STAR FORMATION RATES AND STELLAR MASSES OF $z = 7–8$ GALAXIES FROM IRAC OBSERVATIONS OF THE WFC3/IR EARLY RELEASE SCIENCE AND THE HUDF FIELDS

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ABSTRACT

We investigate the Spitzer/IRAC properties of 36 $z \sim 7$ $z_{850}$-dropout galaxies and three $z \sim 8$ $Y_{098}$ galaxies derived from deep/wide-area WFC3/IR data of the Early Release Science, the ultradeep HUDF09, and wide-area NICMOS data. We fit stellar population synthesis models to the spectral energy distributions to derive mean redshifts, stellar masses, and ages. The $z \sim 7$ galaxies are best characterized by substantial ages (> 100 Myr) and $M/L$ $\approx$ 0.2. The main trend with decreasing luminosity is that of bluing of the far-UV slope from $\beta \sim -2.0$ to $\beta \sim -3.0$. This can be explained by decreasing metallicity, except for the lowest luminosity galaxies (0.1$L_{\odot}$ $\approx$), where low metallicity and smooth star formation histories (SFHs) fail to match the blue far-UV and moderately red $H$ $-$ [3.6] color. Such colors may require episodic SFHs with short periods of activity and quiescence (“on–off” cycles) and/or a contribution from emission lines. The stellar mass of our sample of $z \sim 7$ star-forming galaxies correlates with star formation rate (SFR) according to $\log M^* = 8.70(\pm0.09) + 1.06(\pm0.10)\log\text{SFR}$, implying that star formation may have commenced at $z > 10$. No galaxies are found with SFRs much higher or lower than the past averaged SFR suggesting that the typical star formation timescales are probably a substantial fraction of the Hubble time. We report the first IRAC detection of $Y_{098}$-dropout galaxies at $z \sim 8$. The average rest-frame $U - V \approx 0.3$ (AB) of the three galaxies is similar to faint $z \sim 7$ galaxies, implying similar $M/L$. The stellar mass density to $M_{UV,AB} < -18$ is $\rho^*(z = 8) = 1.8^{+0.7}_{-1.0} \times 10^5 M_\odot \text{Mpc}^{-3}$, following log $\rho^*(z) = 10.6(\pm0.6) - 4.4(\pm0.7)\log (1 + z) [M_\odot \text{Mpc}^{-3}]$ over $3 < z < 8$.

Key words: galaxies: evolution – galaxies: high-redshift

Online-only material: color figures

1. INTRODUCTION

Until recently, only a modest number of relatively bright $z \gtrsim 7$ galaxies were known, mostly from wide-area NICMOS (Bouwens et al. 2008; Oesch et al. 2009; Bouwens et al. 2010c) and ground-based searches (Ouchi et al. 2009; Castellano et al. 2010; Hickey et al. 2010). The arrival of WFC3/IR on board Hubble Space Telescope (HST) has dramatically improved the situation by identifying the large numbers of $z \gtrsim 7$ galaxies by their redshifted UV light. Here, we report on $z \gtrsim 7$ galaxies selected from the WFC3/IR Early Release Science (ERS) observations over the GOODS-South field (Wilkins et al. 2009; Bouwens et al. 2010c), complemented with candidates from the recent ultradeep survey with WFC3/IR over the HUDF09 field (Oesch et al. 2010; Bouwens et al. 2010a; see also McLure et al. 2010; Bunker et al. 2009; Yan et al. 2009).

Little is known about the stellar masses, metal production, and the contribution of star formation to reionization in these galaxies. Mid-infrared observations with the InfraRed Array Camera (IRAC; Fazio et al. 2004) on Spitzer can be used to constrain the stellar masses and ages, which has led to the surprising discovery of quite massive $\sim 10^{10} M_\odot$ galaxies at $z \gtrsim 6$ (Eyles et al. 2005; Yan et al. 2006; Stark et al. 2009) and appreciable ages (200–300 Myr) and $M/L$s as early as $z \sim 7$ (Egami et al. 2005; Labbé et al. 2006; Gonzalez et al. 2010). The overall results suggest that the galaxies formed substantial amounts of stars at even earlier times, well into the epoch of reionization (Stark et al. 2007; Yan et al. 2006; Labbé et al. 2010).

In this Letter, we study the stellar populations of the largest sample of $z \gtrsim 7$ galaxies with IRAC measurements to date, focusing on correlations with luminosity and stellar mass, and implications for the mass density and $z \sim 8$. We adopt an $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$ cosmology with $H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}$. Magnitudes are in the AB photometric system (Oke & Gunn 1983).

2. OBSERVATIONS AND STELLAR POPULATION MODELING

Our sample consists of sources derived from the ultradeep WFC3/IR HUDF, the deep WFC3/IR ERS, and wide-area...
NICMOS over the CDF-S and CDF-N. Candidates were selected using the \( z \sim 7 \) dropouts and \( z \sim 8 \) Y98-dropouts, as used in Oesch et al. (2010), Bouwens et al. (2010b), and Gonzalez et al. (2010); see also Bouwens et al. 2010c). We now briefly discuss the IRAC photometry from the new ERS sample.

The Spitzer/IRAC data over the WFC3/ERS area in the CDF-S \((\approx 23.3 \text{ hr integration time})\) were obtained from the Great Observatories Origins Deep Survey (GOODS; M. Dickinson et al. 2010, in preparation).

The IRAC depths in the 3.6 and 4.5 bands are 27.1 and 26.5 mag \((1\sigma, \text{ total, point source})\), respectively. Obtaining reliable IRAC fluxes of the candidates is challenging because of the contamination from the extended point-spread function (PSF) wings of nearby foreground sources. We remove contaminating flux, by modeling the candidates and nearby sources using their isolated flux profiles and positions in the deep WFC3/IR maps as templates. We convolve the templates to match the IRAC PSF, simultaneously fit them to the IRAC map leaving only the fluxes as free parameters, and subtract the best-fit models to the foreground sources (see Labbé et al. 2006; Wuyts et al. 2007; Gonzalez et al. 2010; de Santis et al. 2007). After cleaning the IRAC images, we perform conventional aperture photometry in the 3.6 and 4.5 bands in 2/5 diameter apertures on 15 of the original \( 18 \) dropout galaxies over the WFC3/IR ERS. Three were too close to bright sources for reliable measurement. Fluxes were corrected by a factor \( \times 1.8 \) to account for light outside the aperture (consistent with point source profiles). Six of the 15 galaxies are undetected in IRAC \(([3.6] < 26.5, 2\sigma)\). Errors include the uncertainty in the best-fit confusion correction, added in quadrature.

We complete the sample with 21 \( z \approx 7 \) galaxies with IRAC measurements from the HUDF (Oesch et al. 2010; Labbé et al. 2010) and from the recent wide-area NICMOS search (Gonzalez et al. 2010; Bouwens et al. 2010c). The total sample consists of 36 \( z \approx 7 \) galaxies spanning 4 mag in \( H_{160} \). To investigate trends with magnitude, we stacked the flux densities of the galaxies in three \( \sim 1 \) mag bins centered on \( H_{160} \approx 26, 27, \text{ and } 28 \), containing 11, 15, and 10 galaxies, respectively. The uncertainties are determined by bootstrapping. Stacking increases the signal-to-noise ratio (S/N), in particular for faint galaxies, where the uncertainty in the mass is driven by the S/N in IRAC.

We derive stellar masses and redshifts by fitting stellar population synthesis models to the average spectral energy distribution (SED) fluxes using the \( \chi^2 \)-fitting code FAST (Kriek et al. 2009). We adopt Bruzual & Charlot (2003, BC03) models with a Salpeter (1955) initial mass function (IMF) between 0.1 and 100 \( M_\odot \). We explore several star formation histories (SFHs) and the effects of metallicity and dust. The differences in more recent models (e.g., Maraston 2005, S. Charlot & G. Bruzual 2010, in preparation) are small and will not be considered in detail (see Labbé et al. 2010). We fit models smoothed to a resolution of 100 Å rest frame, corresponding to the approximate width of the dropout selection windows. Adopting a Kroupa (2001) IMF reduces the stellar masses and star formation rates (SFRs) by 0.2 dex, but does not change other parameters or the quality of fit. The typical uncertainties in the derived average stellar masses, SFRs, age, and \( A_V \) for the stacked SEDs are 0.15 dex, 0.25 dex, 0.3 dex, and 0.1 mag, respectively. The photometry and best-fit model parameters are presented in Table 1.

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10 This paper uses data release DR2 of epoch 2, available from http://data.spitzer.caltech.edu/popular/goods/.

3. STELLAR POPULATIONS AND STAR FORMATION HISTORIES AT \( z \approx 7 \)

Figure 1 (left panel) shows the broadband SEDs of the \( z \approx 7 \) dropout galaxies in the 3 mag bins, with the best-fit BC03 stellar population models. The overall SED shapes are remarkably similar, with a pronounced jump between \( H_{160} \) and \([3.6] \) (or rest frame \( (U - V) \approx 0.5 \)) indicative of a modest Balmer break and evolved stellar populations \((>100 \text{ Myr})\). Focusing on the far-UV continuum, we find the slope \( f_1 \propto \lambda^\beta \) (traced by the \( J_{125} - H_{160} \) color) to be very blue and decreasing from \( \beta \sim -2 \) at \( H_{160} \approx 26 \) to \( \beta \sim -3.0 \) at \( H_{160} \approx 28 \). As discussed by Bouwens et al. (2010b), such extremely blue slopes require low dust content \( A_V < 0.1 \), very low metallicities, and/or very young ages. Small 0.04 mag changes in the WFC3/IR zero points (e.g., McLure et al. 2010) would cause changes of \( \beta \approx 0.17 \), comparable to the random uncertainties. The red \( H_{160} - [3.6] \) color, however, implies more evolved stellar populations \((>100 \text{ Myr})\), leaving the models seemingly unable to match the entire SED.

To explore the mismatch further we consider in more detail the effects on metallicity, SFH, and nebular emission. Figure 1 (right panel) shows the \( J_{125} - H_{160} \) versus \( H_{160} - [3.6] \) colors of the observed stacked SEDs. The lines show predictions of 0.2 \( Z_\odot \) BC03 models for various continuous SFHs (rising, constant, declining). Generally, evolved models are able to reproduce the joint \( J_{125} - H_{160} \) versus \( H_{160} - [3.6] \) colors of the more luminous \( z \approx 7 \) galaxies, but not the colors of the faintest, bluest galaxies. The arrows show the effect of changes in model assumptions, which we will discuss now.

1. Metallicities. Low metallicities (e.g., 0.2 \( Z_\odot \)) do a decent job in producing much bluer \( \beta \) than Solar at a given \( H_{160} - [3.6] \) color. Very low metallicities (1/50 Solar) produce even bluer \( \beta \)'s, but also bluer \( H_{160} - [3.6] \). Metallicity alone appears not enough to fully resolve the discrepancy.

2. Nebular emission. Nebular emission lines (NELs) likely contribute to the IRAC fluxes, reddening the \( H_{160} - [3.6] \) color. Empirical estimates of \([O III]5007 \) emission at \( z > 2 \) are scarce, but we can infer the possible effect from the observed strength of \( H_\beta \) at \( z > 2.2 \) (Erb et al. 2006). Assuming \( W_{H_\beta} = 200 \text{ Å} \) and \( W_{[O III]5007+4959,5007} = 2.5 \times W_{H_\beta} \), appropriate for 0.2 \( Z_\odot \) galaxies at \( z > 2 \) (Erb et al. 2006; Brinchmann et al. 2008), and adopting a redshift distribution of \( z = 6.9 \pm 0.5 \) (Oesch et al. 2010) we calculate a contribution of 0.18 mag to \([3.6] \) and 0.14 mag to \([4.5] \) (see Figure 1). Note, however, that no measurements of nebular lines at \( z \approx 7 \) exist. A second possible effect is nebular continuum emission (NEC), which would cause a reddening of both \( \beta \) and \( H_{160} - [3.6] \) (shown are the models of Schaerer 2002 with \( Z = 1/50 Z_\odot, t = 300 \text{ Myr} \) constant star formation (CSF), and 0% escape fraction). Both would reduce the discrepancy between models and data by allowing the models to extend to redder \( H_{160} - [3.6] \) at a given \( \beta \). Note that the extremely blue \( \beta \) may require high escape fractions \( f_{esc} \gtrsim 0.3 \) (e.g., Bouwens et al. 2010b), which would reduce the contribution of nebular emission.

3. Star formation histories. Declining SFHs can match the colors of the most luminous, redder galaxies, but their far-UV continua are too red for lower luminosity galaxies. In contrast, strongly rising SFHs \((\text{SFR} \propto t^\alpha, \alpha > 1)\) exhibit blue \( \beta \) but never reach red \( H_{160} - [3.6] \) in a Hubble time \((z = 7)\) and are formally excluded at the 95% confidence. CSF is a compromise, providing red \( H_{160} - [3.6] \) colors
generated by on-going assembly of stellar mass, and blue far-UV continua from on-going star formation. Finally, episodic SFH with a 50% duty cycle and 40 Myr duration (i.e., 20 Myr “on,” 20 Myr “off”) is found to have an interesting mix of properties. The luminous active phase of the cycle produces a bluer far-UV continuum for a given \( H_{160} - [3.6] \) color than CSF. The reverse is true in the dimmer passive state. The net result for a steep UV luminosity function (LF) is that the luminosity-weighted average of cycling galaxies displays bluer far-UV at a given \( H_{160} - 3.6 \) than CSF, also reducing the discrepancy.

In summary, the model colors match the observations of luminous \( z \sim 7 \) galaxies reasonably except for the lowest luminosity galaxies, where the blue \( \beta \sim -3 \) and the red \( H_{160} - [3.6] \sim 0.6 \) colors remain challenging to fit. Low-metallicity CSF models come close, but a contribution from nebular line emission to the [3.6] band and/or episodic SFHs are likely needed to resolve the mismatch.

4. STAR FORMATION RATE VERSUS STELLAR MASS AT \( z \sim 7 \)

Independent constraints on the SFHs can be obtained from the relation between SFR and stellar mass, as shown in Figure 2. The SFRs are calculated from the monochromatic 1500 Å luminosity following the prescription of Madau et al. (1998) and corrected for dust using the best-fit AV (mean \( \langle AV \rangle = 0.13 \) mag). The stellar masses are based on BC03 0.2 Z_⊙ models using exponentially declining SFHs with 8 < log \( \tau < 11 \) and reddening \( AV < 0.3 \). Uncertainties are determined by bootstrapping.

### Table 1

Summary of Photometry and Modeling of \( z \sim 7 \) Dropout Galaxies

| Object       | \( B_{435} \)  | \( V_{606} \)  | \( i_{755} \)  | \( z_{850} \)  | \( Y \)  | \( J_{125} \)  | \( H_{160} \)  | \( K \)  | \( [3.6] \)  | \( [4.5] \)  |
|--------------|---------------|---------------|---------------|---------------|---------|---------------|---------------|---------|---------------|---------------|
| ERS-2056344288 | 4.0(7.1)      | 1.2(5.0)      | 6.8(8.6)      | 13.5(9)       | 40.9(11) | 48.6(8)       | 61.3(10)      | –(–)   | 223.1(51)     | 134.7(89)     |
| ERS-2068424221 | –1.66(9.6)    | 2.4(5.5)      | 4.6(9.4)      | 26.4(10)      | 80.5(11) | 78.3(15)      | 56.4(10)      | –(–)   | 158.8(51)     | –5.5(89)      |
| ERS-211644168  | 6.8(6.2)      | 1.5(4.7)      | 7.4(7.5)      | 4.9(8)        | 20.1(8)  | 54.8(10)      | 43.1(8)       | –(–)   | 142.8(83)     | –54.0(89)     |
| ERS-2150242362 | 6.1(8.5)      | 0.9(7.5)      | –3.5(12.5)    | 14.3(15)      | 33.4(15) | 49.0(10)      | 68.7(14)      | –(–)   | 154.4(88)     | 98.9(106)     |
| ERS-2159043147 | 5.2(6.7)      | 4.7(6.0)      | 4.4(9.9)      | 9.2(12)       | 34.4(16) | 87.7(17)      | 79.7(15)      | –(–)   | 132.4(63)     | 193.7(120)    |
| ERS-2154043286 | –0.15(0.0)    | –1.4(4.3)     | 4.8(7.4)      | 17.7(8)       | 45.3(9)  | 45.0(11)      | 36.5(9)       | –(–)   | 11.5(62)      | –13.5(100)    |
| ERS-2160014591 | –6.0(9.9)     | –12.8(7.9)    | 4.7(13.5)     | 24.2(16)      | 68.2(15) | 88.9(16)      | 74.7(14)      | –(–)   | 271.0(87)     | 293.9(134)    |
| ERS-2161941498 | –0.8(7.1)     | –1.4(5.7)     | –3.2(9.8)     | 8.4(12)       | 25.7(10) | 42.9(10)      | 41.6(10)      | –(–)   | 64.4(51)      | 83.2(89)      |
| ERS-2202443342 | 7.2(8.8)      | –3.0(7.2)     | 5.6(10.3)     | 25.4(11)      | 42.5(11) | 55.2(12)      | 50.4(11)      | –(–)   | 145.9(51)     | 111.1(89)     |
| ERS-225241173  | 1.8(5.6)      | –2.0(4.4)     | –11.2(7.6)    | 15.3(8)       | 37.7(9)  | 40.6(8)       | 43.1(8)       | –(–)   | 89.0(51)      | 128.2(89)     |
| ERS-222653006  | –2.5(9.8)     | –8.7(7.6)     | 7.8(12.5)     | 48.6(14)      | 113.3(15) | 125.1(19)     | 182.5(13)     | –(–)   | 462.9(94)     | 276.5(152)    |
| ERS-2229340409 | –0.6(8.3)     | –0.6(7.0)     | 6.2(10.3)     | 18.8(11)      | 49.8(13) | 47.0(8)       | 64.4(11)      | –(–)   | 216.3(51)     | 110.8(89)     |
| ERS-229542044  | –0.2(7.8)     | 1.4(5.7)      | 3.7(10.2)     | 14.5(12)      | 54.8(13) | 70.9(13)      | 67.1(12)      | –(–)   | 124.7(82)     | 83.2(89)      |
| ERS-2352491047 | –3.7(6.0)     | 4.1(4.6)      | 4.9(7.6)      | 8.6(9)        | 19.7(7)  | 28.9(6)       | 31.9(7)       | –(–)   | 34.4(51)      | 54.4(89)      |
| ERS-2354425520 | 3.7(6.2)      | –0.7(4.6)     | 0.7(7.9)      | 15.1(9)       | 46.7(12) | 117.4(12)     | 106.5(11)     | –(–)   | 317.6(53)     | 21.5(101)     |

**Notes.** The optical-to-near-IR fluxes are measured in 0.4 diameter apertures. *Spitzer/IRAC fluxes are measured on the confusion-corrected maps in 25 diameter apertures. Fluxes are corrected to total assuming point source profiles. Units are nanoJy for the SEDs and AB magnitudes for the average colors. The total sample consists of 15 new sources from the WFC3/ERS sample (Bouwens et al. 2010c), nine sources from the NICMOS sample (UDF-1417,696,GNS-1,2,3,4,5,CDFS-4627,HD16-1216; Gonzalez et al. 2010), and 12 from the WFC3/UDS sample (UDFz-4471, 4257,3959, 3958, 3722, 4314, 3677, 3744, 4056, 3638, 3973, 3853; Oesch et al. 2010; Labbé et al. 2010). The stacked 3 band of the z \( \sim 7 \) galaxies is a combination of the Y105 and Y200 bands. SFR_{1500} is the SFR derived from the 1500 Åmonochromatic luminosity using the prescription of Madau et al. (1998) and corrected for dust using the best-fit AV (mean \( \langle AV \rangle = 0.13 \) mag). The stellar masses are based on BC03 0.2 Z_⊙ models using exponentially declining SFHs with 8 < log \( \tau < 11 \) and reddening AV < 0.3. Uncertainties are determined by bootstrapping.

The M/L can also be calculated from the individual galaxies, yielding the same answer (Gonzalez et al. 2010).
scatter of ~0.3 dex. We find no galaxies with SFRs much lower or higher than the past averaged SFR (i.e., strongly bursting or suppressed). Such galaxies would have satisfied our dropout criteria and would lie in the upper left or lower right corner in Figure 2. Their absence suggests that the typical star formation timescales are probably a substantial fraction of the Hubble time. Instead we find that only 4/22 sources with log SFR > 0.7 are undetected at [3.6] and no galaxies in the sample have SFRs substantially less than $M^*/(H_{\text{Hubble}})$.

To illustrate the diagnostic power of the $M^* -$ SFR diagram, we show in the inset of Figure 2 a simulation of galaxies with random formation times and exponentially declining SFRs ($\tau = 200$ Myr) to the same selection limits as our observed sample. The distribution is clearly different, with no correlation between $M^*$ and SFR, suggesting that star formation timescales for $z \approx 7$ galaxies are probably longer than that.

5. THE STELLAR MASS DENSITY AT $z \approx 8$

The detection of $z \approx 8$ galaxies with IRAC is enticing as it enables us to place stronger constraints on the stellar masses of the highest redshift galaxies than possible from the far-UV alone. Recent studies in the HUDF have found no detection (individual or stacked) for $z \approx 8$ galaxy candidates (Labbé et al. 2010), leaving estimates of the stellar mass density at these redshifts highly uncertain.

Here, we perform photometry on the three $z \approx 8$ Y$_{088}$-dropout galaxies in the WFC3/ERS sample of Bouwens et al. (2010c). These candidates are brighter than that found in the HUDF ($H \approx 27$ versus $H \approx 28$). Two galaxies are detected at [3.6] and we calculate an average S/N = 3.7 in [3.6] and S/N = 1.6 in [4.5] for the stack of all three (see Figure 3, top panels). The best fits are $z = 7.7^{+0.18}_{-0.15}$, high stellar age age$_w = 300^{+210}_{-220}$ Myr, mass-to-light ratios $M/L_V = 0.15$ and $M/L_{1500} = 0.1$, and log SSFR = $-8.7$. Overall, these properties are comparable to $H \approx 27$ $z \approx 7$ z$_{850}$-dropouts, suggesting modest evolution in the $M/L$ between $z = 8$ and $z = 7$.

Following the approach of Gonzalez et al. (2010) and Labbé et al. (2010), we derive integrated stellar mass densities at $z \sim 8$ by multiplying the UV luminosity densities integrated to $M_{UV,AB} = -18$ (Bouwens et al. 2010a, 2010c) by the mean $M/L$ derived for the $z \sim 7.7$ galaxies, yielding $\rho^*(z = 8) = 1.8^{+0.7}_{-1.0} \times 10^9 M_\odot$ Mpc$^{-3}$. We also recompute the $z \approx 8$ stellar mass density of Labbé et al. (2010) using the same $M/L$. Figure 4 shows the evolution of the stellar mass density from $z = 3$ to $z = 8$. The evolution over $3 < z < 8$ is well approximated by log $\rho^*(z) = 10.6(\pm 0.6) - 4.4(\pm 0.7) \log(1+z)$ [M$_\odot$ Mpc$^{-3}$].

6. SUMMARY

Using a large sample of 36 z$_{850}$-dropout galaxies based on deep/wide-area WFC3/IR data from the ERS, ultradeep data from the HUDF09, and wide-area NICMOS programs, we

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Footnotes:
12 We caution that source ERSy-2376440061 at [3.6] is close to pixels that are affected by "Muxbleed," which we subtracted using a third-order polynomial fit to the 20'' x 20'' background before performing photometry.
13 Following Labbé et al. (2006), we report SFH-weighted age$_e$, where age$_e = t/2$ for CSF and $t$ is the time elapsed since the start of star formation.
investigate the stellar population properties at extreme redshifts \( z \gtrsim 7 \). The main results are the following.

1. The average rest-frame far-UV slope at \( z \sim 7 \) becomes bluer with decreasing luminosity, from \( \beta \sim -2.0 (L^\ast_{\nu, z=3}) \) to \( \beta \sim -3.0 (0.1L^\ast_{\nu, z=3}) \), as reported by Bouwens et al. (2010b). The rest-frame \( U-V \) becomes bluer as well, but is still moderately red \( U-V \approx 0.3 \) at \( 0.1L^\ast_{\nu, z=3} \), apparently excluding extremely young ages \( <100 \) Myr. If the ages inferred from the simple model fits were correct, galaxies would have started forming stars very early-on, perhaps as high as \( z > 10 \). The blue far-UV slope and red \( U-V \) colors remain a challenge to fit, however, even for substellar metallicity models. Episodic SFHs with periods of activity and quiescence and/or a (~0.2 mag) contribution of emission lines to the [3.6] band may be required to resolve the mismatch.

2. The derived stellar masses correlate with the SFRs at \( z \sim 7 \) according to \( \log M^\ast = 8.70(\pm0.09) + 1.06(\pm0.10) \log SFR \), with relatively low scatter \( \sim 0.25 \) dex. Emission line contributions of \( \approx 0.2 \) mag to both [3.6] and [4.5] would shift the relation by \( \approx -0.2 \) dex in mass. The absence of galaxies with SFRs much lower or higher than the past averaged SFR (i.e., strongly bursting or suppressed) suggests that the typical star formation timescales are probably a substantial fraction of the Hubble time. Note that instantaneously quenched galaxies may fade too quickly to be selected as dropout galaxies.

3. The first Spitzer/IRAC detection of \( z = 8 \) galaxies and their red average \( H_{160} - [3.6] \approx 0.55 \) suggest that luminous early galaxies may have substantial \( M/L_V \approx 0.15 \), similar to \( z \sim 7 \) galaxies. The implied stellar mass density then increases gradually with time following \( \log \rho^\ast(z) = 10.6(\pm0.6) - 4.4(\pm0.7) \log(1+z) \left[M_\odot h^{-1} \mathrm{Mpc}^3\right] \) for \( 3 < z < 8 \).

Deeper IRAC data on \( z > 7 \) galaxies are needed to bolster these results. More NEL measurements of \( z > 2 \) galaxies would help to understand the possible contribution to the broadband fluxes. Additional modeling of the distribution of SFR versus \( M^\ast \) is needed to decipher the SFHs of \( z \sim 7 \) galaxies. Larger samples would enable a more secure assessment of the mass density evolution beyond \( z = 8 \).

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Figure 4. Evolution of the integrated stellar mass density. The red circle shows the $z \approx 7.7$ mass density, derived from the integrated UV luminosity density of Bouwens et al. (2010c) and the mean $M/L$ derived here. All data are converted to a common limit $M_{UV, AB} < -18$, using the UV LFs of Bouwens et al. (2010a). The WFC3/ERS data are corrected by +0.42 dex. The $z = 3–7$ luminous samples ($M_{UV, AB} < -20$) from the literature (Stark et al. 2009, blue circles; Gonzalez et al. 2010, magenta circle) are corrected by +0.38, +0.46, +0.57, and +0.75 dex at $z = 4, 5, 6,$ and 7, respectively. The HUDF requires no correction (Labbé et al. 2010, green circle). The red square shows the $z \approx 8$ sample. The dashed line shows a $\propto (1 + z)^{-4.4}$ evolution. The floating error bar indicates the expected cosmic variance for the $z \sim 8$ sample.

(A color version of this figure is available in the online journal.)

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REFERENCES

Bouwens, R. J., Illingworth, G. D., Franx, M., & Ford, H. 2008, ApJ, 686, 230
Bouwens, R. J., et al. 2010a, ApJ, 709, L133