Lyman Break Galaxies at $z \sim 3$: Giants or Dwarfs?

James D. Lowenthal*, L. Simard†, and D. Koo†

*Dept. of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003
†UCO/Lick Obs., University of California, Santa Cruz, CA 95064

Abstract.
We review attempts to constrain masses of Lyman Break Galaxies. Despite the temptation to identify LBGs with precursors of massive galaxies, we find that there is as yet *no direct evidence* that LBGs are drawn from a massive population, or even a uniform one.

Soon after the discovery of LBGs, it was suggested (Steidel *et al.* 1996) [1] that these luminous, star-forming galaxies or protogalaxies at redshifts $z > 2$ were the sites of massive galaxy formation, perhaps the centers of deep potential wells of dark matter that would eventually become massive ellipticals or spheroids of spirals today. Theorists working with semi-analytical cold dark matter models were quick to point out that they had in fact predicted such objects with their simulations(*e.g.*, Baugh *et al.* 1998) [2]). LBGs at $z > 2$ also show significant clustering, apparently supporting the massive galaxy identification (Giavalisco *et al.* 1998) [3].

An alternate viewpoint, however, was proposed by Lowenthal *et al.* (1997) [4], who suggested that the sizes, morphologies, luminosities, and spectra of LBGs were consistent with their being drawn from either a wide range of galaxy types and masses, or even from a predominately low-mass, bursting dwarf population.

To distinguish between those two scenarios, we have undertaken a program of observations with the 10-m Keck telescope to **measure kinematics of LBGs** in the HDF and other deep HST fields. Our goal is to constrain the masses of LBGs in rough analogy to local rotation curves.

While the sample is still small, early results seem to favor our hypothesis, *i.e.* that LBGs are drawn from a wide range of masses. Recent measurements of emission line widths in the observed near-IR by Pettini *et al.* (1998) [5] seem to support this view.

One particularly interesting example is the source known as C4-06 from Steidel et al., at $z = 2.803$. Its elongated, linear structure shows, in the HDF, two major strings of knots extending over some 2″. Our spectrum of C4-06, obtained with

CP470, After the Dark Ages: When Galaxies were Young (the Universe at 2 < z < 5),
edited by Stephen S. Holt and Eric P. Smith
© 1999 The American Institute of Physics 1-56396-855-X/99/$15.00

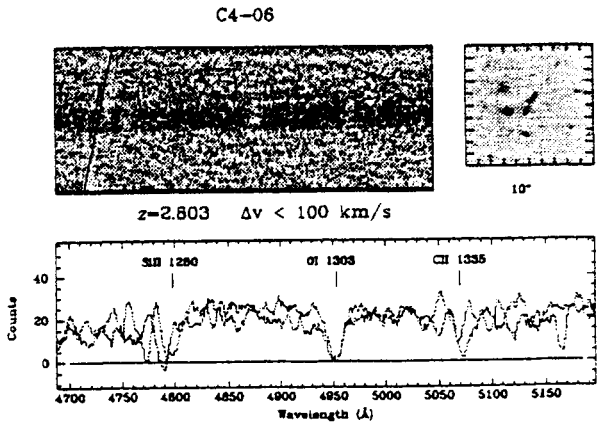

FIGURE 1. (HDF closeup and Keck spectrum of C4-06. Note that the continuum is clearly extended in the 2D spectrum, and that the absorption lines of Si II, O I, and C II are vertical, i.e., no velocity shift is detectable across the system, about 30 kpc in projected size.

the slitlet aligned with the long axis of the galaxy, shows extended emission (Fig. 1 shows a detail), as well as strong absorption lines of Si II 1260, O I 1303, and C II 1335. It is clear that the absorption lines extend over the whole continuum source, and that they are essentially vertical – i.e., there is no detectable rotation or velocity differential over the 20 kpc or so subtended by the object. A cross-correlation of two independent one-dimensional spectra extracted 1″ apart indicates δv consistent with zero, to within the errors of $\sim$ 50km s^{-1}. Adopting a limit of twice that, or $\delta v < 100$ km s^{-1} over 1″(or 12 h_{50}^{-1} kpc for $q_0 = 0.05$), implies a gravitational mass $m < 10^{10}$ M$_\odot$, well under the mass of typical L* galaxies today.

Even without calculating masses, we can directly compare these high-redshift star-forming galaxies to more local systems for more insight into their nature. In the half-light-radius/velocity-dispersion (R_e/σ) plane, for example (Fig. 2a, using δv for σ) three of our HDF sources overlap with low-mass spirals at the low end, while one falls above the envelope defined by high-mass spheroids.

The emission line widths of LBGs measured in the near-IR (rest optical, *e.g.*, Hβ) by Pettini *et al.* (who generally favor a high-mass interpretation) are also consistent with the widths of low-mass local galaxies, including HII galaxies and compact narrow emission line galaxies. Fig. 2b shows those line widths plotted vs. line luminosity

Table 1 summarizes the salient characteristics of LBGs; we have arranged them into those that support a uniform, massive, deep potential well interpretation on the one hand, and a diverse, bursting dwarf interpretation on the other. While these results require confirmation and augmentation, we believe that it is premature to conclude that star-forming galaxies at $2 < z < 4$ selected by their Lyman limit breaks represent a uniform population of high-mass proto-spheroids at the centers of deep, dark matter potential wells. The end products of $U-$ and $B-$band dropout galaxies are more likely to span a range of galaxy types and masses comparable to that *observed locally* in flux- and volume-limited surveys.

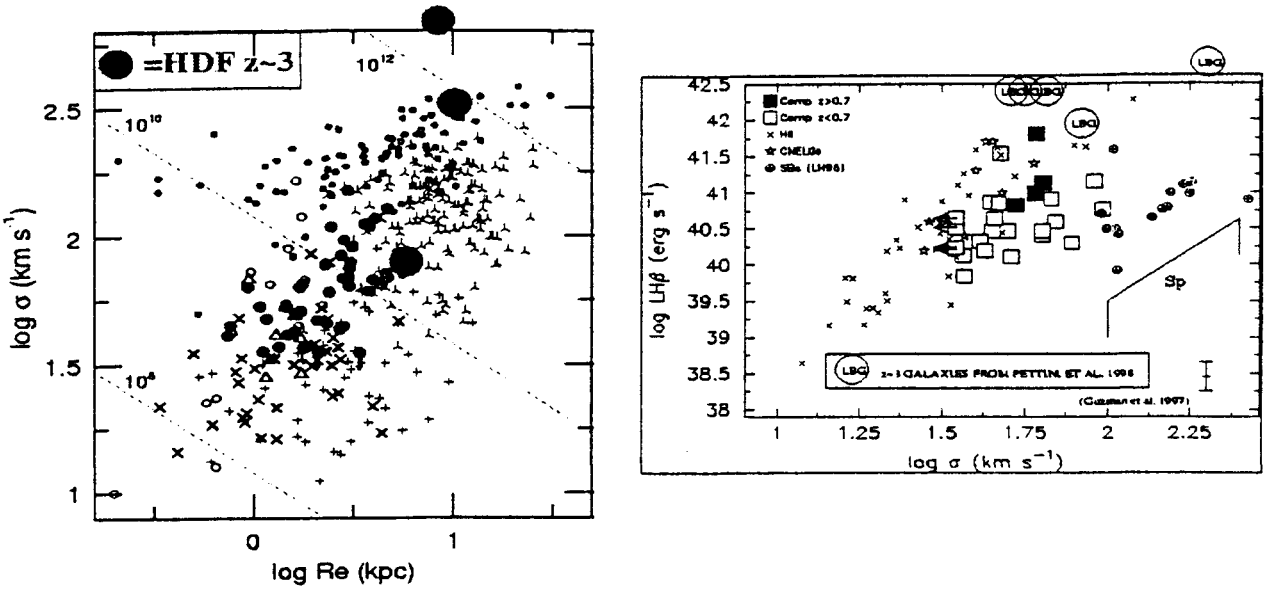

FIGURE 2. **(a)** Pseudo velocity width *vs.* half-light radius for three LBGs compared to normal local galaxies, from our Keck observations. The LBGs appear to span several orders of magnitude in mass. Original plot from Guzman *et al.* 1996. **(b)** Hβ vs. line width for a sample of Lyman Break Galaxies at $z \sim 3$ (from Pettini *et al.*) compared to local galaxies. Two of the points are scaled from [O III] λ5007 or Hα. Note that the emission line widths and luminosities of LBGs are mostly comparable to those of bright HII galaxies.

PUNCH LINE: Lyman Break Galaxies at $z \sim 3$ are plausibly **diverse, low-mass, starbursting dwarfs** that will wind up in a **wide variety** of end products.

ACKNOWLEDGMENTS

This project is being carried out in conjunction with the DEEP collaboration (see http://www.ucolick.org/ deep/home.html). We thank N. Vogt, A. Phillips, and S. Faber for help on observing runs and D. Kelson for providing the data reduction code.

REFERENCES

1. Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJl, 462, 17L
2. Baugh, C. M., Cole, S., Frenk, C. S., & Lacy, C. G. 1998, ApJ, 498, 504B
3. Giavalisco, M., Steidel, C. C., Adelberger, K. L., Dickinson, M. E., Pettini, M. & Kellogg, M. 1998, ApJ, 503, 543
4. Lowenthal, J. D., Koo, D. C., Guzmán, R. Gallego, J., Phillips, A. C., Faber, S. M., Vogt, N. P., Illingworth, G. D., & Gronwall, C. 1997, ApJ, 481, 673
5. Pettini, M., Kellogg, M., Steidel, C. C., Dickinson, M., Adelberger, K. L, & Giavalisco, M. 1998, ApJ, 508, 539

TABLE 1.

UNIFORM, HIGH-MASS CORES	DIVERSE, LOW-MASS CLUMPS
Morphologies & Sizes	
• Uniform Morphologies? • $r^{1/4}$ profiles? • $r_{1/2}$(LBG) $\sim r_{1/2}$(small bulges today)	• Diverse Morphologies! > 50% multiple, irregular • $(B/T)_{med} \sim 0.1$ • $r_{1/2} - M_B$ plot → HII galaxy-like
Numbers and Distributions	
• $n(I < 25) \simeq n(L > L*)$today • Clustering: $\delta_{Gal} \sim 3.5$ → $M_{halo} \sim 10^{12}$M$_\odot$	• $n(L > L*) > 4n(L > L*)$today → requires merging and/or fading to reconcile with local galaxies (especially in clusters) • Sub-galactic clumps in halos could explain δ
Luminosities and Star Formation Rates	
• SFR up to 100M$_\odot$ yr^{-1} (with dust correction) • $L \sim L*$	• $SFR \sim 10$M$_\odot$ yr^{-1} requires 10^{10} yrs to make 10^{11}M$_\odot$ → conflicts with stellar population constraints • Starburst: $L \rightarrow 100 \times L$; $M/L \ll 1$ for HII galaxies
Masses	
• Correlation + CDM → 10^{12}M$_\odot$; Clumps at *center* of large potential • Absorption line EWs → $M_{dyn} > 10^{11}$M$_\odot$ • C4-09: $\Delta v \sim 800$km s^{-1} → 10^{12}M$_\odot$	• Could be clumps *around* large potential • $EW \neq f(M)$ (*e.g.*, shocks, SNe...) • Lyα emission lines narrow → 10^{10}M$_\odot$ (caveats: dust, scattering, outflows...) • K_{obs} ($\simeq V_{rest}$) → $M* < 10^{10}$M$_\odot$ • $\sigma_{H\beta} \sim 70$km s^{-1} → M $\sim 10^{10}$M$_\odot$ • C4-06 kinematics: $M < 10^{10}$M$_\odot$