

Spectroscopy of $z > 3$ Lyman–limit Galaxies

Hyron Spinrad[†]

Arjun Dey[‡]

Daniel Stern[†] & Andrew Bunker[†]

[†]Department of Astronomy, University of California, Berkeley

[‡]NOAO/KPNO, 915 N. Cherry Ave., Tucson AZ 85726

Abstract

We discuss the spectral character of Lyman–limit–selected, star-forming galaxies at $z > 3$. The rest–frame UV spectra of these faint galaxies may show Ly α in either absorption or emission, probably depending upon their local ISM content and geometry. Other UV interstellar resonance absorption lines show considerable variation in strength, likely related to differences in the galactic metal abundances.

We present initial results on B –drop galaxies, generally at $z \sim 4$. Our low–resolution spectrograms show no measurable flux below the redshifted Lyman limit (912 Å). Thus, it is likely that normal, star-forming galaxies at early cosmic epochs did not significantly contribute to the metagalactic ionizing radiation field.

1 Introduction

While not the “main characters” in the Academy colloquium, actively starforming galaxies are now routinely discovered and made available for study through color–selection. U – and B –dropouts, galaxies targeted for the redshifted Lyman–limit spectral discontinuity at 912 Å in the U – and B –bands, are important in the early Universe because of their ubiquity (*c.f.* Steidel *et al.* 1996a,b). The U –drops are several percent of the total deep number counts at $R \sim 24^m$ (corresponding to $B \sim 25^m$), with an absolute surface density of ~ 3 galaxies per square arcminute on the sky. Moderate power radio sources are far less numerous, with surface densities of $\sim 2 \times 10^{-3}$ radio sources per square arcminute at $S_{1.4 \text{ GHz}} = 10 \text{ mJy}$.

In an informal collaboration with C. Steidel and M. Pettini, we have pursued moderate resolution observations of the brightest ($R \sim 23^m$) $z \sim 3$ star-forming galaxies discovered by Steidel and collaborators (*e.g.*, Steidel & Hamilton 1992; Steidel *et al.* 1996a). Typical sources are at $z \sim 3$ and require long integrations at Keck with the LRIS spectrograph. For the fainter and (usually) more distant B -drop galaxies ($z \sim 4$), lower spectral resolution observations are obtained. This work is part of an ongoing effort to study ‘normal’, *i.e.*, non-AGN, young galaxies at the earliest cosmic epochs.

2 Spectral Character of Lyman-Limit Galaxies

The spectral character spanned by our current U -drop sample is illustrated in Figure 1. The galaxy spectra have been aligned in their rest frames, so that the rather large range in emission and absorption strengths is easily visible. In particular, note the bimodal Ly α morphology, the variation in strength of the P-Cygni line profiles due to O-star winds (*e.g.* C iv $\lambda\lambda$ 1548, 1551 Å; Si iv $\lambda\lambda$ 1394, 1403 Å), and the variation of the primarily interstellar lines such as Si ii λ 1260 Å, O i λ 1302 Å, C ii λ 1335 Å, Fe ii λ 1608 Å, and Al ii λ 1670 Å (see Table 1).

To be more specific, note that Ly α emission is strong and slightly asymmetric with a broader red wing in HDF FF D16 (from the HDF flanking field) and Q 0000 D6 (from a quasar field, Steidel & Hamilton 1992), while Ly α is a broad absorption feature in CB58 (the lensed galaxy behind the cluster MS 1512+36, Yee *et al.* 1996) and HDF 4-555.1 (the hotdog-shaped galaxy in the HDF; Bunker *et al.* 1998).

A trend is also visible in the growth of the stellar, stellar-wind, and the ISM absorptions as one proceeds down the Figure 1 spectra from HDF FF D16 to CB58. The strength of the metallic ISM absorptions correlates with Ly α absorption and anti-correlates with Ly α emission, though the general shape of the local UV continuum over $\lambda\lambda$ 1240 – 1600 Å suggests that the galaxies considered here all have an ample supply of ionizing photons. A simple scenario with a smooth distribution of cold, neutral gas and a moderate or increasing metal abundance level as one goes down Figure 1 toward CB58 would be consistent with our spectra.

The spectra of some distant star-forming galaxies, such as HDF FF D16 and the mean HDF U -dropout spectrum of Lowenthal *et al.* (1997) show weak P-Cygni and ISM lines suggestive of low metal abundance, perhaps even below that of the O-stars in the SMC (near $1/5^{\text{th}}$ solar from UV spectra; Walborn *et al.* 1995, Haser *et al.* 1998). Stellar winds, ISM, and the few weak photospheric

Table 1. UV Spectral Lines from Star-forming Galaxies at $z > 3$.

Emission from the Gas	Interstellar Absorptions
Ly α λ 1216Å	Ly β λ 1025Å
HeII λ 1640Å	Ly α λ 1216Å(damped?)
CIII] λ 1909Å	SiII λ 1260Å
	OI λ 1302Å
	CII λ 1335Å
	SiIV $\lambda\lambda$ 1394,1403Å
	SiII λ 1526Å
	CIV $\lambda\lambda$ 1549Å
	FeII λ 1608Å
	AlII λ 1670Å

P-Cygni Wind Lines	Photospheric Lines
NV λ 1240Å	CIII λ 1175Å
SiII λ 1260Å	SiIII λ 1417Å
OI λ 1302Å	CIII λ 1427Å
CII λ 1335Å	SV λ 1502Å
SiIV $\lambda\lambda$ 1394,1403Å	
SiII λ 1526Å	
CIV $\lambda\lambda$ 1549Å	

absorption lines are relatively strong, however, in HDF 4-555.1 and CB58, implying an abundance level near solar for these two galaxies at $z \sim 2.8$, though abundances estimated from saturated lines should of course be treated with caution.

The presence of weak but definite P-Cygni line profiles of the nominal ISM absorptions from low-ionization species such as O I λ 1302 Å and C II λ 1335 Å is surprising: O-stars in the Galaxy and the Magellanic clouds do not show P-Cygni profiles for their low-ionization resonance lines, nor are these features seen in the few high-quality HST spectra of nearby star-burst galaxies (*c.f.* Heckman & Leitherer 1997). One speculative idea we may offer is that these lines may be caused by the onset of a “galactic superwind” in young systems with extreme star-formation rates, *i.e.*, $> 10 M_{\odot} \text{ yr}^{-1}$ (for a low-density open

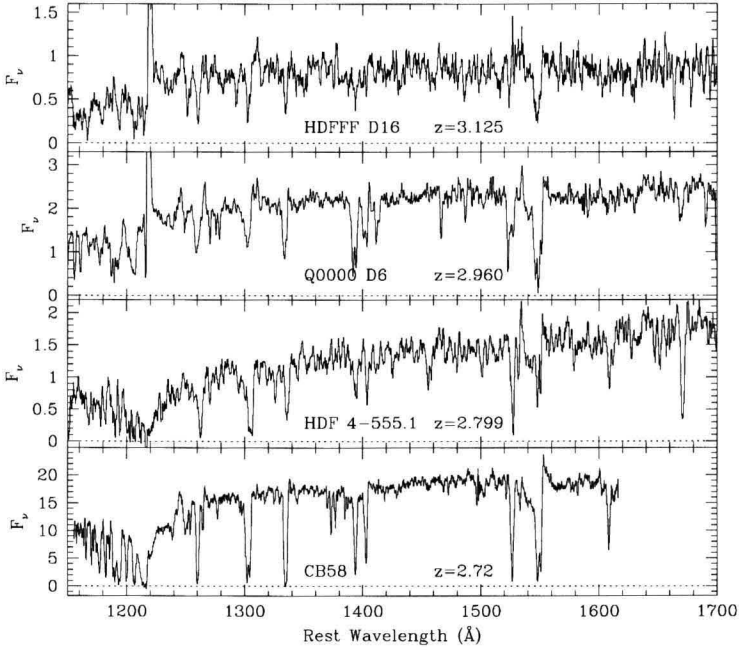


Figure 1. A sequence of UV spectra of four Lyman-limit galaxies, arranged from highest redshift to lowest redshift. Note the large range in line strengths present. In particular, Ly α (λ 1216 Å) is visible in both emission and absorption, while primarily interstellar resonant lines (see Table 1) show considerable variation in strength, possibly related to metallicity in these young star-forming galaxies. The Ly α absorption galaxies also appear redder in their continua at $\lambda > 1300$ Å.

Universe and $H_0 \sim 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$). Here the ionization level of outflowing gas may be lower than in individual Galactic O-stars. HST UV spectra of nearby star-bursts like M82 might help future comparison objects.

Dust reddening is a poorly-constrained but important issue for these distant star-burst systems; a slightly-reddened UV continuum can lead to substantially underestimating the true integrated luminosities. We have compared the spectrum of the hotdog galaxy (HDF 4-555.1) to IUE-based stellar models by Leitherer *et al.* (1995). We find that the galaxy spectrum is well fit by the oldest of Leitherer *et al.*'s continuous star formation synthetic models (a population

age of at least 9 Myrs and a stellar upper mass boundary of $80 M_{\odot}$). Thus the deep UV light from the galaxy is still dominated by OB-stars. The shape of the continuum is consistent with a visible extinction of $A_V = 0.2^m$, implying extinction 2 – 3 times higher at the $\lambda 1300 \text{ \AA}$ continuum. These conclusions are based on a poorly known extinction curve, and the unknown placement of the OB-stars and the geometry of the dust leads to further uncertainty. The deepest portion of the Ly α absorption profile in the hotdog galaxy is likely to arise from the stellar photospheres augmented by additional interstellar gas; modeling suggests $N(H) \sim 10^{20} \text{ cm}^{-2}$ (a borderline damped Ly α system), roughly consistent with the strength of the metallic ISM lines and the above-mentioned dust extinction. An age of several tens of Myr for the dominant stellar population is consistent with fitting the broad-band optical/near-IR colors to the (dust-reddened) models of Bruzual & Charlot (1993), although this should be treated as lower limit as it is comparable to the dynamical time, and synchronizing star bursts across the galaxy on time-scales less than this is probably aphysical.

On the best spectra of Q 0000 D6 we resolve two high-velocity systems separated by $\sim 500 \text{ km s}^{-1}$; large scale galactic winds driven by SNe may be consistent with this dynamical complexity. However, we note that Giavalisco *et al.* (1996) suggest that Q 0000 D6 is dynamically-relaxed, on account of its $r^{\frac{1}{4}}$ de Vaucouleurs profile. This is difficult to reconcile with the multiple velocity components we observe.

3 A Brief Glimpse at B -Dropouts ($z \sim 4$ Galaxies)

It is conceptually straightforward, but observationally intensive, to continue the Lyman-limit imaging to yet higher redshifts. Deep imaging in the photometric bands of $BVRI$, or the Gunn system bands including gri , can be used to select B -dropout candidates, implying $z \sim 4$, instead of the U -dropouts at $z \sim 3$ discussed above.

Our *entrée* to this subfield came from $BVRI$ images around the distant radio galaxy 6C 0140+326 ($z = 4.41$; Rawlings *et al.* 1996). The Keck direct images go quite faint, so in September 1997 we located ~ 13 potential B -dropouts and observed 6 of them spectroscopically with Keck/LRIS using a slit mask (*c.f.* Dey *et al.* 1998). These targets range in redshift from $z = 3.602$ and $z = 4.020$. None have the redshift of the (centrally positioned) radio galaxy! Redshifts in

excess of 4.5 would have been allowed by our photometric constraints.

Four of the six galaxies show moderate to strong Ly α emission. Two show broad absorption at Ly α . Si II λ 1260 Å is seen in absorption in several of the six *B*-drops. C IV $\lambda\lambda$ 1548, 1551 Å with a (noisy) P-Cygni profile is detected in 4 of the galaxies. All the systems show some Lyman forest discontinuity at λ 1216 Å; in four of them it is quite strong with a flux ratio ~ 2 across the break.

The one consistent feature of the *B*-drop spectral continua is that the galaxy flux is at or very close to zero below λ 912 Å. Inspection of the spectrum below Ly α show that all have no flux at $\lambda_0 < 912$ Å, but a detectable weak continuum near λ 1025 Å (the Ly β region). Future papers will be more quantitative about this discontinuity. We note, however, that since radiation that can ionize hydrogen is undetected in any of our *B*-drop galaxies it is implausible that ionizing radiation from young galaxies can replace the QSO ionization at $z > 4$, even considering that the co-moving space density of radio-loud and radio-quiet quasars is known to decline after their $z \sim 2$ peak.

One can hope that in the future the photometric high-redshift locator techniques can be extended to even larger redshifts.

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