission line in QSO spectra (also $z > 4$) is moderately steep, but has a typical $\Delta v_2 \approx 800 \text{ km s}^{-1}$, but often $> 1000 \text{ km s}^{-1}$.

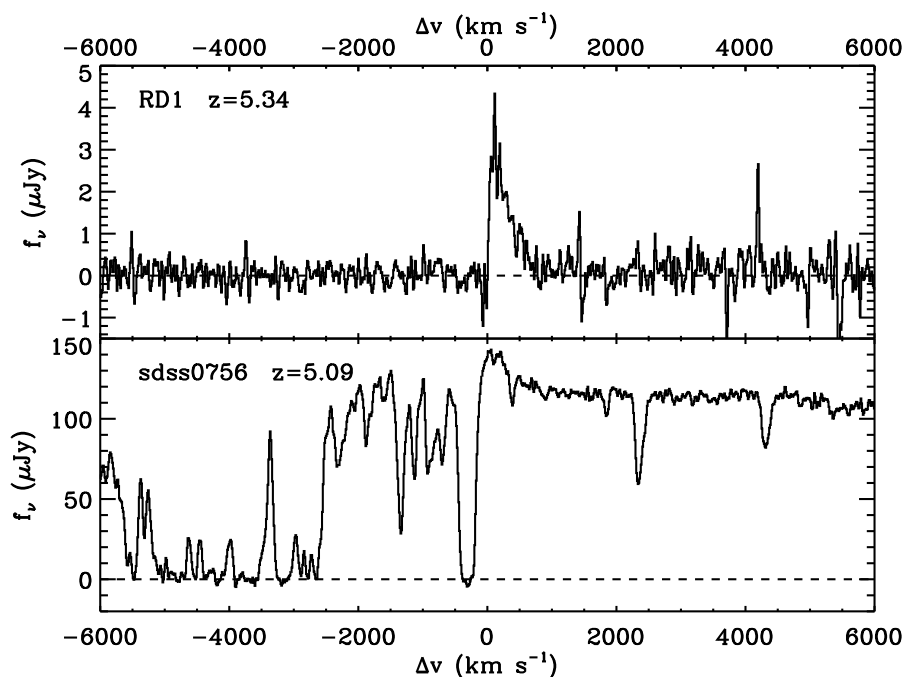


FIGURE 7: The steepness of the ultraviolet side of the Ly α emission line in a QSO ($z = 5.09$) and a faint galaxy, RD1 ($z = 5.34$, Dey *et al.* 1998). The very sharp and rapid decline of the blue side in the distant galaxy may be indicative of nearby (surrounding?) neutral gas. On the other hand, the QSO presumably ionizes much of any circumgalactic H originally present (with a small Δv) Thus the QSO line and continua are detectable to $\Delta v_2 \simeq 2500 \text{ km s}^{-1}$. Reductions and Figure by S. Dawson.

Our interpretation of this systematic difference between UV-luminous QSOs and UV-fainter galaxies is straightforward. In proximity to the luminous ultraviolet radiation field of the QSOs H is very thoroughly ionized and thus doesn't absorb Ly α photons at small Δv . On the other hand, a galaxy's UV ionizing radiation may not escape (or fully escape - see Dawson *et al.* 2002). Thus the rapid decline on the blue side of Ly α may simply augur the existence of neutral gas in the circumgalactic environment near the galaxy. The effect may increase with

redshift, but this is not yet well documented. This trend is potentially of interest in our present and future attempts to document the degree of IGM ionization near active objects and also on a diffuse, larger scale. Our coverage in redshift implies that we are looking back close to the re-ionization redshift, between $z = 6$ and $z = 20$, apparently.

1.4.7 Current Redshift Record Breakers With Ly α Emission or Absorption Breaks

In Table 3 we list published or otherwise secure “record redshifts” for galaxies; most have prominent Ly α emission lines or at least a strong Ly α forest absorption.

We note that since 1999 astronomers have added at least 25 galaxies with $z \geq 5$. This is an impressive and useful score; however, a more physical analysis of several aspects of the pioneering effort is now an obvious and desired second approach. Also, the morphologies of the continuum and Ly α lines may provide useful information on the environs of very early galactic systems. The cut-off date for entries in Table 8.3 was 2003 February.

1.5 The Future

Wide-field narrow-band and broad-band imaging with large ground-based telescopes have considerable promise. Narrow-band and broad-spectral-band studies of the sky areas already earmarked for multi-wave observation is one useful approach. It is already been successful in the Hubble Deep Fields. Such imaging photometry has already turned up distant galaxies, especially at $z = 5.7$ and $z = 6.6$ (airglow windows for narrow-band studies). We know of several groups planning to search for Ly α emitters at the highest redshifts available to CCD detectors ($\lambda \approx 9200 \text{ \AA}$; $z_\alpha = 6.6$). A more ambitious plan would be to utilize IR detectors at the best (OH-band-free) sky windows in J band ($\lambda \approx 12,000 \text{ \AA}$; $z = 9$). Exploration of the interval $6.6 \leq z \leq 9$ should bring us to the edge of the re-ionization epoch where the first stars and quasars began to ionize (again) the halos around collections of dark matter and baryons. A schematic cartoon (Pentericci *et al.* 2002b) is shown by Loeb & Barkana (2001). Is it realistic? We’ll hope that very distant galaxy images and spectra will tell us about very early star formation at the end of the long “dark age”. At this time it is uncertain as to whether the first luminous and ionizing objects were star-forming galaxies! But something or some process began star-formation through the darkness and led to the formation of young stars and young galaxies. We may soon barely detect these faint “first galaxies” with our telescopes and intellects.

1.6 Acknowledgments

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TABLE 3: Census of Galaxies Confirmed at $z \gtrsim 5$

z	Source	Reference	NB	LBG	ser	other	lens
6.578	SDFJ 132418.3	Kodaira et al.	x				
6.56	HCM 6A	Hu et al.	x				x
6.541	SDFJ 132415.7	Kodaira et al.	x				
5.869	BDF1:19	Lehnert and Bremer		x			
5.83	CDFS 5144	GOODS		x			
5.783	CDFS SBM03#3	Bunker et al. 2003		x			
5.746	LALA5 1-03	Rhoads et al.	x				
5.744	BDF1:10	Lehnert and Bremer		x			
5.74	SSA22-HCMI	Hu et al.	x				x
5.700	LALA5 1-06	Rhoads et al.	x				
5.69	LAE J1044-0130	Ajiki et al. 2002	x				
5.674	LALA5 1-5	Rhoads et al. 2002	x				
5.655	LAE J1044-0123	Taniguchi et al.	x				
5.649	BDF2:19	Lehnert and Bremer		x			
5.631	HDF 36246-1511	Dawson et al. 2001			x		
5.621	Lynx R-drop	Stern et al. in prep		x			x
5.60	HDF 4-473	Weymann et al. 1998		x			
5.576	Abell 2218 lens	Ellis et al. 2001			x		x
5.46	NDFWS R-drop	Dey et al., in prep.		x			
5.34	HDF 3-951.0	Spinrad et al. 1998		x			
5.34	RD1	Dey et al. 1998			x		
5.190	HDF 36246-1511	Dawson et al. 2001			x		
5.19	TN J0924-2201	van Breugel et al. 1999				x	
5.19	ES1	Dawson et al. 2001			x		
5.186	HDF 36246-1511	Barger et al. 2002				x	
5.12	A1689 lens	Frye et al. 2002		x			x
5.056	BDF1:26	Lehnert et al. 2002		x			
5.018	BDF1:18	Lehnert et al. 2002		x			
4.99	Cetus R-drop	Stern et al. in prep		x			

Notes on the initial discovery techniques – NB = narrow-band selected; LBG = continuum Lyman-break/Lyman-forest break selected; ser = serendipitously identified; other = selected in other manner (e.g., radio-selected, X-ray selected); lens = known gravitational lens.

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