LYMAN BREAK GALAXIES AND THE REIONIZATION OF THE INTERGALACTIC MEDIUM

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ABSTRACT

Near-infrared observations of Lyman break galaxies at redshifts of \( z \approx 3 \) are beginning to provide constraints on ages, star formation histories, dust content, metallicities, and stellar masses. At present, uncertainties of more than an order of magnitude are typical for many of these parameters. It is nonetheless interesting to ask what the stellar population models imply for the existence and luminosities of Lyman break galaxies at higher redshift.

To this end we examine the inferred star formation rates in two well-studied samples of galaxies as a function of redshift out to \( z = 10 \) for various best-fitting and limiting cases. Taken at face value, the generally young ages (typically \( 10^{8.2 \pm 0.5} \) yr) of the \( z = 3 \) Lyman break galaxies imply that their stars were not present much beyond \( z = 4 \). By \( z = 6 \) the cosmic star formation rate \( \dot{\rho}_{\text{SF}} \) from the progenitors of these galaxies is less than 10\% of \( \dot{\rho}_{\text{SF}} \) at \( z = 3 \pm 0.5 \), even for maximally old models, provided the derivative of the star formation rate \( \text{SFR}(t) \) is monotonic. The escaping Lyman continuum radiation from such galaxies would be insufficient to reionize the intergalactic medium. Thus, other sources of ionizing photons (e.g., very massive Population III stars) may be needed, and the more normal Lyman break galaxies may be a phenomenon confined to redshifts of \( z \approx 4 \). This conclusion changes if \( \text{SFR}(t) \) was episodic, and we examine the parameters of such bursty star formation that might be consistent with both the \( z = 2-4 \) luminosity functions and the \( z \approx 3 \) spectral energy distributions.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: stellar content

1. INTRODUCTION

Studies over the past several years have revealed a nascent population of galaxies at redshifts of \( z = 2-4 \) with properties that are in many ways similar to those of local starburst galaxies (Giavalisco, Steidel, & Macchetto 1996; Steidel et al. 1996). These galaxies are identified by their strong UV continuum emission and by the presence of strong spectral breaks at Ly\( \alpha \) and the Lyman limit (rest frame of 1216 and 912 Å, respectively). Near-infrared photometry of such Lyman break galaxies (LBGs) provides access to the rest-frame optical portion of their spectra and hence greatly improves the constraints on their stellar populations (Sawicki & Yee 1998). Two recent studies (Papovich, Dickinson, & Ferguson 2001, hereafter PDF01; Shapley et al. 2001) have explored a broad range of stellar population models for LBGs varying age, star formation timescales \( \tau_{\text{sf}} \), metallicities \( Z \), and reddening \( E(B-V) \). Our goal in this Letter is to examine the implications of these stellar population models for LBGs at higher redshift. This is a simple thought experiment. In reality, we expect star formation histories to be more complex than these simple models (which, for example, ignore chemical evolution entirely), and we expect galaxy merging to be extremely important at these high redshifts. Nevertheless, the spectral energy distributions (SEDs) of the individual galaxies at \( z \approx 3 \) should reflect the products of this evolution, and some of the broad implications for star formation rates versus time are relatively insensitive to the details.

One motivation for exploring galaxy evolution at \( z > 5 \) is to understand the connection between galaxies and the physical conditions in the intergalactic medium (IGM). Observations of quasar absorption lines indicate that the IGM was highly ionized out to redshifts of \( z \approx 6 \), while very recent observations suggest that it was more neutral at higher redshifts (Becker et al. 2001; Djorgovski et al. 2001). It is not known whether 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.

Estimates for the number of ionizing photons needed to reionize the IGM range from 1 to 15 photons per H atom (Madau, Haardt, & Rees 1999; Haiman, Abel, & Madau 2001), requiring UV luminosity densities at \( z \gtrsim 6 \) as high as those observed at \( z = 3 \). If the stellar populations responsible for reionization formed with an initial mass function (IMF) similar to that observed in present-day stellar populations, then the remnants of these populations must account for a portion of the light emitted by \( z = 3 \) LBGs. It is thus interesting to explore whether simple models can provide sufficient reionizing photons at \( z \approx 6 \) without violating the stellar population constraints for the \( z \approx 3 \) LBGs.

We review the LBG stellar population constraints in § 2. In § 3 we turn the clock back on the stellar population models and compute \( \dot{\rho}_{\text{SF}}(z) \) to higher redshift. In § 4 we discuss the implications and in § 4.3 the modifications of the star formation history, \( \text{SFR}(t) \), or the IMF that might be required to account for both the \( z \approx 4 \) LBG luminosity function and reionization. Throughout this Letter we adopt the cosmological parameters \( h, \Omega_m, \Omega_o, \Omega_k = 0.7, 1.0, 0.3, 0.7 \).
2. LYMAN BREAK GALAXY STELLAR POPULATIONS

PDF01 studied a sample of spectroscopically confirmed LBGs from the Hubble Deep Field–North in the redshift range $2.0 \leq z \leq 3.5$. The data included UV-optical photometry from the Wide-Field Planetary Camera 2, J- and H-band photometry from the Near-Infrared Camera and Multi-Object Spectrometer, and $K_s$-band photometry from the Kitt Peak National Observatory 4 m Mayall telescope (Dickinson 1998). Fluxes were determined from profile-weighted photometry, which accounts for the point-spread function (PSF) variations and image blending. Stellar population models from the 2000 version of the Bruzual & Charlot (1993) code were fitted to 31 galaxies, varying metallicity, $e$-folding timescale $t_{SF}$, age, IMF (Salpeter, Miller-Scalo, Scalo), extinction, and extinction law (SMC; Calzetti et al. 2000). The geometric mean of the best-fitting 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 $z = 3.15$. PDF01 showed there to be very few galaxies at $z = 3$, even considering those that might have escaped Lyman break selection, with colors consistent with significantly older ages.

Shapley et al. (2001) analyzed $G$, $R$, $J$, and $K_s$ photometry for a sample of galaxies with spectroscopic redshifts of $2.2 < z < 3.4$. Colors were determined from isophotal apertures on PSF matched images. Solar metallicity stellar population models from the 1996 incarnation of the Bruzual & Charlot (1993) code were fitted, with various values of $t_{SF}$, age, and extinction. The Calzetti (1997) attenuation law was adopted, and Shapley et al. report results for only the best-fit continuous star formation models ($t_{SF} = \infty$) 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 of $z = 3.4$ for a typical galaxy observed at $z = 3$.

Clearly, the inferred ages for monotonic star formation histories in these two studies are very young. PDF01 also found that a substantial fraction of the stellar mass could be hidden in a “maximally old,” passively evolving population that formed instantaneously at $z = \infty$. Inferred LBG masses typically increase by a factor of 3 in such models. For our purposes, the interesting point is that the SFR appears unlikely to have been constant over a Hubble time—i.e., $M_*/t_{SF}$, the stellar mass divided by the Hubble time at the LBG redshift, is typically much less than the measured SFR at $z \sim 3$. This generic conclusion is unlikely to be very sensitive to the details of the stellar population models.

3. TURNING BACK THE CLOCK

In exploring the implications of these models, we consider three limiting cases: (1) a single burst of star formation, (2) continuous star formation starting at some time $t$, and (3) a two-burst model. Multiple-burst models would be intermediate between these cases. Figure 1 shows the SFR as a function of redshift inferred for each galaxy in the PDF01 sample for solar metallicity models. Models with $0.2 Z_\odot$ give younger ages and higher SFRs. Figures 1a and 1b show single-burst models with SFR $\propto e^{-t_{SF}t}$ and continuous star formation models. In the burst models, only one out of the 31 galaxies would have been present at $z = 6$. In the oldest continuous star formation models, six out of 31, or 19%, would have been present at $z = 6$. Figure 1c shows the results for the best-fit solar metallicity continuous star formation models of Shapley et al. (2001). The models imply that only 17% of the galaxies were present at $z = 6$.

Models of type 3 with two distinct episodes of star formation allow more star formation at higher redshift. PDF01 fitted naturally 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 younger population. The SFR predicted at $z = 6$ from such maximally old components is zero because all star formation happened at higher redshift. Starbursts induced by mergers are likely to be spread out over a range of redshifts. If the older burst in the LBGs is put at a 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 versus time for $10^7$ yr $< t < 2 \times 10^9$ yr, we find $L_B \propto t^{-\alpha}$ for a Salpeter IMF for an instantaneous burst in the Bruzual & Charlot solar metallicity models. The $B$ band is chosen because the older burst population contributes mostly longward of $\lambda_{rest} = 3000$ Å (see PDF01, Fig. 19). This fading exponent is slightly shallower than that adopted by Hogg & Phinney (1997) because of the narrower age range used for our estimate. A Scalo IMF would fade more gradually, as would a lower metallicity model. The allowed mass in a burst as a function of age is $M(z) = M_{\max}(age/t_{SF})^{\alpha}$, where $M_{\max}$ is the maximum mass allowed in an instantaneous burst formed at $z = \infty$. If each galaxy had an instantaneous probability $P(z)$ of forming stars in a burst of typical duration $\delta t$, then the average SFR per galaxy from an ensemble of such galaxies would be $M(z)P(z)\delta t$. For simplicity we adopt a constant $P(z)$ from $z = 10$ to the observed LBG redshift $z_{\text{obs}}$. [We consider varying $P(z)$ in § 4.3.] The ensemble-average SFR is thus $\bar{\xi}(z) = M(z)/(t_{\text{obs}} - t_{\text{ini}})$, where $t_{\text{ini}}$ is the age of the universe at $z = 10$ and $t_{\text{obs}}$ is the age of the universe at the redshift of the LBG. In the current generation of semianalytic hierarchical models, the rate of star formation due to mergers decreases at
z > 3 (Cole et al. 2000; Somerville, Primack, & Faber 2001). Therefore, our assumption of constant $P(z)$ puts a higher proportion of star formation at high redshift.

Figure 1d shows the SFR versus redshift implied by such a stochastic model for two individual galaxies in the PDF01 sample. The low-redshift spikes in the SFR 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 results become clearer if we consider the entire sample of galaxies. Figure 2 shows the evolution of $\rho_{SFR}(z)$ with time relative to that at $z = 3$ computed by summing up the models shown in the previous figures. Figure 2a shows the monotonic star formation histories. For these cases the inferred comoving density of star formation declines dramatically from $z = 3$ to higher redshift. The stochastic burst model is shown by the solid curve in Figure 2b. Even if we put the maximum mass allowed in stochastic starbursts at redshifts of $z > z_{min}$, the SFR at $z = 6$ is still a factor of 3 below that at $z = 3$.

4. IMPLICATIONS

4.1. The Luminosity Function at $z \sim 4$

All of the star formation histories considered so far imply a dramatic decline in SFR by $z = 4$. However, the observed LBG rest-frame UV luminosity functions are very similar at $z = 3$ and 4, and the integrated SFRs derived therefrom differ by a factor of only $1.1 \pm 0.4$ (Steidel et al. 1999). 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.

4.2. Reionization

If all of the ionizing photons come from star formation, Madau et al. (1999) estimate that the amount of star formation needed is

$$\dot{\rho}_{SFR} \approx 0.013 f_{esc}^{-1} \left(1 + z\right)^3 \left(\frac{\Omega_b h_0^2}{0.08}\right)^2 C_{30} M_\odot yr^{-1} \text{Mpc}^{-3},$$

(1)

where $f_{esc}$ is the mean fraction of Lyman continuum radiation that escapes from galaxies, $\Omega_b$ is the baryon density, $h_0$ is the Hubble constant in units of 50 km s$^{-1}$ Mpc$^{-1}$, and $C_{30} = 30(\mu_{1500}/\mu_{2175})^2$ is the hydrogen clumping factor. Adopting $f_{esc} = 0.1$, the required density of star formation for reionization in this model is a factor of 1.3 times higher than the dust-corrected $\rho_{SFR}$ at $z \sim 3$ measured by Steidel et al. (1999). In contrast, the SFRs inferred from the SED fits imply a sharp decrease in $\rho_{SFR}$ between $z = 3$ and 6. For the monotonic star formation histories, this decrease is at least 1 order of magnitude. Even for the case of stochastic bursts, the SFR is still well below that needed for reionization. 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 (Haiman et al. 2001), and all models fall short even if $f_{esc} = 1$.

4.3. What Kind of Starbursts Are Needed?

In the discussion above, we adopted a uniform starburst probability $P(z)$ and found that such a model was unable to produce enough photons at $z \sim 6$ to account for reionization (while at the same time fitting $z = 3$ LBG SEDs). One simple modification would be to increase the burst probability at high redshift. Keeping $P(z)$ uniform, we require that bursts occur with uniform probability over the redshift range $z_{min} < z < z_{max}$ and vary $z_{min}$ and $z_{max}$ until the SFR at $z = 6$ equals that at $z = 3$. Independent of $z_{max}$, we find that values of $z_{min} > 4.4$ are required to achieve this. Thus, LBG evolution would be characterized by an early epoch of star formation responsible for reionization, followed by a lull, followed by increased star formation at $z \sim 3$. This kind of behavior might be caused by reheating of the IGM during reionization (Cen & McDonald 2001). However, such a scenario would increase the discrepancy at $z = 4$.

More star formation can be hidden in bursts if the bursts fade faster. For a first-order estimate, we adopt a power-law fading model $L(t) \propto t^{-\gamma}$. For a Salpeter IMF in the B band, $\gamma = 0.8$. We vary $\chi$ until the UV luminosity density at $z = 6$ equals that at $z = 3$. We find that a fading exponent $\gamma =$...
−1.1 is required. As shown by the dashed curve in Figure 2b, such a model still falls short of the observed luminosity-density at $z = 4$ but is within the uncertainties. If the IMF is a power law $\Phi(M) dM \propto M^{-1.1}$, a fading exponent $\alpha = -1.1$ requires an IMF slope of $x = 0.5$ compared to the Salpeter value of $x = 1.35$ (for an instantaneous burst solar metallicity stellar population). A steeper fading slope $\alpha = -1.2$ (corresponding to an IMF slope of $x = 0.3$) is needed to bring $\rho_{SFR}$ 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 $10^8$–$10^9$ yr). However, the requirement for faster-than-Salpeter fading is robust. Furthermore, the fading must be even faster if galaxies have on average more than two burst episodes.

5. CONCLUSION

In summary, we find that the monotonic star formation histories that best match $z = 3$ LBG spectra fail (by a large factor) to provide enough photons to reproduce the luminosity density at $z = 4$ or to reionize the IGM at $z \approx 6$. Even stochastic burst models, which permit factors of 3–10 more mass to be formed at higher redshift, fail to resolve the shortfall. We are left with a variety of more complex alternatives:

1. If we require that the stellar populations responsible for reionization formed with typical Galactic IMF ($x \sim 1.35$) and that such star formation did not show a pronounced gap between $z = 6$ and 3, then we must conclude that the remnants of the stellar populations responsible for reionization do not reside in $z = 3$ LBGs. This is possible, for example, if undetected dwarf galaxies with number densities higher than the extrapolation of the LBG luminosity function dominate the ionizing background.

2. The SEDs of $z = 3$ LBGs allow for a separate epoch of normal IMF star formation at very high redshift provided that such star formation ceased by $z \approx 6$, leaving a gap in star formation until $z \approx 4$. This solution to the reionization problem glosses over the need to explain the $z = 4$ LBG luminosity function.

3. Reionization could have been caused by stellar populations heavily weighted toward massive stars (Larson 1998; Abel, Bryan, & Norman 2000; Oh et al. 2001). If this phenomenon was confined to high redshift (e.g., high-mass, zero-metallicity Population III stars), then the remnants could reside in lower redshift LBGs as black holes or neutron stars. This solution to the reionization problem also fails to solve the $z = 4$ LBG problem.

4. Both problems can be resolved if the star formation in LBGs was episodic and the stars formed with a top-heavy IMF. Bursts of star formation associated with mergers are a natural consequence of hierarchical models of galaxy formation and are incorporated to varying degrees into many of the current semi-analytical models (Kauffmann & Haehnelt 2000; Cole et al. 2000; Somerville et al. 2001). With the assumption that the starburst probability $P(z)$ is constant over $3 \leq z < 10$, we find that an IMF slope of $x = 0.3$–0.5 would be required to explain both the relative constancy of the LBG luminosity function over the range $2 \leq z < 4.5$ and plausibly provide enough star formation at $z \approx 6$ to reionize the IGM. Top-heavy IMFs could in principle result from higher interstellar medium pressure during mergers (Padoan, Nordlund, & Jones 1997; Chiosi et al. 1998; but see Scalo et al. 1998). Local tests are difficult to carry out because the remnants of the massive stars responsible for producing the UV photons at high redshift are neutron stars or black holes today. In the Galactic bulge, the best-fit slope for the mass function for $M < 1 M_\odot$ is $x = 0.33$ (Zoccali et al. 2000). Microlensing experiments (Udalski et al. 1994; Alcock et al. 1997) do not yet rule out the possibility that this slope could have continued up to $100 M_\odot$. More direct constraints on the star formation histories of LBGs will improve greatly over the next few years with the advent of the Space Infrared Telescope Facility, the Advanced Camera for Surveys, and ultimately the Next Generation Space Telescope.

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