SLOW EVOLUTION OF THE SPECIFIC STAR FORMATION RATE AT $z > 2$: THE IMPACT OF DUST, EMISSION LINES, AND A RISING STAR FORMATION HISTORY

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ABSTRACT

We measure the evolution of the specific star formation rate ($\text{sSFR} = \text{SFR}/M_{\text{stellar}}$) between redshift 4 and 6 to assess the reported “constant” sSFR at $z > 2$. We derive stellar masses and star formation rates (SFRs) for a large sample of 750 $z \sim 4$–6 galaxies in the GOODS-S field by fitting stellar population models to their spectral energy distributions. Dust extinction is derived from the observed UV colors. We evaluate different star formation histories (SFHs, constant and rising with time) and the impact of optical emission lines. The SFR and $M_{\text{stellar}}$ values are insensitive to whether the SFH is constant or rising. The derived sSFR is very similar (within 0.1 dex) in two $M_{\text{stellar}}$ bins centered at 1 and $5 \times 10^9 M_\odot$. The effect of emission lines was, however, quite pronounced. Assuming no contribution from emission lines, the sSFR for galaxies at $5 \times 10^9 M_\odot$ evolves weakly at $z > 2$ ($\text{sSFR}(z) \propto (1 + z)^{0.6 \pm 0.1}$), consistent with previous results. When emission lines are included in the rest-frame optical bands, consistent with the observed Infrared Array Camera [3.6] and [4.5] fluxes, the sSFR shows higher values at high redshift following $\text{sSFR}(z) \propto (1 + z)^{1.0 \pm 0.1}$, i.e., the best-fit evolution shows a sSFR $\sim 2.3 \times$ higher at $z \sim 6$ than at $z \sim 2$. This is, however, a substantially weaker trend than that found at $z < 2$ and even that expected from current models for $z > 2$ ($\text{sSFR}(z) \propto (1 + z)^{2.5}$). Even accounting for emission lines, the observed sSFR trends at $z > 2$ are still in tension with theoretical expectations.

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

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1. INTRODUCTION

Large samples of Lyman break galaxies (LBGs) have allowed for the study of the properties of high-redshift galaxies up to $z \sim 8$ (e.g., Bouwens et al. 2012, 2011; Dunlop et al. 2012; Finkelstein et al. 2012, 2010; González et al. 2010, 2011; Labbé et al. 2010a, 2010b; Lee et al. 2012; McLaren et al. 2010, 2011; Oesch et al. 2010, 2012; Papovich et al. 2011; Schaerer & de Barros 2010; Stark et al. 2009; Wilkins et al. 2011). These samples are the result of large investments on high quality Hubble Space Telescope (HST) data over deep fields like GOODS (Giavalisco et al. 2004) that have rich complementary multi-wavelength coverage. Several studies have explored the observed UV and optical colors of these galaxies. Through the standard technique of synthetic stellar population (SSP) modeling of the observed spectral energy distributions (SEDs), the physical properties of these galaxies, such as the stellar mass ($M_{\text{stellar}}$), star formation rate (SFR), dust attenuation, age, etc., have also been explored (e.g., Yan et al. 2006; Eyles et al. 2005; Stark et al. 2009; González et al. 2010, 2011; Papovich et al. 2011; Lee et al. 2012; Bouwens et al. 2009, 2012).

These studies have shown that, at rest-frame UV and optical wavelengths where LBGs are more amenable to observations, the SEDs show very similar colors with weak trends of bluer colors as a function of decreasing UV luminosity and increasing redshift (Bouwens et al. 2009, 2012; Wilkins et al. 2011; Finkelstein et al. 2012; but see also Dunlop et al. 2012). As a direct consequence of this, the physical properties estimated through SED fitting, using simple models, are also remarkably similar.

Particularly intriguing are the results that indicate that the specific star formation rate (sSFR) of sources with a given $M_{\text{stellar}}$ remains approximately constant from $z \sim 2$ to $z \sim 7$ (Stark et al. 2009; González et al. 2010; McLaren et al. 2011). In particular, González et al. (2010) shows that for sources with $M_{\text{stellar}} = 5 \times 10^9 M_\odot$, the sSFR shows no evidence for significant evolution ($\text{sSFR} \sim 2 \text{Gyr}^{-1}$) from $z \sim 7$ to $z \sim 2$. Such a result is at odds with the fairly generic theoretical expectation that the sSFR should decrease monotonically with cosmic time (e.g., Weintrnann et al. 2011; Khochfar & Silk 2011).

Although suggestive, much of the early work pointing toward a relatively constant sSFR was limited in many important aspects and based on a number of simplifying assumptions. For example, early work assumed zero dust extinction for the SFRs of $z > 4$ galaxies. This was motivated by the very blue UV colors observed in the galaxy SEDs, which have subsequently been measured more accurately thanks to the better wavelength coverage provided by HST/WFC3 observations (e.g., Bouwens et al. 2012). Early works also adopted exponentially declining or constant star formation histories (SFHs). This is in apparent contradiction with the evolution of the UV luminosity function (LF), which suggests that rising SFHs are a better match for the evolution of galaxies in early cosmic times (e.g., Papovich et al. 2011). Finally, much of the early work did not correct for the effect of optical emission lines on the estimate of stellar masses ($M_{\text{stellar}}$), and hence on the sSFRs.

Several recent studies have attempted to redress some of these shortcomings. Bouwens et al. (2012), for example, used new measures of the dust extinction (based on UV colors) to correct the earlier sSFR estimates at $z \sim 4$–7. Schaerer & de Barros (2010) considered the possible effects of the optical emission lines on the stellar masses and sSFRs derived for high-redshift
galaxies, and this effort has been considerably extended in de Barros et al. (2012; see also Curtis-Lake et al. 2013).

In this paper we attempt to bring more consistency in the exploration of the aforementioned issues, exploring the effect of dust reddening in the UV colors, SFRs, and $M_\text{stellar}$ measurements, as well as the effects of choosing a SFH that better matches the evolution of the UV LF, simultaneously. The goal is to make estimates for the physical properties of $z > 4$ LBG that use empirically motivated assumptions that better match a larger range of observations. We plan to investigate whether this new set of assumptions still shows an approximate plateau in the sSFR at $z > 2$ or shows evidence for an increase toward high redshift as predicted by theory.

We now provide a brief plan for this paper. In Section 2, we briefly describe the observational data and selection criteria used. In Section 3, we describe our approach to stellar population modeling, detailing the specific assumptions that we make and the effects these assumptions have on the physical properties we derive for LBGs. In Section 4 we present the new measurements of the sSFR at high redshift. We discuss the results in Section 5, and summarize our findings in Section 6.

Throughout, we use a ($H_0$, $\Omega_m$, $\Omega_\Lambda$) = (70 km s$^{-1}$, 0.3, 0.7) cosmology when necessary and we quote all magnitudes in the AB system (Oke & Gunn 1983).

2. DATA

This work is based on a large sample of star-forming galaxies in the $z \sim 4$–7 redshift range found using the Lyman break technique (Steidel et al. 1996) primarily in the ultra-deep HUFD/WFC3 field (e.g., Oesch et al. 2010), and the deep Early Release Science (ERS; Windhorst et al. 2011) fields. For the $z \sim 6$ (i-dropout) search, we have also used the more recent CANDELS GOODS-S data to obtain a larger sample. All these fields have deep HST/ACS (Giavalisco et al. 2004) and WFC3/IR imaging, as well as the 23 hr Spitzer/IRAC data from the GOODS program (Giavalisco et al. 2004). The sample has already been presented in González et al. (2011), Bouwens et al. (2007), and Bouwens et al. (2012) but we provide a short summary here.

2.1. HST ACS and WFC3/IR Photometry and Sample Selection

Over the ERS and the CANDELS GOODS-S field, both the Advanced Camera for Surveys (ACS) optical ($B_{353}$ $V_{606}$ $i_{775}$ $z_{850}$) and the WFC3/IR ($Y_{105}$ $J_{125}$ $H_{160}$) images from HST reach depths of $\sim$28 mag (5σ measured on 0.35 diameter apertures). In the HUDF field, the ACS optical data ($BVIZ$) are 1.5–2 mag deeper, and the WFC/IR data ($Y_{105}$ $J_{125}$ $H_{160}$) are 1.5 times deeper than the ERS.

The HST photometry for these sources was performed using the SExtractor code (Bertin & Arnouts 1996). The images were registered to a common frame and then point-spread-function (PSF)-matched to the $H_{160}$-band data. SExtractor was run in double-image mode with the detection image constructed from all images with coverage redward of the relevant Lyman break. Fluxes are measured using Kron-style photometry. The criteria used to select sources are as follows (for details and contamination rates please refer to Bouwens et al. 2007):

- $z \sim 4B$-dropouts:

$$B_{353} - V_{606} > 1.1 \land (B_{353} - V_{606} > (V_{606} - z_{850}) + 1.1) \land (V_{606} - z_{850} < 1.6),$$

- $z \sim 5V$-dropouts:

$$(V_{606} - i_{775} > 0.9(i_{775} - z_{850}) + 1.9) \lor (V_{606} - i_{775} > 2) \land (i_{775} - z_{850} < 1.3),$$

- $z \sim 6i$-dropouts:

$$(i_{775} - z_{850} > 1.3) \land (z_{850} - J_{125} < 0.8).$$

The combined samples contain a total of 729 sources at $z \sim 4$, 178 at $z \sim 5$, and 277 at $z \sim 6$ (see Table 1).

2.2. Spitzer/IRAC Photometry

While the HST/ACS and WFC3/IR data allow us to find LBGs at $z \geq 4$ and to study their rest-frame UV light, data from Spitzer/IRAC is needed to sample the rest-frame optical light from such high-redshift galaxies. These constraints are crucial to derive reliable stellar masses from SED fitting (Papovich et al. 2001; Labbé et al. 2010a).

The HUDF and the ERS fields were imaged with Spitzer in the four Infrared Array Camera (IRAC) channels as part of the Spitzer GOODS program (Dickinson et al. 2003). In this work we only make use of the two most sensitive channels centered at 3.6 and 4.5 μm respectively. The images have integrations of $\sim$23.3 hr (the HUDF was imaged twice, thus amounting to a total exposure of $\sim$46.6 hr). The depths of the images were measured dropping 2′5 diameter apertures in empty regions of the image and determining the rms. After applying a 1.8 times flux correction to account for the light outside such aperture in the case of a point source, the depths correspond to 27.8 mag (1σ) for a single 23.3 h image in the [3.6] channel and 27.2 mag for the [4.5] channel.

The size of the IRAC PSF, however, is too broad to use standard photometric techniques on our sample of faint LBGs. The flux within an aperture is expected to be contaminated by flux from neighboring sources spilling over onto the same aperture. The neighboring sources are in general brighter and the contaminating fluxes can be significant. The availability of higher resolution images (though at different wavelengths) with HST allows us to model the source and its neighbors and subtract off the expected contaminating flux in our apertures. This method has already been described in several previous works (Labbé et al. 2006, 2010a, 2010b; González et al. 2010, 2011; Wuyts et al. 2007; de Santis et al. 2007). After the area around the source has been cleaned from the flux of neighbors, we perform standard aperture photometry using 2′5 diameter apertures. An aperture correction is derived from the higher resolution “template” image, in this case the WFC3/IR $H_{160}$ image. This image is convolved to the resolution of IRAC and an aperture correction factor is estimated for a 2′5 diameter

| $z \sim 4$ | $z \sim 5$ | $z \sim 6$ |
|---|---|---|
| ERS | 270 (524) | 77 (123) | 29 (36) |
| HUDF | 137 (205) | 41 (55) | 54 (59) |
| CANDELS | 143 (182) | | |
| Total | 407 (729) | 118 (178) | 226 (277) |

Notes. Number of sources in our $z \sim 4$, $z \sim 5$, and $z \sim 6$ samples. IRAC photometry of these sources requires fitting and subtraction of the flux from surrounding foreground neighbors. This is not possible in all the cases. The table shows the number of sources in our samples with clean IRAC photometry and the total number of sources in these samples in parenthesis. To improve the number statistics at $z \sim 6$ we have extended the sample by including the GOODS-S CANDELS data.
aperture. This correction factor is then applied to the fluxes measured with IRAC and involves multiplying the flux of sources (in 2.5 diameter apertures) by 1.8 in both the [3.6] and [4.5] IRAC channels, consistent with the correction one would apply to point sources.

The cleaning procedure cannot always produce acceptable models of the source and neighbors, resulting in poor subtractions for approximately 40% of the cases. The individual cleaned stamps were inspected by hand and those with poor subtractions were excluded from the subsequent analysis. This criterion mostly depends on the feasibility of modeling the neighboring sources, and as a consequence, is not expected to introduce any significant biases in our results.

3. STELLAR POPULATION MODELING

It has been customary to study the physical properties of high-redshift galaxies by comparing their observed UV and optical SEDs with SSP models. The quality of the flux constraints is generally not adequate to constrain all model parameters simultaneously. In particular, models with a variety of metallicities, initial mass functions (IMF), and SFHs can all reproduce the flux constraints almost equally well. As a result, these model parameters must be constrained independently or fixed to reasonable values. In the following analysis we have assumed a Salpeter (1955) IMF with cutoffs at 0.1 and 100 $M_{\odot}$.

It is expected that the metallicities of high-redshift galaxies be somewhat lower than that of local galaxies. For example, Maiolino et al. (2008), from a small sample of $z \sim 3.5$ galaxies determines gas metallicities of $\sim 0.2 Z_{\odot}$. A number of other observational studies have also found similar metallicities (e.g., Pettini et al. 2000), and 0.2 $Z_{\odot}$ is also expected in many carefully constructed cosmological hydrodynamical simulations (e.g., Finlator et al. 2011). In our analysis we therefore assume a fixed metallicity of 0.2 $Z_{\odot}$. The resulting SFRs and stellar masses, which are the focus of this work, are only weakly sensitive to this assumption.

For the SFHs, most early studies have generally assumed models with SFRs that decline exponentially as a function of $\tau$ left as a free parameter. The particular case $\tau \rightarrow \infty$, which corresponds to models with constant star formation (CSF), is sometimes used as the fiducial model. Because in a smooth SFH the UV luminosity can be directly linked to the SFR, these SFHs would predict a UV LF that shifts to brighter luminosities at increasing redshift (or one that remains constant in the CSF case), which is at odds with the current determinations of the UV LF at $z > 4$ (Bouwens et al. 2007, 2012; McLure et al. 2009; Oesch et al. 2010). If the SFHs, are in fact smooth, then the observed overall dimming of the UV LF predicts a mean SFH that is better characterized by a rising SFR (Papovich et al. 2011; Stark et al. 2009; Reddy et al. 2012). P. Oesch et al. (in preparation), shows that the evolution of the UV LF can be well reproduced by an exponentially rising SFH with a characteristic timescale $\tau \sim 500$ Myr (see also Smit et al. 2012; Papovich et al. 2011). In deriving the physical properties of galaxies in our samples, we will look in detail at the extent to which these parameters depend on whether we assume a constant or rising star formation (RSF) history. We particularly examine the effects on the sSFR and its evolution with redshift.

3.1. Reddening

In addition to the necessary simplifying assumptions described at the beginning of this section, other complications remain in the SED fitting process. In particular, it is known that the effects of reddening produced by dust and the reddening produced as a consequence of the aging of the population are largely degenerate. This does not have a substantial impact on the stellar masses which generally remain constrained within $\sim 0.3$ dex for a range of ages, but the varying dust corrections have a direct impact on the determination of the SFRs.

This degeneracy cannot be broken with the current data. However, one potentially fruitful way forward for us is to not consider the full range of stellar population models available to us (with ranging ages and dust extinctions) and to estimate the dust extinction for individual galaxies based on the UV continuum slope we observe using known IRX-β relations (e.g., Meurer et al. 1999). Not only does this approach have some justification based on observations of $z \sim 0-2$ galaxies (e.g., Meurer et al. 1999; Reddy et al. 2012), but following this approach we are able to naturally reproduce the UV color-luminosity and UV-to-optical color–luminosity relations.

Figures 1 and 2 show the observed colors of our $z \sim 4-6$ samples. The top panel of Figure 1 shows the observed $i_{775} - [3.6]$ color as a function of observed $[3.6]$ mag. The different symbols are used to divide the IRAC detected (2σ, solid blue circles), the marginal detections (1σ–2σ, open squares), and the non-detections (open gray circles). The histogram shows the color distribution of the sample. The two solid horizontal lines show the minimum color (corresponding to a $> 10$ Myr old population) and maximum color (set by the age of the universe at $z \sim 3.5$) of a CSF model in the absence of dust reddening. The thick dashed line is a fit to the detected points only and shows a trend to redder UV-to-optical colors for brighter galaxies.

The middle panel of the figure shows the UV-slope characterized by $\beta (f_\beta \propto \lambda^{\beta})$, as a function of the magnitude in the [3.6] channel. A similar trend to redder colors for brighter sources is observed. The UV-slope $\beta$ was measured by fitting a power law to all the available HST/ACS and WFC3/IR photometric points for any given source (e.g., as done by Bouwens et al. 2012 or Castellano et al. 2012).

Bouwens et al. (2012) study the dependence of $\beta$ with UV luminosity and finds a similar trend (see also Finkelstein et al. 2012; McLure et al. 2011). As argued in that work, $\beta$ can be affected by several factors but it is most strongly dependent on the total dust content (which sets the normalization applied to the dust curve assumed).

The bottom panel of Figure 1 shows the result of applying a dust reddening correction derived solely from the UV-slope to the UV-to-optical color. We find that the uncorrected trend in UV-to-optical colors versus [3.6] is best fit by the relation $(i_{775} - [3.6]) = -0.25 \times [3.6] + \text{const}$ After applying the dust correction the trend is now flatter $(i_{775} - [3.6])_{\text{dust-corrected}} = -0.10 \times [3.6] + \text{const}$ and most sources in the sample are in the color range that is covered by our dust-free CSF models (see also Oesch et al. 2013). The trend in UV-to-optical colors (after removing the effect of dust) still shows a slight dependence on the [3.6] luminosity, but this is probably due to the fact that sources that are brighter in the rest-frame optical are on average older. This is similar to the results shown in Labbé et al. (2007), who show that the UV and UV-to-optical color trends exhibited by star-forming galaxies in the $z \sim 0.7-3.5$ range can be primarily explained by the effects of dust reddening, with a small contribution due to age. Figure 2 shows a very similar behavior at $z \sim 5$ and 6.

In view of this result, and to alleviate the difficulties produced by the age-dust degeneracies, in the following modeling we
establish the dust reddening directly from the observed UV slope $\beta$ following the Meurer et al. (1999) relation:

$$A_{1600} = 4.43 + 1.99\beta,$$

where $A_{1600}$ is the attenuation in magnitudes at 1600 Å. The attenuations at other wavelengths are determined using a Calzetti et al. (2000) extinction curve. Sources with $\beta < -2.23$ are assigned $A_{1600} = 0$. 

3.2. Photometric Redshifts

Spectroscopic redshifts at $z > 4$ are sparse and generally biased toward bright sources or sources with Ly$\alpha$ emission. Given the limited spectroscopic sample and their current biases we will instead rely on photometric redshifts derived from our SED fitting with the code FAST (Kriek et al. 2009).

The models used to estimate these redshifts correspond to the Bruzual & Charlot (2003, BC03) stellar population models with constant SFH (described in more detail below). These models do not incorporate emission lines.

One of the goals of the current study is to assess the effect that emission lines can have on the properties derived through SED fitting, in particular on the sSFR. Adding emission lines to the models can have important effects on the photometric redshifts that will also impact the stellar masses. For example, if emission lines are included in the models, galaxies with significantly blue observed [3.6]–[4.5] colors are more likely to be placed at a redshift where emission lines can contribute to the IRAC photometry. This is because the optical colors of the stellar continuum are usually red and only the addition of emission lines can produce blue colors—at particular redshifts. If the photo-$z$ places the galaxy at a redshift where the IRAC photometry is contaminated by emission lines, the derived stellar masses will be lower compared to the case without emission lines.

A problem arises because the strengths of the lines and the line ratios assumed and added to the models have a directly impact on the photometric redshift likelihood and, as a consequence, on the stellar masses. We would like to study the effects of different assumptions for the strengths of the emission lines and it would be useful to disentangle the effects of the emission lines on the photometric redshift and on the stellar masses.
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Figure 3. Photometric redshift distribution of each of the samples (histograms) compared to the redshift distribution expected from the color selection criteria described in Section 2.1 (solid lines). The photometric redshifts are determined using the rest-frame UV photometry only and ignoring the IRAC photometry to avoid possible effects introduced by the rest-frame optical emission lines on the photometric redshifts. The redshifts are primarily driven by the observed wavelength of the Lyman break. The photometric redshifts shown here are used for the SED modeling throughout the analysis.

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

Since we will concentrate mostly on the effects that emission lines have on stellar mass and SFR, we have chosen to derive photometric redshifts (and confidence intervals) excluding the IRAC photometry, effectively removing the possible effect of optical emission lines on the photometric redshifts. Hence these redshifts are mostly driven by the observed wavelength of the Lyman break. The phot-zs are only derived once and are used throughout (in particular, the same phot-z are used for all the modeling variations explored in the paper).

Figure 3 shows the redshift distributions obtained for each sample (we have ignored secondary redshift solutions in the phot-z). These are in very good agreement with the expectations from the LBG selection (e.g., Bouwens et al. 2007).

3.3. The Constant Star Formation Model

We have used the FAST (Kriek et al. 2009) SED fitting code to fit the observed rest-frame UV + optical SEDs of the galaxies in our sample with a set of SSP models (we use the Bruzual & Charlot 2003 models). In this section we present the results obtained when a smooth CSF rate history is assumed. We have assumed a metallicity $Z = 0.2 Z_\odot$, and a Salpeter (1955) IMF with cutoffs at $0.1 M_\odot$ and $100 M_\odot$. The photometric redshifts (and the confidence intervals) used throughout the modeling do not include the IRAC photometric measurements or constraints (see Section 3.2). The set of models considered in this section only include fits to the stellar continuum fluxes. They do not include emission lines. Models that include emission lines are considered later.

Additionally, and as described in previous sections, we do not leave the reddening by dust as a free parameter in our modeling, but rather fix it based on the observed UV slope $\beta$ (Equation (1)). In doing so, we greatly simplify the stellar population modeling of high-redshift galaxies by eliminating the very significant degeneracy between dust and age. While the impact of this degeneracy on the derived stellar mass is generally $\lesssim 0.3$ dex.

The results of the SED fitting procedure are shown in Figure 4. The figure shows the SFR versus $M_{\text{stellar}}$ for the $z \sim 4$ (top, blue), $z \sim 5$ (middle, green), and $z \sim 6$ (bottom, red) sources. The dashed lines show the minimum and maximum values of $M_{\text{stellar}}$ that our models allow for. The distributions are very similar at all redshifts, suggesting little evolution of

Figure 4. SFR vs. $M_{\text{stellar}}$ relation for our samples at $z \sim 4$ (top, blue), $z \sim 5$ (middle, green), and $z \sim 6$ (bottom, red). Only sources with reliable cleaned IRAC photometry are considered (see text Section 2.2). Stellar masses and SFRs were derived assuming a CSF history. The dust reddening in the model has been derived directly from the UV slopes $\beta$ of each sources according to Equation (1). In all panels, solid circles indicate sources that are detected ($>2\sigma$) in the Spitzer/IRAC [3.6] channel and hence their masses can be more accurately estimated; open squares indicate marginal detections ($1\sigma$–$2\sigma$); and open gray circles indicate IRAC-undetected galaxies. The dashed lines indicate the minimum and maximum $M_{\text{stellar}}$ that a galaxy can reach assuming that it has been forming stars at a constant rate, for the minimum age included in our models (10 Myr) and for the age of the universe at $z \sim 3.5, 4.5,$ and 5.5 (from top to bottom).

(A color version of this figure is available in the online journal.)
Figure 5. Comparison of the SFRs derived using different model assumptions. In all panels, the solid symbols represent sources that are detected (>2σ) in IRAC [3.6], open squares show marginal detections (1σ–2σ), and open gray circles show IRAC-undetected sources. The top row shows the comparison of the SFRs derived assuming rising star formation histories and constant star formation histories. The bottom row shows the effect that correcting for optical emission lines have on the SFRs. The solid lines correspond to the identity. Overall, we find that the derived SFRs are not very sensitive to the model assumptions.

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

this relation, consistent with previous results that use similar assumptions (Stark et al. 2009; González et al. 2010, 2011). It should be noted, however, that in previous works, the relation presented generally corresponds to SFRs that have not been corrected for dust extinction. Figure 4 shows the intrinsic SFRs, i.e., after correction for dust reddening and dimming. The stellar masses have been derived from the same models used to derive the SFR. The fact that the relations still show little evolution is a consequence of the UV and optical colors being similar, implying similar properties of the galaxies as a function of redshift, including dust corrections (see also González et al. 2012; Bouwens et al. 2012).

A small fraction of the sample shows ages that are extremely young, crowding the 10 Myr dashed line. These sources are generally sources that are marginally detected or non-detected in the IRAC channels. The very blue UV-slopes of these sources dominate the fitting, driving them to young ages. It is possible that they are indeed very young but this is hard to establish with the depths of the IRAC data used here (see also Oesch et al. 2013; where the fraction of young sources at z ~ 4 is estimated to be very small at the bright end based on the rest-frame UV-to-optical colors). The analysis in this paper focuses on the more massive sources that are detected in Spitzer/IRAC, so this small fraction of the population should not bias our main results.

In the following sections we explore the impact of two important ingredients that have not been taken into account in our previous modeling. We use the results from the CSF model as our base for comparison. Our first major consideration is the impact of assuming a rising SFH (which reproduces better the evolution of the UV LF at z > 3) on our SFR and stellar mass estimates. Our second major consideration is to explore the effects of emission lines on the derived physical parameters.

3.4. The Rising Star Formation Model

Under the assumption of a smooth SFH, the UV luminosity of galaxies is related to their SFR (e.g., the Madau relation; Madau et al. 1998; see also the SFR functions derived from the UV LFs—Smit et al. 2012). The exact form of the relation does not change strongly between different smooth SFHs if the ages considered are older than ~100 Myr. Based on this relation, the previously presented model with a CSF history, makes a clear prediction for the evolution of the UV LF: it predicts a LF that does not change with redshift. This has been thoroughly ruled out using large samples of LBGs at z > 4 (e.g., Bouwens et al. 2007, 2011; Oesch et al. 2010).

The observed UV LF evolves with cosmic time showing a brighter characteristic magnitude at lower redshifts at least until z ~ 3. A model that better matches the observed evolution is one in which the average SFR of galaxies rises with time (e.g., Papovich et al. 2011; Reddy et al. 2012; Smit et al. 2012), something that has also been predicted in several numerical simulations (e.g., Finlator et al. 2011; Jaacks et al. 2012a).

By following sources at a constant cumulative number density \( n(<M_{UV}) = 2 \times 10^{-5} \text{ Mpc}^{-3} \) as a function of redshift, Papovich et al. (2011) derive a best fit exponentially rising SFH of the form SFR \( \propto e^{(z-\tau)/\tau} \), with \( \tau = 420 \) Myr (they find a slightly better fit using a linear model but the differences are not large). A similar analysis at multiple values for the number density yields a similar result, with a best fit \( \tau \sim 500 \) Myr at all densities (P. Oesch et al., in preparation). The goal of the following analysis is to study the effects of such a model on the determination of the stellar masses and SFRs. The details of the SFH used are not important as long as it agrees (or at least agrees better than the CSF model) with the evolution of the UV LF.

We have re-determined the SFRs and stellar masses for the galaxies in our sample using a RSF model as described before
A CSF is assumed. The strength of the emission lines assumed can be seen in Figure 7. The effects on the stellar mass are larger at this redshift.

Figure 6. Comparisons of the stellar masses we derive using different model assumptions. In all panels, the solid symbols represent sources that are detected (>2σ) in IRAC [3.6], open squares show marginal detections (1σ−2σ), and open gray circles show IRAC-undetected sources. The solid line corresponds to the identity. The left column shows the z ∼ 4 sample (blue), the middle is the z ∼ 5 (green), and the right column shows the z ∼ 6 sample. The horizontal axis shows the stellar masses derived from a model with exponentially rising star formation rate (SFR ∝ M^−1/τ, where t ∼ t_0 is the age, and τ = 500 Myr). This model is explicitly constructed to reproduce the observed evolution of the UV LF. Both M_{CSF} and M_{RSF} are derived with models with stellar continuum only. When only the detected sources are considered, the mean M_{CSF} and the M_{RSF} are consistent with each other, but with a scatter of −0.25 dex. The IRAC undetected and marginal detections show a slightly larger mass for the RSF determinations. The vertical axis for the lower set of panels shows the determinations of the stellar mass using a model that assumes strong optical emission lines which evolve with redshift (see Section 3.4). A CSF is assumed. The strength of the emission lines assumed can be seen in Figure 7. The effects on the stellar mass are larger at z ∼ 6 where they cause an average decrease in the stellar mass of −0.26 dex for IRAC detected sources. This is expected as both IRAC channels present large contributions of flux from emission lines at this redshift.

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

As can be seen in the Figure 6 (top row) there is a significant scatter (∼0.25 dex) in the comparison between the CSF and the RSF stellar masses. The mean value, however, does not change significantly when the IRAC detected sources are considered (solid circles). The IRAC-undetected sources, meanwhile, show a slight bias toward larger RSF masses, but this could be attributed to the poor constraints in the rest-frame optical, which is very important to derive stellar masses. This is consistent with a recent report by Reddy et al. (2012), who also find that the average M_{stellar} does not change between models with CSF and RSF for a sample of galaxies at z ∼ 2–3. It is however, inconsistent with the reports of Papovich et al. (2011), who finds larger stellar masses when a RSF is assumed. In their analysis, however, the age is fixed with a formation redshift z = 11, artificially fixing the ages of the sources.

There is one important observation regarding the RSF models. A significant fraction of the sources that we have modeled result with ages that correspond to the maximal allowed in our set of models. This is a result of the fairly red UV-to-optical colors exhibited by these galaxies (after dust reddening corrections). The models considered here only include stellar continuum light, and as a consequence, these red colors can only be interpreted as older ages. Two possible ways to alleviate this tension are: the presence of emission lines that would contribute to the flux measured with Spitzer/IRAC (Schaerer & de Barros 2010); or a non-smooth component to the SFH such that the SFH is rising on average but there is a characteristic duty cycle that make the colors redder at any given age (Labbé et al. 2010a; see also recent simulation results by, e.g., Jaacks et al. 2012b). Since many of the sources that present maximal age at z ∼ 4 are expected to be free of emission line contamination given their redshifts, the actual solution to the problem is probably a combination of both scenarios.

In summary, both the SFRs and the stellar masses obtained from the RSF are on average the same as for the CSF model. We would therefore not expect the average sSFR to be substantially affected by whether one adopts a RSF or CSF history for the stellar population modeling.

3.5. The Possible Impact of Optical Emission Lines

We turn now to the effect of the possible contribution of emission lines to the rest-frame optical photometry. These lines are not expected to affect significantly the SFRs derived from SED fitting but they can, in principle, have a strong effect on the values derived for the stellar masses.
It has been suggested that a (possibly large) fraction of the flux detected with Spitzer/IRAC from galaxies at \( z \gtrsim 4.5 \) could be coming from nebular regions associated with star formation in the form of emission lines (e.g., Schaerer & de Barros 2010). Unfortunately, it is not possible to directly observe these emission lines in \( z > 4 \) galaxies with spectroscopy using current facilities.

Nonetheless, we can infer the approximate strength of these emission lines indirectly. For example, in a recent study, Shim et al. (2011) used a spectroscopic sample at \( 3.8 < z < 5.0 \) to study the \( \text{H}\alpha \) EW from broad band photometry. In this redshift range, \( \text{H}\alpha \) falls in the IRAC [3.6] filter, adding to the rest-frame optical continuum flux at this wavelength. However, \( \text{H}\alpha \) does not contribute to light in the adjacent \( K \)-band or IRAC [4.5] filters, making it possible to infer the EW of this emission line. Shim et al. (2011) find a median \( \text{H}\alpha \) EW of \( \sim 480 \) \( \text{Å} \). While this experiment shows that there is a fraction of the star-forming population at \( z \sim 4 \) with strong line emission, the objects selected by Shim et al. (2011) are not expected to be typical for the full population. In a recent similar study, Stark et al. (2013) find a lower mean \( \text{H}\alpha \) EW = \( 270 \) \( \text{Å} \) in the same redshift interval. Independent evidence for extreme line emitters at \( z \gtrsim 2 \) come from Atek et al. (2011) who identify a large sample of such objects at \( z \sim 2.5 \) based on \( \text{HST} \) WFC3/IR Grism data.

Since the direct observation of emission lines at these redshifts is not currently possible, we need to make assumptions based on our understanding of these lines at lower redshift. At \( z \sim 2-2.5 \), for example, Erb et al. (2006) find that the rest-frame EW of \( \text{H}\alpha \) for galaxies with \( \log_{10}(M_{\text{stellar}}/M_\odot) \sim 10.0-10.5 \) is \( \sim 100 \) A. The EW shows an increase with decreasing \( M_{\text{stellar}} \). Moreover, this EW also seems to increase toward higher redshift. In a study based on \( \text{HST} \) Grism spectroscopy from the 3D-HST survey (Brammer et al. 2012), Fumagalli et al. (2012) find that the \( \text{H}\alpha \) EWs of \( 10^{10-10.5} M_\odot \) galaxies at \( z \sim 0-2.5 \) are best fit by the following relation:

\[
EW(z) \sim 15.8 \times (1+z)^{1.52} \text{Å},
\]

The typical strength of the optical emission lines at higher redshifts and lower masses will likely remain uncertain for some time. In the following, we estimate the effects that seem plausible based on these observations.

We take two different approaches. In our first, more conservative approach, we will assume that the mean \( \text{H}\alpha \) EW observed at \( z \sim 2-2.5 \) (Erb et al. 2006) remains constant at \( 100 \) A at all redshifts \( z > 3 \) and stellar masses. Given the trends in the EW described earlier with stellar mass and redshift, this is likely an underestimate of the EW exhibited by real galaxies at very high redshift. A more extreme approach is to assume that the trends observed at \( z \sim 0-2.5 \) continue to higher redshifts following the same extrapolation (Equation (2)). We call this the maximal emission line model. For each of the models (conservative and maximal) we derive the strength of all the other emission lines based on the flux ratios from Anders & Fritze-v. Alvensleben (2003) assuming a \( Z = 0.2 Z_\odot \) metallicity and a flat \( F_{\nu} \) underlying optical continuum (i.e., flux ratios between the lines correspond exactly with EW ratios). Then we calculate the contribution of the emission lines to the broadband magnitudes assuming the redshifts derived from the CSP models in Section 3.2. Figure 7 shows the emission line contributions (in magnitudes) that we estimate as a function of redshift. The solid histograms (arbitrary normalization) show the redshift distribution of our samples.

In a previous study (González et al. 2011), we examined the median SEDs of this sample by stacking the photometry in bins of UV luminosity. The SEDs of \( z > 4 \) galaxies show a consistent excess in their [3.6] flux over their [4.5] flux which, as argued in that work, can be explained by the effect of emission lines. It was shown in that work that a simple model with \( \text{H}\alpha \) EW = constant = 300 A can simultaneously reproduce the observed UV-to-optical and [3.6]–[4.5] colors exhibited for the sample (the corresponding EWs for the other most prominent optical lines are \( EW_{\text{rest}}(\text{O} \text{II}, \text{H}\beta, \text{O} \text{III}) = (189, 105, 670) \) A, respectively). This EW is very similar to the value predicted by the maximal model at \( z \sim 6 \).

Next, we subtract the emission line contribution from the photometry, and we refit the SEDs with CSF and RSF models.
As expected, the SFRs derived in this way are unchanged in both cases (Figure 5, bottom row). This is because the SFRs of star-forming galaxies (with ages g 100 Myr) depend almost exclusively on the UV fluxes, which are unaffected by these emission lines. The effects on the stellar masses can be seen in Figure 6 (bottom row). This figure only shows the effects for the maximal model. The effects from the conservative model are much smaller.

The impact of the emission lines on the stellar mass of galaxies is largest for the z ~ 6 sample. This is expected, since at this redshift there are strong emission lines affecting both the [3,6] (Hβ and [O iii]) and the [4,5] (affected by Hα) channels. The average change in stellar mass estimates ΔMstellar for IRAC detected sources at this redshift is ~0.26 dex for the maximal model (and only 0.1 dex for the conservative model). Correcting for emission lines results in lower stellar masses and higher sSFRs for galaxies (see also Curtis-Lake et al. 2013). The impact of this on the evolution of the sSFR, however, is not straightforward to assess, since correcting for the effect of the emission lines on the mass shifts sources to lower mass where the sSFR may also be higher.

4. THE sSFR AT z ~ 2

In the preceding sections we have studied the effects that different stellar population modeling assumptions have on the SFR and Mstellar estimates for high-redshift LBGs. We have shown that the SFRs do not depend on whether a rising SFH or CSF is considered in the modeling. The SFRs are also not significantly affected when emission lines, which affect the rest-frame optical fluxes, are taken into consideration. For the simple smooth RSF that we consider, the average Mstellar derived for these galaxies does not change systematically with respect to the CSF model (although there is a scatter of ~0.25 dex in the values determined). When the emission lines are considered, however, the stellar masses could be ~0.26 dex smaller at z ~ 6.

Figure 8 shows the sSFR determined from our sample as a function of redshift z ~ 4 (see also Table 2). The left panels show the mean sSFRs derived from a CSF model and the right panels show the results using the exponentially rising SFH. The top panels correspond to stellar continuum only models and the bottom panels consider the effects of emission lines assuming the average contribution expected from the maximal model. The mean sSFRs were determined for galaxies in two different mass bins Mstellar = 5 × 10^9 M⊙ and Mstellar = 5 × 10^9 M⊙. Top left: the mean sSFR derived assuming a CSF history and models with stellar continuum only (i.e., ignoring the effects of emission lines). The mean values were estimated after removing extreme values (sSFR ~ 100 Gyr^-1) which correspond to the minimum ages in our grid of models (10 Myr). This rejection does not cause significant differences, as can be seen by comparing the blue (with rejection) and gray circles (without rejection). Top right: mean sSFR derived assuming an exponentially rising SFH and models with stellar continuum only. The mean sSFR values do not change significantly for the RSF model relative to that for a CSF model (see Top left panel). Bottom left: assuming our maximal model for the average strength of the emission lines, we re-model the galaxies first assuming a CSF SFH. The behavior is similar to that shown in the top left panel—blue open circles are repeated here for comparison. Rejecting extreme values makes a slightly larger difference in this case but only at z ~ 6. Bottom right: the mean sSFR derived assuming an exponentially rising SFH and also assuming our maximal model for the average strength of the emission lines—this is our preferred model. Again very similar behavior is seen. Overall, the mean sSFR at z ~ 4 and 5 varies weakly with both redshift and mass in all models. The data suggest that galaxies in the lower mass bin may have slightly larger mean sSFR values but the evidence is weak and the difference is at most 0.1 dex. Differences appear at z ~ 6 but depend on the model assumptions. In all cases, the sSFR evolution with redshift is only mild.

(A color version of this figure is available in the online journal.)
The corresponding sSFR for the galaxies that were rejected is sSFR \sim 100 \text{ Gyr}^{-1} (Table 2 indicates the number of sources rejected in each bin). The effect of keeping such galaxies is very small as illustrated for the more massive bin by the gray symbols in Figure 8.

Comparing the mean sSFRs estimated for both mass bins, the data may suggest that the less massive galaxies present slightly larger sSFRs. However, the differences are small (\lesssim 0.1 dex) and very uncertain. For both mass bins and regardless of the modeling assumptions, the sSFR shows very little variation with redshift from \( z \sim 4 \) to \( z \sim 5 \), consistent with previous reports (Stark et al. 2009; González et al. 2010; McLure et al. 2011). However, there are important differences among the \( z \sim 6 \) determinations. These variations mostly reflect the fact that the sSFR at \( z \sim 6 \) is highly sensitive to the modeling assumptions.

It should be noted that the galaxies that make up the top and bottom panels in the top panel the \( M_{\text{stellar}} \) from CSF models with no emission lines is considered whereas in the bottom, the masses used correspond to the ones derived when the \( \text{maximal} \) model of emission lines is assumed. This is important because if the same galaxies were considered, then their sSFRs should be larger when the emission lines are considered (because their masses are lower). Most importantly, this effect would be stronger at \( z \sim 6 \), suggesting a stronger evolution of the sSFR with redshift. This does not seem to be the case when galaxies within the same mass bin are compared.

The mean sSFR values derived with all the model assumptions are approximately \( \sim 3 \text{ Gyr}^{-1} \), slightly larger than previous reports (without dust corrections or emission lines) and the values reported at \( z \sim 2–3 \) (Daddi et al. 2007, 2009; Reddy et al. 2012; see Figure 9). A weighted best fit to the evolution of the sSFR as a function of redshift is: \( \log(sSFR(z)/\text{Gyr}^{-1}) = -0.1(\pm 0.1) + 1.0(\pm 0.1) \log(1 + z) \). This fit was obtained considering the low redshift results from Daddi et al. (2007; \( z \sim 2 \)) and Reddy et al. (2012; \( z \sim 2–3 \)) as well as the values derived here for the mean sSFR at \( z \gtrsim 4 \) (taking the RSF with \( \text{maximal} \) emission line model as our fiducial values). The weights used correspond to the random errors. Since the random errors are not available for many determinations in the literature, the weights were normalized based on the sizes of the samples. Our result suggests a mean sSFR that increases slightly with redshift; however, the evolution observed is much weaker than that seen at \( z < 2 \). It is also inconsistent with the slope expected from theoretical models which generally follow closely the specific halo accretion rate, resulting in \( sSFR(z) \propto (1 + z)^{2.5} \) (e.g., Weimann et al. 2011; Bouché et al. 2010; Davé 2008). If the CSF model without emission lines is assumed instead, the derived evolution is flatter: \( sSFR(z) \propto (1 + z)^{0.6\pm 0.1} \).

### 5. DISCUSSION

Many of the earliest studies of the sSFR at high redshift had suggested that the sSFR did not evolve strongly at \( z \gtrsim 2 \) (González et al. 2010; Stark et al. 2009; McLure et al. 2011). This is very different from the behavior observed at lower redshifts and also from the expectations of theoretical models that consistently predict a sSFR that declines monotonically with cosmic time when halos of a constant mass are studied (e.g., Weimann et al. 2011; Bouché et al. 2010; Davé 2008). Most earlier studies, however, did not determine the SFRs and \( M_{\text{stellar}} \) in a way that was clearly self-consistent, did not adopt SFHs which are consistent with the evolution of the UV LF, and also did not account for the effects of nebular emission lines in the stellar population modeling.

More recently, however, there have been some efforts to redress these shortcomings. For example, Bouwens et al. (2012) focus on correcting previous sSFR determinations to reflect the latest estimates of dust extinction. Another example is the work of de Barros et al. (2012) where there is an effort to correct for the impact of the emission lines on the inferred stellar masses. Stark et al. (2013) also explores the effect of emission lines using a modeling technique very similar to the one presented here. In general, all these recent studies, including the present work, have suggested somewhat higher sSFRs at \( z \gtrsim 4 \). It is worth noting, though, that despite the growing consensus that the SFRs at \( z \gtrsim 4 \) increase, there is fairly large difference in the magnitude of evolution derived. In the following we compare to a couple of recent results with the goal of highlighting the main analysis differences that yield to the different results.

#### 5.1. Comparison to de Barros et al. (2012)

In de Barros et al. (2012) the authors find an order of magnitude larger sSFRs at \( z > 4 \) than is found at \( z \sim 2 \), the sSFRs we
et al. (2012) do not impose any constraints on the dust, metallicity, or age in modeling the photometry of high-redshift galaxies. By not restricting the model parameter space through various simplifying assumptions, de Barros et al. (2012) observe considerable scatter in the properties of many of their sources (equivalent to lower sSFRs, see Figure 8). The derived dependence of the sSFR on redshift is much weaker than that observed at $z < 2$ and that expected from the theoretical expectations at $z > 2$.

Figure 9. Mean specific SFR as a function of redshift for galaxies with estimated stellar masses $\log_{10}(M_{\ast}/M_\odot) = 9.4 - 10$, corresponding to our $5 \times 10^9 M_\odot$ bin. The values at $z < 4$ are taken from the literature (Damen et al. 2009; Noeske et al. 2007; Daddi et al. 2007; Reddy et al. 2012). The solid gray points correspond to previous reports from the literature at $z \gtrsim 4$ (Stark et al. 2009; González et al. 2010) and the open gray points correspond to these values after a simple correction for dust extinction is made (Bouwens et al. 2012). The blue crosses are from Stark et al. (2013). The open hexagons at $z \gtrsim 4$ are the new results from our stellar population modeling of the full rest-frame UV and optical SED. These results were derived assuming an exponentially rising SFH (RSF) and the average emission line flux is subtracted based on the maximal model described in Section 3.4. The dust reddening was derived using the Meurer et al. (1999) relation and the measured UV slopes, $\beta$. The error bars correspond to random errors. Our estimate of the systematic error, is given as well in the upper left corner. Our sSFR estimates depend weakly on the modeling assumptions (see Figure 8). The differences between our results and those of Stark et al. (2013) arise from them using UV-luminosity-binned averages vs. our mass-binned averages (see Section 5.2 for details). A weighted best fit of our measured sSFR as a function of redshift at $z > 2$ is log(sSFR($z$)) = $-0.1(\pm 0.1) + 1.0(\pm 0.1)\log(1 + z)$ (which incorporates the values derived at $z \sim 2$ by Daddi et al. 2007; $z \sim 2-3$ by Reddy et al. 2012; and the $z \gtrsim 4$ from this work). The derived dependence of the sSFR on redshift is much weaker than that observed at $z < 2$ and that expected from the theoretical expectations at $z > 2$ (e.g., Neinstein & Dekel 2008; dashed line).

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

5.2. Comparison to Stark et al. (2013)

In a recent study Stark et al. (2013) explores the impact of rest-frame optical emission lines on the stellar masses and sSFR derived through SED fitting at $z \gtrsim 4$. Their analysis is similar in many regards to the one presented here but they find a sSFR evolution that is much faster with redshift, in agreement with theoretical expectations. As we discuss below, it appears that the reason for this difference is that the consideration of the effect of the $M/L$ scatter turns out to play an important role.

The SED modeling assumptions used in Stark et al. (2013) are very similar to the ones we have used here, and the resulting SFR and stellar mass estimates for individual sources are in good agreement, as can be seen in Figure 10. Only sources that are detected in IRAC ($\gtrsim 2\sigma$) are shown in the figure (background points). The large open squares correspond to our estimates for the median SEDs stacked by UV luminosity from González et al. (2011) and the dashed lines correspond to the trends derived by Stark et al. (2013) based on the same stacked SEDs. This figure makes it clear that there is broad overall agreement in the basic properties derived.

The way in which the average sSFR is determined at a given redshift, however, causes important differences in the conclusions. The results presented in the Stark et al. (2013) work are based on the best-fit log($M_{\ast}/M_\odot$)-$M_{\text{uv}}$ relation derived from the stacked SEDs. These stacked SEDs are binned according to their UV luminosity. Their average sSFRs at a given redshift, then, correspond to UV luminosity binned averages. This is similar to the result by Bouwens et al. (2012), who only apply an improved dust correction to the luminosity binned results but Stark et al. (2013) also include mass corrections due to the effect of emission lines.

In the present analysis we estimate the sSFR in bins of stellar mass. Within a given bin there will be galaxies with lower than average luminosities but high $M/L$ ratios, as well as bright galaxies with low $M/L$ ratios. Since fainter galaxies are more numerous, the distribution of $M/L_{\text{uv}}$ ratios within the bin is skewed to high $M/L$ ratios (equivalent to lower sSFRs, see large filled squares in Figure 10).

Stark et al. (2013) recognize and discuss the differences that the $M/L$ ratio distribution at a given mass cause on the mean
sSFR (see also Reddy et al. 2012). They report that, at $z \sim 4$, the mass binned average sSFR could be 2.8 times lower if a symmetric scatter of 0.5 dex (the observed scatter reported in González et al. 2012) was assumed instead of no scatter. Nevertheless, they report their results assuming zero scatter in $M/L$ and suggest that the above effect could be offset by possibly higher UV luminosity to SFR conversion factors at higher redshift. Meanwhile, in our estimates we consider the observed $M/L$ distribution at a given mass. Neither approach is perfectly correct, but this explains why our estimates of the sSFRs are lower.

Ideally, we should use the intrinsic distribution of $M/L$ ratios, as opposed to the observed distribution which is broader due to modeling and observational uncertainties. A reliable estimate of the intrinsic scatter in $M/L$ ratios is out of the scope of this paper given the absence of rest-frame optical spectroscopy, and will likely have to wait until James Webb Space Telescope. Here we just note that our results reported in Table 2 are consistent with those of Stark et al. (2013) if a symmetric intrinsic scatter of 0.3 dex in $\log(M_{\text{stellar}})$ is added to their mean relation at $z \sim 4$ (0.2 dex at $z \sim 6$).

It is interesting to note that in the works of de Barros et al. (2012), Stark et al. (2013), as well as our study, the sSFR evolution from $z \sim 4$ to $z \sim 5$ is quite small (for a given set of assumptions, in particular, for SFH and emission line strengths). As shown in Figure 6, at these redshifts emission lines have only a weak effect on the stellar masses and SFRs. Differences in the sSFR appear only at $z > 5$, which is also when emission lines can have a bigger impact on the stellar population modeling. Furthermore, there is only $\sim 240$ Myr between $z \sim 5$ and $z \sim 6$. Even though it is possible that the differences in sSFR arising between $z \sim 6$ and $z \sim 5$ are real, it seems surprising that significant changes manifest themselves at the same redshift where emission lines potentially play a large role in the SED modeling (especially considering how uncertain are the assumed EWs).

We conclude that the sSFR at a constant stellar mass changes only weakly with cosmic time when full consideration is given to the scatter in $M/L$—with or without the consideration of emission lines (Figures 8 and 9). A fit to the maximal emission line estimates of the sSFR, which includes the values at $z \sim 2–3$ reported in the literature (Daddi et al. 2007; Reddy et al. 2012), yields a best fit to the evolution of the sSFR $\propto (1 + z)^{0.26 \pm 0.1}$, indicating that the best-fit sSFR is higher by $\sim 2.3 \times$ at $z \sim 6$ than at $z \sim 2$ (compared to the factor $\sim 8.3 \times$ predicted in most simulations). When emission lines are not included in the models (as in our CSF model), the exponent is lower: $0.6 \pm 0.1$. The evolution we derive at $z \gtrsim 2$ is less than expected from the lower-$z$ trends and is not consistent with the predictions from numerical simulations (e.g., Neistein & Dekel 2008; Weinmann et al. 2011).

6. SUMMARY

We take advantage of the ultra-deep and wide-area ACS $+$ WFC3/IR $+$ Spitzer observations of the GOODS-S field to derive flux measurements for a sizable sample of $z \sim 4–6$ galaxies and use these measurements to more thoroughly quantify their SFRs, stellar masses, and other properties. We have explored the effects of using a reddening law based on the UV colors only (Meurer et al. 1999) and investigated the impact of the SFH by alternatively considering constant star formation (CSF) and smoothly rising star formation (RSF) models. We have also studied the effects of optical emission lines on the SFR and stellar masses assuming two different models for the emission line strengths. Our goal has been to quantify the impact of these assumptions in estimating the sSFR of LBGs which has previously been reported to show little evolution at $z \sim 2–7$ (González et al. 2010; Stark et al. 2009; McLure et al. 2011). The RSF history explored here matches the evolution of the UV LF (e.g., Papovich et al. 2011; Smit et al. 2012) and is in good agreement with the predictions from recent smooth particle hydrodynamics simulations (Finlator et al. 2011). Our main findings are the following:

1. At a given redshift, LBGs that are fainter in the rest-frame optical show bluer UV colors. This is consistent with the previously reported trends of bluer UV colors for fainter galaxies (Bouwens et al. 2009, 2012; Wilkins et al. 2011). The UV-to-optical colors are also bluer for fainter sources (Papovich et al. 2004; González et al. 2012). Such luminosity-dependent trends could arise from a dependence...
of the dust content on mass (or luminosity) or from redder stellar populations as a result of aging with a smooth SFH (see also Labbé et al. 2007; Bouwens et al. 2009, 2012; González et al. 2012).

2. Assuming that the UV slope reddening is caused by dust alone as in Equation (1) (Meurer et al. 1999; and following a Calzetti et al. 2000, dust law), the dust-corrected UV and UV-to-optical colors can be reproduced by dust-free CSF models. A residual trend toward bluer colors at lower luminosities can be caused by the effects of aging of the population (see also González et al. 2012).

3. We find that the SFRs derived assuming a CSF history do not change when a smoothly rising SFH (RSF) is used instead. The RSF that we use is chosen to match the evolution of the UV LF (SFR $\propto$ $e^{(z-2)/\tau}$; $\tau = 500$ Myr). The mean stellar masses are also unchanged when the RSF is assumed, although there is a significant scatter of about 0.25 dex in the $M_{\text{stellar,CSF}}/M_{\text{stellar,RSF}}$ relation.

4. We explore the effects of emission lines assuming two different models for the strength of the lines as a function of redshift. Regarding the SFRs and stellar masses, the impact of adding emission lines with strengths consistent with the trends at lower redshifts is important, but modest. The inclusion of emission lines only affects our derived stellar masses. For the maximal emission lines model, the stellar masses are up to 0.26 dex lower at $z \sim 6$ (and the SFR larger; see also Curtis-Lake et al. 2013). For the model with lower emission line strengths, the masses change by about 0.1 dex.

5. We estimate the SFR for galaxies in two stellar mass bins in our samples at $z \sim 4, 5,$ and 6. There is a hint that the SFRs of lower mass sources may be slightly larger than those of more massive systems. In particular, for the CSF model, $1 \times 10^9 M_\odot$ galaxies have SFRs that are $\sim 0.1$ dex larger than sources with $5 \times 10^9 M_\odot$ (cf. Bouwens et al. 2012). However, the uncertainties are still large, and therefore the current results are also consistent with no change in the SFR with mass. Using a RSF model does not change this result.

6. At a fixed stellar mass, the derived SFRs show only a modest amount of evolution over the redshift range $z \sim 6$ to $z \sim 2$—even when the effects of optical emission lines are included. The SFR shows a dependence on redshift $\propto (1+z)^{0.8\pm0.1}$, i.e., a factor $\sim 2.3 \times$ higher at $z = 6$ than at $z \sim 2$ (assuming the RSF model with maximal emission line strength). This appears to be inconsistent with simulations, which generally predict a faster increase with redshift SFR $\propto (1+z)^{3.5}$, i.e., a factor $\sim 8.3$ times higher at $z \sim 6$ than at $z \sim 2$. The evolution we derive is also much slower than observed at lower redshifts $z \sim 2$.

7. The previous conclusion is somewhat in contrast with the conclusions derived by de Barros et al. (2012) and Stark et al. (2013) who argue for stronger evolution at $z > 2$, similar to that seen in simulations. The differences with Stark et al. (2013), in particular, seem to arise from our inclusion of the $M/L$ scatter at a given UV luminosity. Stark et al. (2013) also consider the effect of scatter in the $M/L$ on the SFR, but argue that this effect may be offset by higher UV luminosity-to-SFR conversion factors which could be more common at higher redshift. At present, it is not clear which SSFR determination is most accurate, due to the several observational uncertainties (e.g., nebular line EWs, intrinsic scatter in $M/L$ ratios, see Section 5.2).

Larger samples, e.g., from the full CANDELS survey, may help elucidate some of these currently open questions.

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