Lyman Break Galaxies in the NGST Era

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Abstract. With SIRTF and NGST in the offing, it is interesting to examine what the stellar populations of \( z \approx 3 \) galaxies models imply for the existence and nature of Lyman-break galaxies at higher redshift. To this end, we “turn back the clock” on the stellar population models that have been fit to optical and infrared data of Lyman-break galaxies at \( z \approx 3 \). The generally young ages (typically \( 10^{8.5} \) yr) of these galaxies imply that their stars were not present much beyond \( z = 4 \). For smooth star-formation histories \( SFR(t) \) and Salpeter IMFs, the ionizing radiation from early star-formation in these galaxies would be insufficient to reionize the intergalactic medium at \( z \approx 6 \), and the luminosity density at \( z \approx 4 \) would be significantly lower than observed. We examine possible ways to increase the global star-formation rate at higher redshift without violating the stellar-population constraints at \( z \approx 3 \).

1 Introduction

Near-infrared photometry provides access to the rest-frame optical portion of Lyman-break galaxy spectra; studies are beginning to provide some insight into the evolutionary status of LBGs. The stellar masses are reasonably well constrained at \( M^* = 3 \times 10^{10} M_\odot \pm 0.5 \text{dex} \) \cite{10, 12, 14}. These stellar masses are similar to estimates of the masses from kinematics \cite{11, 9}, and together they suggest that Lyman break galaxies must grow substantially if they are to become \( L^* \) galaxies by redshift \( z = 0 \). Other stellar-population parameters such as ages, metallicities, extinction, star-formation rates and star-formation timescales are very poorly constrained by the fits to the spectral-energy distributions, leaving room for a variety of evolutionary paths both prior to and after \( z \sim 3 \).

At some point above redshift \( z \sim 6 \) the intergalactic medium was reionized. It is not known if the sources of ionization were stars or quasars, or whether the stars responsible for the reionization had a mass function at all similar to that observed in the Milky Way. It is also unclear whether reionization itself had a major role in regulating subsequent galaxy formation, for example by suppressing star formation in low-mass galaxy halos. As new facilities such as SIRTF and NGST come on line, understanding the causes and effects of reionization will be one of the major goals. With that in mind, we shall briefly review the capabilities of the Space Infrared Telescope Facility (SIRTF), the Hubble Space Telescope Advanced Camera for Surveys (HST ACS), and the Next Generation Space Telescope for studying Lyman break galaxies. We will then look at the stellar population parameters of the \( z \sim 3 \) samples of Lyman-break galaxies and attempt to turn the clock back to predict their star-formation rates at higher
redshift. We find a somewhat surprising result: that the models imply a luminosity density at \( z = 4 \) significantly below that observed, and fail to produce enough ionizing photons at \( z = 6 \) to account for reionization. We discuss modifications of the models that might be needed to avoid these problems.

2 Lyman-Break Galaxies in the GOODS Era

When the HDF-N/WFPC2 observations were made, \( z \approx 3 \) was the frontier for galaxy surveys. Today it stands at \( z \approx 6 \), where we know very little: only that some galaxies and QSOs already existed, and that their energetic output may have just risen to the point of reionizing the IGM [1, 6]. From \( z = 6 \) to 3, the age of the universe more than doubles, and its density decreases more than five-fold. We expect corresponding changes in the galaxy population, but measuring this evolution will require large large, systematic surveys for galaxies at \( z > 4 \) to compare with more than 1000 Lyman break galaxies (LBGs) now known at \( z \approx 3 \) [13]. Color selection at \( z \approx 5 \) to 6 requires deep imaging at \( \lambda \geq 0.9 \mu m \). However, from the ground even the brightest \( z > 5 \) galaxies are barely detectable. If there is no evolution between \( z = 3 \) and 6, we expect an \( L^*_{UV} \) LBG to have \( m_i = 25.7 \) at \( z = 5 \), and \( m_z = 26.0 \) at \( z = 6 \). The HST Advanced Camera for Surveys (ACS) will easily reach these limits thanks to the dark sky and sharp image quality, which also provide greatly reduced photometric error, incompleteness, and contamination due to confusion with other (mostly foreground) objects. An \( L^* \) LBG detected at \( z = 6 \) by ACS will also be detectable in ultra-deep integrations with the IRAC detector aboard SIRTF. Depending on the quality of the point-spread function such detections will either be marginal (requiring prior knowledge of source positions and possibly statistical co-addition of multiple galaxies for a secure detection) or clear cut (if the PSF is as good as measured in pre-flight tests). Figure 1 illustrates the expected yield of \( z \sim 5.5 \) LBGs from the GOODS survey from a simple extrapolation of the \( z = 3 \) luminosity function. We expect several hundred to of order 1000 candidates.

3 Lyman-break Galaxies in the NGST Era

The Next Generation Space Telescope, slated for launch before 2010, is expected to be a \( \sim 6.5 \) m passively-cooled telescope with exquisite sensitivity from 0.6 to 28 \( \mu m \). Three focal-plane instruments are planned: an optical/near-IR camera with a \( 4' \times 4' \) field of view, a low-resolution (\( R \sim 100 - 1000 \)) near-IR spectrograph (to be built by ESA), and a mid-IR camera/spectrograph. At 4.5 \( \mu m \), an exposure time of 5 seconds will be required to match the 50-hour depth of IRAC GOODS images. Presuming that observations from SIRTF, ACS and WFC3 are successful, by the time NGST launches galaxy populations at \( z < 6 \) should be reasonably well understood. However, the fact that reionization occurs at \( z \gtrsim 6 \) suggests that the earliest luminous structures formed at still higher redshift.

By redshift \( z = 3 \) the massive stars that reionized the universe (if indeed stars were responsible) exist only as undetectable remnants. However, if early
Fig. 1. Top: Number of sources per unit redshift per logarithmic flux interval anticipated in the GOODS survey region. Solid and dashed lines show the average number of galaxies and QSOs, respectively, per unit redshift $5 < z < 10$ from Haiman & Loeb (1998). Dotted lines show a model based on the measured luminosity function of LBGs at $z \sim 3$, with $L^*$ scaled with redshift as $(1 + z)^{-3/2}$, i.e., following the Press-Schechter relationship for halo mass. Error bars represent Poisson statistics on galaxies recovered at $z \sim 4, 5,$ and 6 using simple $B$, $V$, and $i$-dropout criteria. Fluxes have been scaled to equivalent $z$-band fluxes using a typical LBG SED. Bottom: Total galaxy counts at $z = 5.5 \pm 0.5$ vs. the 10σ limiting depths (in nJy) of various surveys, for a non-evolving LBG luminosity function (shaded bars) and for one with the evolution adopted in the upper panel (solid bars). Under these assumptions the HDF should have had 10-30 $z \sim 5.5$ galaxies, consistent with tentative identifications via photometric redshifts. The GOODS ACS survey will yield 300-1000 secure identifications. Estimates of high-$z$ galaxy numbers are also shown for the GOODS $SIRTF$ 25-hour depth survey, under two assumptions that bracket the range of expected sensitivities due to uncertainties in the on-orbit IRAC PSF. Predicted numbers (nominal PSF) are shown also for the planned (0.3 deg$^2$) 3-hour IRAC GTO survey of the Groth strip. A cosmology with $\Omega_M, \Omega_\Lambda, h = (0.3, 0.7, 0.65)$ is adopted.

generations of stars formed with a Salpeter or Scalo initial mass function (IMF), lower-mass cousins of the ionizing sources would still be on the main sequence at $z = 3$, and would perhaps reside in Lyman-break galaxies. Existing optical and near-IR observations of LBGs yield constraints on stellar populations that can be used to explore this possibility. Papovich, Dickinson & Ferguson [10]
studied a sample of spectroscopically-confirmed LBGs from the Hubble Deep Field North (HDF) in the redshift range $2.0 \leq z \leq 3.5$. The UV-optical data were drawn from WFPC-2 observations, and the infrared from NICMOS J and H-band observations and from $K_s$-band observations with the infrared imager IRIM at the KPNO 4m Mayall telescope [5]. Stellar-population models from 2000 version of the Bruzual-Charlot [2] code were fit to 31 galaxies, varying metallicity, e-folding timescale $\tau_{SF}$, age, IMF (Salpeter, Miller-Scalo, Scalo), extinction, and extinction law 3, 4. The geometric mean of the best-fit ages for the sample is 0.12 Gyr for the solar metallicity case. Thus a typical galaxy observed at $z = 3.0$ would have “formed” at $z = 3.15$. Shapley et al. [12] analyzed groundbased photometry for a sample of galaxies with spectroscopic redshifts $2.2 < z < 3.4$. The published paper reports results for the best-fit continuous star-formation models ($\tau_{SF} = \infty$) to the 74 galaxies for which acceptable fits were obtained. The median best-fit age for this sample is 0.32 Gyr, implying a formation redshift $z = 3.4$ for a typical galaxy observed at $z = 3$.

In Figure 2a, we show the star-formation histories derived for each galaxy in the two samples, under various assumptions. The top panel shows exponentially-declining models. The second and third panels show models with a constant star-formation rate (where only the age, extinction, and total stellar mass are free parameters). In the exponentially decaying models only one out of the 31 galaxies would have been present at $z = 6$. In the oldest continuous-star-formation models from [10], six out of 31 or 19% would have been present at $z = 6$. The Shapley et al. [12] models imply that only 17% of the galaxies were present at $z = 6$.

Models with two distinct episodes of star formation allow more star formation at higher redshift. Papovich et al. [10] fit maximally-old models to their LBG sample, deriving constraints on the mass of an old population that formed with a Salpeter IMF in an instantaneous burst at $z = \infty$. This model quantifies how much stellar mass can be hidden “underneath the glare” of the young population that dominates the UV/Optical radiation from each galaxy. However, the star-formation rate predicted at $z = 6$ from such maximally old components is zero, because all star-formation happened at higher redshift. It is more likely that starbursts induced by mergers are spread out over some range of redshift and do not occur in all galaxies simultaneously. If the older burst in the LBGs is put at redshift lower than $z = \infty$, the mass in the burst must be lower. Rather than fit a whole suite of models of different burst redshifts, we can, to a good approximation, scale the allowable mass in the old component by a power-law fading model. By fitting the B-band luminosity vs. time for $10^7 < t < 2 \times 10^9$ yr, we find $L_B \propto t^{-0.8}$ for a Salpeter IMF for an instantaneous burst in the Bruzual & Charlot solar-metallicity models. If each galaxy had an instantaneous probability $P(z)$ of forming stars at redshift $z$, and a typical burst had a duration $\Delta t$ the average SFR from an ensemble of such galaxies would be $\xi(z) = M(z)P(z)/\Delta t$, where $M(z)$ is average mass formed in each burst and $\Delta t$ is the average duration of each burst. For simplicity we adopt a constant $P(z)$ from $z = 10$ to the observed LBG redshift $z_{\text{obs}}$. 
Fig. 2. *Left:* Star-formation rate vs. time for individual galaxies, as inferred from the SED models. The top panel shows the best-fit models with exponentially declining SFR. Panel (b) shows the star-formation histories from continuous star-formation models from [10] characterized by a stellar mass $M$ and an age. Panel (c) shows the same kind of continuous star-formation model for the Shapley et al. [12] sample. Panel (d) shows two examples of the stochastic burst model described in the text applied to galaxies 97 and 1115 in the PDF01 sample. *Right:* Global star-formation rate vs. time for all of the models, normalized to the rate at $z = 3$. In the top panel, the solid curve is for the PDF01 $\tau$ models. The short-dashed curve is for their continuous star-formation models. The long-dashed curve is for the Shapley et al. [12] continuous star-formation models. The bottom panel shows the star-formation rate vs. time for the stochastic burst models with a Salpeter IMF (solid) and a top-heavy IMF with $x = 0.5$ (dashed). Star-formation rates are normalized to the mean in the range $2.5 < z < 3.5$.

Figure 2d shows the SFR vs. redshift implied by such a stochastic model for two individual galaxies (numbers 97 and 1115) in the PDF01 sample. The low-redshift spikes in the star-formation rate correspond to the young component that dominates the light at the observed redshift; the star-formation progressing to higher redshift represents the mean for an ensemble of stochastic bursts. Obviously any single galaxy would simply show two spikes of star formation for this kind of model, but if we consider such a galaxy as a proxy for millions of others, the star-formation history shown in the figure represents the maximal rate of star-formation due to stochastic bursts as a function of redshift.

The constraints become clearer if we consider the entire sample of galaxies. Figure 3 shows the evolution of $\dot{\rho}_{\text{SFR}}(z)$ with time relative to that at $z = 3$ computed by summing up the models shown in the previous figures. The top panel shows the smooth star-formation histories. For these cases the inferred
co-moving density of star formation declines dramatically from \( z = 3 \) to higher redshift. Even if we put the maximum mass allowed in stochastic-starbursts at redshifts \( z > z_{\text{observed}} \), the star-formation rate at \( z = 6 \) is still a factor of 3 below that at \( z = 3 \), as shown by the solid curve in Fig. 3b.

Adopting \( f_{\text{esc}} = 0.1 \), the required density of star-formation for reionization in the Madau, Haiman & Rees [8] model is a factor of 1.3 times higher than the dust-corrected \( \dot{\rho}_{\text{SFR}} \) at \( z \sim 3 \) measured by [13]. In contrast, the star-formation rates inferred from the SED fits imply a sharp decrease in \( \dot{\rho}_{\text{SFR}} \) between \( z = 3 \) and \( z = 6 \). The problem becomes even more severe if a significant fraction of the baryons are already collapsed into minihalos at the time of reionization. In this case the required number of ionizing photons increases by a factor of 10-20 [7], and all models fall short even if \( f_{\text{esc}} = 1 \).

There is another, perhaps more serious, problem with the star-formation histories derived so far: all the models imply a dramatic decline in star-formation by \( z = 4 \). But the observed LBG rest-frame UV luminosity functions are very similar at \( z = 3 \) and \( z = 4 \), and the integrated star-formation rates derived therefrom differ only by a factor of 1.1±0.4 [13]. Thus the star-formation histories derived from the \( z = 3 \) LBGs are in direct conflict with the star-formation rates derived for the \( z = 4 \) LBGs.

More star formation can be hidden in bursts if the bursts fade faster. If the fading exponent over an age range \( 10^7 - 2 \times 10^9 \) yr is \( \zeta \), the additional increase in stellar mass that can be hidden relative to a Salpeter IMF is roughly \( t_7^{-\zeta - 0.8} \), where \( t_7 \) is the age in units of \( 10^7 \) yr. At an age of 1 Gyr a factor of four more stellar mass can be hidden if \( \zeta = -1.1 \) than if \( \zeta = -0.8 \). Indeed, changing the fading exponent to \( \zeta = -1.1 \) is sufficient to make the allowed star-formation rate at \( z = 6 \) equal to the star-formation rate at \( z = 3 \). The global star-formation rate from such a model is shown as a dashed curve in Fig. 2b. If the IMF is a powerlaw \( \phi(M) dM \propto M^{-(1+x)} \), a fading exponent \( \zeta = -1.1 \) requires an IMF slope \( x = 0.5 \) compared to the Salpeter value \( x = 1.35 \) (for an instantaneous-burst solar-metallicity stellar population). A steeper fading slope \( \zeta = -1.2 \) (corresponding to an IMF slope \( x = 0.3 \)) is needed to bring \( \dot{\rho}_{\text{SFR}} \) at \( z = 4 \) to within a factor of 1.3 of that at \( z = 3 \). Lower metallicities require even more top-heavy IMFs. Options other than varying the IMF are of course possible (e.g. evolved stellar populations could be hidden by dust that builds up over timescales of \( 10^8 \) to \( 10^9 \) yrs). However, the requirement for faster-than-Salpeter fading is robust. Furthermore, the fading must be even faster if galaxies on average have more than two burst episodes.

Constraints on the star-formation histories of LBGs will improve greatly over the next few years with the advent of SIRTF and ACS. Observations with these instruments will further narrow the parameter space available for bursty or episodic star-formation. Such observations will set the stage for the detailed exploration of galaxy formation in the “pre-reionization” era at \( z > 6 \) with NGST.

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References
[1] Becker, R. H., et al. 2001, astro-ph/0108097
[2] Bruzual, A. G., & Charlot, S. 1993, ApJ, 405, 538
[3] Calzetti, D., Armus, L., Bohlin, R. C., Kinney, A. L., Koornneef, J., & Storchi-Bergmann, R. 2000, ApJ, 533, 682
[4] Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
[5] Dickinson, M. 1998, in The Hubble Deep Field, ed. M. Livio, S. M. Fall, & P. Madau (Cambridge: Cambridge University Press), 219
[6] Djorgovski, S. G., Castro, S., Stern, D., & Mahabal, A. A. 2001, ApJ, 560, L5
[7] Haiman, Z., Abel, T., & Madau, P. 2001, ApJ, 551, 599
[8] Madau, P., Haardt, F., & Rees, M. J. 1999, ApJ, 514, 648
[9] Moorwood, A. F. M. 2002, this conference
[10] Papovich, C., Dickinson, M. E., & Ferguson, H. C. 2001, ApJ, 559, 620
[11] Pettini, M., Shapley, A. E., Steidel, C. C., Cuby, J.-G., Dickinson, M., Moorwood, A. F. M., Adelberger, K. L., & Giavalisco, M. 2001, ApJ, 554, 981
[12] Shapley, A. E., Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., & Pettini, M. 2001, ApJ, 562, 95
[13] Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1
[14] Yamada, T. 2002, this conference