STAR FORMATION IN AEGIS FIELD GALAXIES SINCE $z = 1.1$: THE DOMINANCE OF GRADUALLY DECLINING STAR FORMATION, AND THE MAIN SEQUENCE OF STAR-FORMING GALAXIES

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ABSTRACT

We analyze star formation (SF) as a function of stellar mass ($M_*$) and redshift $z$ in the All-Wavelength Extended Groth Strip International Survey. For 2905 field galaxies, complete to $10^{10}(10^{11})$ M$_\odot$ at $z < 0.7(1)$, with Keck spectroscopic redshifts out to $z = 1.1$, we compile SF rates (SFRs) from emission lines, GALEX, and Spitzer MIPS 24 µm photometry, optical-NIR $M_*$ measurements, and HST morphologies. Galaxies with reliable signs of SF form a distinct "main sequence" (MS), with a limited range of SFRs at a given $M_*$ and $z$ ($1 \sigma \approx 0.3$ dex). The range of log (SFR) remains constant to $z > 1$, while the MS as a whole moves to higher SFR as $z$ increases. The range of the SFR along the MS constrains the amplitude of episodic variations of SF and the effect of mergers on the SFR. Typical galaxies spend $\sim 67\%(95\%)$ of their lifetime since $z = 1$ within a factor of $\pm 2(4)$ of their average SFR at a given $M_*$ and $z$. The dominant mode of the evolution of SF since $z \sim 1$ is apparently a gradual decline of the average SFR in most individual galaxies, not a decreasing frequency of starburst episodes, or a decreasing factor by which SFRs are enhanced in starbursts. LIRGs at $z \sim 1$ seem to mostly reflect the high SFR typical for massive galaxies at that epoch. The smooth MS may reflect that the same set of few physical processes governs SF prior to additional quenching processes. A gradual process like gas exhaustion may play a dominant role.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: starburst

1. INTRODUCTION

Deep galaxy surveys have found consistently that the star formation rate (SFR) per unit stellar mass ($M_*$) depends strongly on both $M_*$ and redshift $z$, with the bulk of star formation (SF) occurring earlier in massive galaxies than in less massive systems (e.g., Guzmán et al. 1997; Brinchmann & Ellis 2000; Juneau et al. 2005; Bauer et al. 2005; Bell et al. 2005; Pérez-González et al. 2005; Feulner et al. 2005; Papovich et al. 2006; Caputi et al. 2006; Reddy et al. 2006). High-SFR objects are observed to be more abundant at higher $z$; it is often assumed that a part of these reflect a greater frequency of merger-driven starburst episodes at earlier times. However, a comprehensive observational picture of the relationship between SF and mass to $z \sim 1$, including objects with a wide range of both masses and SF rates, has been lacking.

This Letter is part of a series of papers that study the evolution of the SFR and $M_*$ in field galaxies out to $z = 1.1$ in the All-Wavelength Extended Groth Strip International Survey (AEGIS). We combine SFR measurements from deep Multi-band Imaging Photometer for Spitzer (MIPS) 24 µm imaging, Keck/DEEP2 spectra, and Galaxy Evolution Explorer (GALEX) UV photometry, allowing us both to recover obscured SF in IR-luminous galaxies and to include lower SFR objects not detected at 24 µm. Using optical–near-IR derived $M_*$ measurements, we analyze the evolution of the SFR as a function of $M_*$ and $z$; we also analyze Hubble Space Telescope (HST) Advanced Camera for Surveys imaging and rest-frame colors to support the interpretation of SFR indicators.

We adopt a concordance cosmology ($H_0 = 70$ km s$^{-1}$Mpc$^{-1}$, $\Omega_\Lambda = 0.3$, $\Omega_\text{M} = 0.7$). Values of $M_*$ and SFR are based on a Kroupa (2001) initial mass function, following recent results by Hopkins & Beacom (2006).

2. DATA SET

Our sample includes all field galaxies with DEEP2 spectroscopic redshifts $z \leq 1.1$, in the area where Spitzer MIPS 24 µm photometry and $K$-band imaging to 22 AB mag are available; (see Davis et al. 2007). Stellar masses were obtained from spectral energy distribution (SED) fits to optical/NIR photometry by Bundy et al. (2006); errors are $\leq 0.3$ dex, with a mean and rms of 0.1 and 0.05 dex and $< 4\%$ of errors $> 0.2$ dex.

Figure 1 shows data in the $M_*$ range where the sample is $> 80\%$ complete, adopting the completeness analysis by Bundy et al. (2006; see also Cimatti et al. 2006), for a total of 2905 galaxies. We draw conclusions only where the sample is $> 95\%$ complete [$M_* \geq 10(10.8) \times M_\odot$ for $z < 0.7(1)$; see vertical lines in Fig. 1]. For galaxies with robust 24 µm detections ($f > 60$ µJy), SFRs were derived following Le Floc’h et al.
(2005), using Chary & Elbaz (2001) SED templates; using templates from Dale & Helou (2002) yields no significant differences. We then add to the 24 μm–based SFR the SFR estimated from DEEP2 emission lines (Hα, Hβ, or [O ii] λ3727, depending on z) with no extinction correction, to account for SF from unobscured regions. This approach is similar to that employed by Bell et al. (2005); utilizing rest-frame UV continuum SFRs (as they did) in place of emission-line fluxes yields consistent results. Galaxies below the 24 μm detection limit are not dominated by highly extincted SF; for these, we use extinction-corrected SFRs from emission lines; these can probe to roughly 10 times lower SFRs than the 24 μm data and are slightly more sensitive at high z and cover a larger area than GALEX data. Emission-line luminosities (as calculated in Weiner et al. 2006) were transformed to an Hα luminosity using average line ratios measured from DEEP2 data (Hβ/Hα = 0.198, [O ii]/Hα = 0.69; B. J. Weiner 2006, private communication) and transformed to the SFRs using the Hα calibration of Kennicutt (1998). The DEEP2 Hβ/Hα ratio corresponds to an extinction of 1.30 mag at Hα assuming case B recombination, which was applied to correct the emission-line SFRs. We use fixed rather than M*–dependent line ratios (à la Weiner et al.), because these predict extinction-corrected SFRs slightly in excess of the 24 μm–derived SFRs for high-mass galaxies. Our simple but robust approach yields results in good agreement with SFRs derived from GALEX data, extinction-corrected based on UV spectral slopes.

For objects with both J24 μm < 60 μJy and emission-line signal-to-noise ratio (S/N) < 2, we estimate a 2 σ upper limit on SFRs from the most sensitive emission line available, by adding 2 σ to the measured uncertain SFR, or, for nondetections, to the limit of S/N > 2–detectable emission-line SFRs at the galaxy’s redshift. We again apply A_Hα = 1.30 for extinction corrections, certainly an overestimate since extinction is lower in more weakly star-forming galaxies (Hopkins et al. 2001).

We have performed a suite of tests of these SF estimates, finding that adopting different SFR tracers changes results moderately (K. G. Noeske et al. 2007, in preparation); qualitative results are unaffected. Random errors in our 24 μm–based SFRs are ±0.1 dex from photometry and ~0.15 dex from scatter in the f(24 μm) to L(IR) conversion (see Marcillac et al. 2006), yet total random errors are expected to be 0.3–0.4 dex (see Bell et al. 2005). For extinction-corrected emission-line SFRs, random errors are ~0.35 dex, including scatter about the assumed mean extinction.

3. RESULTS

Figure 1 shows the SFR as a function of M* in four independent redshift bins. The following discussion refers only to the stellar mass range where the sample is >95% complete, marked by the vertical dotted lines in each redshift bin. We identify three different categories of galaxies:

1. The majority of galaxies show clear signs of SF, either robust 24 μm detections or, at lower M*, blue colors and emission lines (blue symbols in Fig. 1). Quantitative HST morphologies (Gini/M20: Lotz et al. 2007; CAS: Conselice 2003) classify ≤25% of these galaxies as early types (E, S0, Sa), and ≥90% show visual signs of SF such as blue regions and dust lanes. Most of them lie on the “blue cloud” (e.g., Willmer et al. 2006), although some of the massive ones are red, likely dusty, star-forming galaxies (Bell et al. 2005). This category (blue symbols in Fig. 1) comprises 67%/56% of the sample at z < (>) 0.7 in the M* range where the sample is complete.

2. Clearly separated are galaxies without robust 24 μm (>60 μJy) or emission-line (S/N > 2) detections (orange arrows in Fig. 1). The upper limits on their SFRs are conservatively high (§ 2), such that the true separation between the sequence and the other galaxies is likely larger than it appears here. Almost all (>95%) of these galaxies are on the red sequence, and ≥90%/80% at z < (>) 0.7 have early-type quantitative morphologies including early-type mergers, while ≥90% at z > 0.7 have early-type visual morphologies with no hints of current SF. These galaxies contribute 29%/30% of the sample at z < (>) 0.7.

3. Scattered below the star-forming sequence are galaxies with robust emission-line detections but no significant 24 μm emission, 5%/14% of the sample at z < (>) 0.7. All of these galaxies (green plus signs in Fig. 1) are on the red sequence, and their Hα, Hβ emission-line equivalent widths tend to be low (a few angstroms). Yan et al. (2006) and Weiner et al. (2006) showed that the bulk of the line emission in red galaxies out to intermediate redshifts is due to LINER/AGN emission, not SF. We find that 75% of those galaxies with [O ii] and Hβ detections show LINER-like line ratios, and ≥55%/70% at z < (>) 0.7 have early-type quantitative and visual morphologies that are typical.
for local LINERs (Yan et al. 2006). Line emission in these red galaxies thus appears to be dominated by LINERs/AGNs, particularly at \( z > 0.7 \) where they are more frequent. Their SFRs, derived from emission lines (Fig. 1), will mostly be overestimated. However, we find visual signs of SF in the HST images in \( \pm 30\% \) of these galaxies, comparable to the fraction of non-linearly quantitative morphologies; these may be dominated by SF.

The star-forming galaxies form a distinct sequence of SFRs with \( M_\odot \), which we term the “main sequence” (MS). The red lines in Figure 1 enclose 34\% of galaxies both above and below the median (red circles) and thus indicate the equivalent of \( \pm 1 \sigma \) for a Gaussian distribution. The width of the MS measured in this way (the range in SFR about the median at a given \( M_\odot \)) is about \( \sigma_{\text{MS}} = 0.35 \) dex and seems to remain approximately constant in our sample over the redshift range \( 0.20 < z < 1.1 \). Subtracting a lower limit of non-systematic scatter in SFR (\( \sim 0.2 \) dex; §2) in quadrature yields an upper limit of \( \sim 0.3 \) dex on the intrinsic scatter, which is still broadened by the width of the \( z \) bins, and by additional spread from combining different SFR tracers. Errors in \( M_\odot \) hardly affect \( \sigma_{\text{MS}} \).

The slope of the MS is shallower than unity, \( \log \left( \text{SFR} \right) = (0.67 \pm 0.08) \log \left( M_\odot \right) - (6.19 \pm 0.78) \), for \( M_\odot \) between \( 10^{9} \) and \( 10^{11} M_\odot \), and \( z = 0.2 \)–0.7. There is a trend for the slope to flatten to higher \( z \), but the completeness limits do not allow a robust quantification. A further important result is that the normalization of the MS evolves strongly over the redshift range of our sample; the median SFR at fixed \( M_\odot \) evolves downward by a factor of 3, measured at \( 10^{11} M_\odot \), from the our highest (median \( z = 0.98 \)) to our lowest (median \( z = 0.36 \)) redshift bin. Importantly, it appears that the whole of the MS shifts downward with time, rather than just the upper envelope decreasing, which was also reported by a recent GALEX study at \( z = 0.7 \) (Zamojski et al. 2007). A straightforward interpretation of these observations is that normal star-forming galaxies possess a limited range of SFRs at a given \( M_\odot \) and \( z \), which is presumably set by whatever physical processes regulate SF in quiescent disks. Galaxies that are not on the MS, in categories 2 and 3 above, are observed during or after quenching of the SF activity, with either low-level or no current SF, or LINER/AGN activity.

4. DISCUSSION

4.1. Completeness: Is the Main Sequence Real?

It is obviously crucial to determine whether the MS that we have identified is real or could be caused by selection effects or observational biases. We address the following possible causes of incompleteness or bias in our sample, again restricting the discussion to the \( M_\odot \) range where we claim that the sample is >95\% complete: (1) Could the optically selected DEEP2 parent sample be missing a significant number of galaxies, or are there galaxies in the DEEP2 sample that lack a successful redshift determination because of low S/N? (2) Could we be significantly underestimating the SFRs in galaxies in our sample due to biases in our SF indicators?

1. The DEEP2 spectroscopic selection (\( R_{\text{AB}} < 24.1 \)) has been shown to be complete in the \( M_\odot \) ranges indicated in Figure 1 (vertical lines), from comparisons to various surveys with spectroscopic and deep photometric redshifts, including in particular the \( K \)-selected K20 survey, which should be less affected by extinction (Willmer et al. 2006; Bundy et al. 2006; Cimatti et al. 2006). For galaxies that are below our 24 \( \mu \)m detection limit, we expect the extinction to be moderate and would expect these galaxies to be picked up in \( K \)-selected surveys, but no such population is found to be missed by DEEP2.

More obscured populations can be probed through the deep Spitzer Infrared Array Camera (IRAC) 3.6 \( \mu \)m data in AEGIS, which at a given redshift are a proxy for \( M_\odot \), yet are barely affected by extinction. We have compared the distribution of \( f(24 \mu \text{m}) \) at a given \( f(3.6 \mu \text{m}) \) and \( z \) in the DEEP2 \( R_{\text{AB}} \)-selected sample and an IRAC \( f(3.6 \mu \text{m}) \)-selected sample with IRAC-based photometric redshifts. We find no evidence that DEEP2 misses a significant population of heavily obscured, star-forming galaxies at \( z \approx 1 \), which could populate the area above the upper boundary of the MS. This agrees with the results of Houck et al. (2005) and Weedman et al. (2006) in the large-area NOAO Deep Wide-Field Survey, which indicate that such missed \( f(24 \mu \text{m}) \)-bright, optically faint galaxies at \( z < 1 \) would contribute <1\% of our sample.

2. The 24 \( \mu \)m completeness limit (horizontal black dashed line in Fig. 1) intersects the MS in each redshift bin. As discussed in §3, most galaxies below the MS are red, early type, non-SF, and/or LINER/AGN-dominated (shown as orange arrows and green plus signs). However, a fraction show spiral/late-type morphologies or visual signs of possible SF (§3). In principle, these red galaxies could have dust-obscured SF, unrecovered by emission lines, yet lie below the 24 \( \mu \)m detection limit. Their true SFRs could then be anywhere up to the 24 \( \mu \)m limit, in which case they may not be a distinct population but rather a downward continuation of the MS. If this were the case, these galaxies would make up \( \leq 10\% (20\% \) of the MS at \( z < 0.7 \). We can constrain the maximal effect of missed, dust-obscured SF in these galaxies on the 1\% range of SFRs along the MS by including in the calculation of \( \sigma_{\text{MS}} \) all red, 24 \( \mu \)m-undetected galaxies with spiral/late-type morphologies, and H\alpha, H\beta, and/or [O ii] line emission down to spurious detections (i.e., 100\% error in equivalent width). For the extremes of either only the emission line SFR or the maximal SFR, corresponding to the 24 \( \mu \)m limit, the measured width of the MS increases by \( \sim 0.05 \) dex or not at all, respectively.

Thus, we argue that the relatively sharp upper limit of the MS is real, as our selection does not miss obscured sources with high SFRs. The sharpness of the lower limit is more uncertain with our current data, but we find that only a small fraction of galaxies that we placed below the MS could have underestimated SF rates that would “blur out” the lower edge of the MS. Very deep 24 \( \mu \)m data at \( z \sim 1 \) from the Great Observatories Origins Deep Survey (D. Elbaz 2006, private communication) unambiguously confirm this result, particularly a well-defined lower boundary to the sequence.

4.2. Constraints on Episodic Star Formation

Studies based on local samples (Brinchmann et al. 2004; Salim et al. 2005 for the Sloan Digital Sky Survey; Lee 2006) have illustrated a relationship between the SFR and \( M_\odot \), and have identified two populations: galaxies on a star-forming sequence and “quenched” galaxies with little or no detectable SF. At higher \( z \), previous studies (see §1) had merely described an upper envelope of SFRs in the SFR-\( M_\odot \) diagrams. We have employed a variety of SFR tracers and other evidence from AEGIS to show that the SF sequence persists out to \( z \sim 1 \), with a similar dispersion in log (SFR) at fixed \( M_\odot \) but with a decrease in normalization of a factor of 3 from \( z = 0.98 \) to \( z = 0.36 \), measured at \( M_\odot = 10^{11} M_\odot \). The global SFR density has also decreased by a factor of 3 over this same interval (Hopkins 2004, eq. [3]). One possible physical explanation for this de-
cline is a decreasing contribution from starbursts in gas-rich galaxy mergers. However, if this were the dominant factor causing the decline, we would expect to see the upper envelope of the MS move downward with time, with the region populated by "normal" galaxies maintaining the same normalization. This is contrary to what we see in AEGIS: the region of the SFR-M$_\star$ space populated by MS galaxies at $z \sim 0$ (Brinchmann et al. 2004) is nearly empty at $z \sim 0.7$–1, although these galaxies should be detectable in our survey.

We can use our observed MS to quantitatively constrain the duty cycle of episodic variations of SFRs around an average level. We adopt the densely populated peak of the SFR distribution (the median) as this baseline level. The 1(2) $\sigma$ range about the median of log (SFR), $\pm 0.3(0.6)$ dex, include 68%(95%) of the galaxies. We can hence infer that SFR variations exceeding $\pm 0.3(0.6)$ dex, factors of 2(4), have duty cycles <32%(5%). These correspond to total times of <2.5(0.4) Gyr since $z = 1$. The amplitude of these variations ($\sim 4$) is consistent with gas-poor or minor mergers, rather than the peak SFR of gas-rich major mergers (Springel 2000; Cox et al. 2006). Excursions in SFR $>5$ times above the median are rare, ~1%, consistent with galaxies spending $\leq 100$ Myr in such strong burst episodes since $z = 1$. Of course these arguments are only valid in a statistical sense: a fraction of galaxies could have a lower average level of SF and undergo larger excursions but at the expense of reducing the allowed range of SFRs for the remainder of the population.

Previous studies have found that $\sim 30\%$ of SF at $z \sim 0.7$ occurs in morphologically disturbed galaxies (Wolf et al. 2005; Bell et al. 2005) or close pairs (Lin et al. 2007). Semianalytic models predict that about 5% of the SF at $z \sim 0.7$ is due to major mergers, with the contribution due to minor mergers being more uncertain but ranging from $\sim 11\%$ to 45% (Somerville et al. 2001; Wolf et al. 2005). These direct constraints and theoretical expectations are consistent with the conclusions that we have drawn here from the SFR-M$_\star$ distributions. A related comment pertains to the nature of luminous infrared galaxies [LIRGs; $L(8–1000\ \mu m) > 10^{11} L_\odot$]. LIRGs at $z \sim 0$ are rare, mostly interacting galaxies (Sanders & Mirabel 1996) with strong starbursts (SFR $\approx 5$ times above those of typical spirals). At $z \sim 1$, LIRGs seem to mostly represent the high level of SFRs in almost all massive SF galaxies, rather then extreme starbursts (Fig. 1).

In summary, we suggest a picture in which we are witnessing a gradual decline in the SFR of most galaxies since $z \sim 1$, accompanied by rapid quenching in a fraction of (massive) galaxies. Presumably, the regularity and constant dispersion of the MS out to $z \sim 1$ means that the same physics that regulates SF in local disk galaxies is operating, indicating significant evolution either in the gas supply or SF efficiencies over this interval.

In the accompanying Letter (Noeske et al. 2007), we show that the slope and evolution of the MS can be understood as gradual gas exhaustion in a model in which galaxy age and SF timescales are a function of galaxy mass, and the dispersion of the MS is interpreted as resulting from a spread in age and SF timescales at a given mass.

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STAR FORMATION IN AEGIS FIELD GALAXIES SINCE $z = 1.1$: STAGED GALAXY FORMATION AND A MODEL OF MASS-DEPENDENT GAS EXHAUSTION


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ABSTRACT

We analyze star formation (SF) as a function of stellar mass ($M_*$) and redshift ($z$) in the All-Wavelength Extended Groth Strip International Survey, for star-forming field galaxies with $M_* \geq 10^{10} M_\odot$ out to $z = 1.1$. The data indicate that the high specific SF rates (SFRs) of many less massive galaxies do not represent late, irregular or recurrent, starbursts in evolved galaxies. They rather seem to reflect the onset (initial burst) of the dominant SF episode of galaxies, after which SF gradually declines on gigayear timescales to $z = 0$ and forms the bulk of a galaxy’s $M_*$. With decreasing mass, this onset of major SF shifts to decreasing $z$ for an increasing fraction of galaxies (staged galaxy formation). This process may be an important component of the “downsizing” phenomenon. We find that the predominantly gradual decline of SFRs described by Noeske et al. can be reproduced by exponential SF histories ($\tau$ models), if less massive galaxies have systematically longer $\tau$-folding times $\tau$, and a later onset of SF ($z_\tau$). Our model can provide a first parameterization of SFR as a function of $M_*$ and $z$, and quantify mass dependences of $\tau$ and $z_\tau$, from direct observations of $M_*$ and SFRs up to $z > 1$. The observed evolution of SF in galaxies can plausibly reflect the dominance of gradual gas exhaustion. The data are also consistent with the history of cosmological accretion onto dark matter halos.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: starburst

1. INTRODUCTION

In an accompanying Letter (Noeske et al. 2007, hereafter Paper I), we have studied star formation rates (SFRs) as a function of stellar mass ($M_*$) and $z$, for field galaxies in the All-Wavelength Extended Groth Strip International Survey (AEGIS) out to $z = 1.1$. Star-forming galaxies form a defined “main sequence” (MS) with a limited range of SFRs at a given $M_*$ and $z$. This smooth sequence suggests that the same set of few physical processes governs SF in galaxies, unless quenching of their SF occurs. The evolution of SF along the MS appears dominated by a gradual decline of SFRs in individual galaxies since $z \sim 1$, not by an evolving frequency or amplitude of starbursts. The dominant process that governs SF since $z \sim 1$ is hence likely a gradual one, an obvious candidate being gas exhaustion.

SF histories (SFHs) are known to depend on galaxy mass and morphological type, both from studies of local galaxies (e.g., Tinsley 1968; Searle et al. 1973; Sandage 1986; Heavens et al. 2004), and from distant galaxy surveys (see references in § 1 of Paper I). The common picture is that massive galaxies formed the bulk of their stars early and on shorter timescales, while numerous less massive galaxies evolve on longer timescales, a phenomenon generally linked to the “downsizing” phenomenon reported by Cowie et al. (1996).

In this Letter, we show that a simple model of gas exhaustion with mass-dependent parameters can reproduce and parameterize the observed SFR as a function of $M_*$ and $z$. Gas exhaustion may thus be responsible for the gradual decline of SFRs that dominates SFHs since $z \sim 1$ along the MS, i.e., in star-forming field galaxies. Following previous authors, we consider specific SFRs (SSFRs), i.e., SFR/$M_*$, a simple but powerful indicator of galaxy SFHs (e.g., Kennicutt et al. 2005). We argue that the onset of major SF occurs systematically later in less massive galaxies.

2. DATA SET

As in Paper I, we take advantage of the sensitivity and panchromatic nature of AEGIS; combined SFRs from deep Multi-band Imaging Photometer for Spitzer (MIPS) 24 µm images and DEEP2 spectra recover obscured SF in IR-luminous galaxies and achieve a large dynamic range in SF by including galaxies not detected at 24 µm. For a description of the data, SFR tracers, and $M_*$ measurements, see § 2 of Paper I. We consider all galaxies with robust SFR tracers a MS galaxy—either 24 µm–detected, or blue sequence galaxies with signal-to-noise ratio $>2$ emission lines (Hα, Hβ, or [O II] $\lambda 3727$), thereby excluding red LINER/AGN candidates (see Paper I). As shown in Paper I, this selection likely misses at most <10%/20%) of the normally star-forming MS galaxies at $z \leq 0.7$, likely less.

We tested the effects of using different combinations of SFR and $M_*$ measures, including Galaxy Evolution Explorer (Galex) UV-based SFRs and $M_*$-values from the color-M/L relation of Bell et al. (2003). All qualitative results of this work are robust against the choice of SFR tracer or $M_*$ estimate, yet quantitative results vary (see § 4.1).

3. PARAMETERIZATION THROUGH $\tau$ MODELS

Interpreting the SSFR versus ($M_*$, $z$) diagrams in terms of mass-dependent SFH is not straightforward, as $M_*$ grows with time for SF galaxies. Here we present the use of a simple exponential model SFH ($\tau$ models; eq. [1]) with mass-dependent parameters to quantify mass dependences of SF timescales and...
Fig. 1.—SSFR (yr\(^{-1}\)) vs. \(M_\star\) for 3658 star-forming (main sequence; Paper I) AEGIS galaxies. Filled blue circles: SFRs from Spitzer MIPS 24 \(\mu\)m and DEEP2 emission lines (Paper I). Open blue circles: Blue galaxies without 24 \(\mu\)m detection, SFRs from extinction-corrected emission lines. Galaxies with no reliable signs of SF, including red LINER/AGN candidates (Paper I), are not shown. Black circles and error bars: Median and sample standard deviation of \(\log{\text{SSFR}}\) main-sequence galaxies, in the range where the sample is 195% complete. The black dot-dashed line repeats the green (left) and red (right) models in the \(M_\star\) lowest \(z\) bin.

Left: \(\tau\) models with fixed formation redshift \(z_f\) and mass-dependent \(\tau\) (colored curves). Massive galaxies can be reproduced assuming high \(z_f > 2\), less massive galaxies require \(z_f < 2\), unphysical for massive galaxies. Right: Staged \(\tau\) models (red), where both \(\tau\) and \(z_f\) are mass-dependent. Red dashed lines show the effect of varying \(z_f\) and \(\tau\) at a given \(M_\star\). The delayed onset of SF (lower \(z_f\)) in a fraction of less massive galaxies accounts for the increase of SSFRs at low \(M_\star\) without requiring a large fraction of galaxies to simultaneously undergo starbursts.

Previous authors have successfully employed \(\tau\) models with different \(\epsilon\)-folding times \(\tau\) to reproduce the spectrophotometric and chemical evolution of different Hubble types and masses (e.g., Tinsley 1968; Searle et al. 1973; Koo et al. 1993; Bicker et al. 2004; Savaglio et al. 2005; Weiner et al. 2006). The apparent dominance of smoothly declining SFRs in individual galaxies (Paper I) supports the use of \(\tau\) models, which are a one-zone approach to describe SF through continuous gas exhaustion. We adopt simple closed-box conditions where galaxies have a baryonic mass \(M_\star\) that is initially gaseous, later the sum of gas \((M_g)\) and stellar mass \(M_\star\). For instantaneous recycling, with a recycled gas fraction \(R = 0.5\) (Kroupa initial mass function [IMF]; Bell et al. 2005), and a SF efficiency \(\epsilon\) such that the SFR \(\Psi = \epsilon M_g\), one obtains

\[
\Psi(M_g, z) = \Psi(z_f) \exp \left( -\frac{T}{\tau} \right),
\]

where \(z_f\) is the “formation redshift” where SF begins and \(T\) is the cosmic time at redshift \(z\). The initial SFR at a given \(\tau\) is then \(\Psi(z_f) = \epsilon M_g = [\tau(1 - R)]^{-1} M_\star\). We parameterize the mass dependence of \(\tau\) as a power law of the baryonic mass of the galaxy \(M_\star\): 

\[
\tau(M_\star) = c_\alpha M_\star^{\alpha}.
\]

Figure 1 (left column) shows examples of equation (1) in the SSFR-M\(_\star\) plane, compared to the median SSFR of the MS, for different \(z_f\), \(c_\alpha\), and \(\alpha\).

### 3.1. Staged \(\tau\) Models

Figure 1 (left column) shows that models with mass-dependent \(\tau\) can crudely reproduce the median MS of SF galaxies and its redshift evolution for galaxies with \(M_\star \geq 10^9 M_\odot\) out to \(z \sim 1\), if formation redshifts \(z_f \sim 2\) are adopted for all galaxies. However, the models fall short of reproducing the high SSFRs of less massive galaxies. The model SSFRs remain systematically too low, unless we adopt a very low \(z_f\), unphysical for massive galaxies. The reason is the monotonic decline of the SFR of \(\tau\) models. Their present-to-past average SFR (Kennicutt et al. 2005),

\[
b(t) = \frac{\Psi(t)}{\langle \Psi \rangle_T} = \frac{\Psi}{M_\star} \frac{T}{1 - R},
\]
is always <1. The limit for \( \tau = \infty \) is \( b = 1 \), which corresponds to the constant SFR that would have formed a galaxy’s \( M_* \) since \( z_f \). Empirically, the behavior of the MS suggests declining SFHs \((b < 1)\), which causes a conflict between the high SSFR for low-mass galaxies and the assumption that all galaxies started forming stars at high \( z_f \). Adopting such high \( z_f \), an early start of SF, implies low past-average SFRs: \( b = 1 \) then corresponds to low SSFRs, reflected in the low upper limits to the SSFRs of \( \tau \) models. For these \( z_f \), the high SSFRs of many less massive galaxies would imply \( b > 1 \), a current SFR above the past-average level, i.e., an episode of enhanced SF (Fig. 1, left; Fig. 2).

The increase of the highest SSFRs toward less massive galaxies can be reproduced by allowing the onset of SF to be delayed to lower \( z_f \) in less massive galaxies (see the models for different \( z_f \) in Fig. 1, left). We parameterize \( z_f \) as a function of a mass, similarly to \( \tau \), an approach we refer to as staged \( \tau \) models:

\[
1 + z_f(M_*^b) = c_3 M_*^{b_2}.
\]

This model interprets high SSFRs as the early epoch of smooth SFHs with lower \( z_f \), rather than late episodes of enhanced SF. It is physically motivated, not an attempt to force an oversimplified model to fit complex SFHs (see § 4.2). Staged \( \tau \) models (Fig. 1, right column) provide a better description of the median of the MS than \( \tau \) models with fixed \( z_f \) in the \( M_* \) range where the sample is complete, and appear to describe the data also toward lower \( M_* \). Staged models that consider a moderate range of \( z_f \) and \( \tau \) at a given mass (dashed red curves) also reproduce the upper envelope of the MS, which is complete at all observed \( M_* \) and \( z_f \), and the lower envelope and apparent broadening of the MS toward lower masses. Models with a range of \( z_f \) but no trend with mass would merely introduce a scatter and an offset in the asymptotic SSFRs at low masses but would not change the slope of SSFR(M*) to first order (see the models for different \( z_f \) in Fig. 1, left column).

The staged \( \tau \) model in Figure 1 (right) is given by

\[
\tau = 10^{2.07} (M_*^b) -1 \text{ yr}, \quad (1 + z_f) = 10^{-2.7} (M_*^b)^{0.63}.
\]

We calculated \( \chi^2 \) to scan the model parameter space, but equation (6) is hand-adjusted to reproduce the median and upper and lower limits of the data. Results of a simple \( \chi^2 \) minimization to the median would be misleading: best values for all four parameters in equations (3) and (5) depend considerably on systematics of, e.g., SFR and \( M_* \) estimates, and the IMF; also, the \( \tau(M_*^b) \) dependence is mainly constrained by massive galaxies (Fig. 1), where our number statistics are poor, and the \( z_f(M_*^b) \) relation at low masses, where data are incomplete. An evaluation of the relevant uncertainties must incorporate scatter in \( \tau(M_*^b) \) and \( z_f(M_*^b) \) or a scatter about smooth SFHs, and is postponed to a forthcoming paper.

4. DISCUSSION

4.1. \( \tau \) Models, Gradual Decline of Star Formation

By direct measurement of SFRs and \( M_* \) over a large range in mass and \( z \), we confirm that the commonly adopted exponential model SFHs can reproduce the average SFH of MS galaxies. This model can quantify the mass dependence of the associated SF timescales \( \tau \) and of the \( z_f \). The mass dependences of \( \tau \) and \( z_f \), and \( M_* \), growth through SF, conspire to reproduce the decline of SFRs that is similar over a wide \( M_* \) range (Paper I; Zheng et al. 2007).

Notably, \( \tau \) models are a simple approximation of SF that declines due to gradual gas exhaustion. Their ability to reproduce the evolution of the MS of SF galaxies, along with the limited range of SFR on the MS, implies that gradual gas exhaustion with mass-dependent timescales is a plausible driver of the dominant evolution of SF in galaxies \( z \geq 10^4 \) \( M_* \) since \( z = 1 \).

We chose a closed-box model, which is sufficient to reproduce the coevolution of SF and \( M_* \). Linking the model \( M_* \) to, e.g., dark matter halo masses should involve the observed relation between both values at a given \( z \), to account for gas accretion and removal in galaxies, which are both not well understood. The \( \tau \) models’ similarity to the data does not imply a closed-box scenario where gas is merely turned into stars. Additional processes that gradually deplete cold gas—heating or loss—and scale roughly with the SFR would also produce SFHs that resemble exponentials. These processes include feedback from SF, and conceivably AGNs, given the likely coevolution of stellar bulges and black holes (e.g., Granato et al. 2004). Short \( \tau \) obtained for massive galaxies may largely reflect such gas-loss processes rather than very efficient SF.

We have considered the depletion of an existing gas reservoir, but the decline of the SFR at a given mass is also compatible with the cosmological decline in accretion onto dark halos. This can be approximated for halo masses near \( 10^{12} \) \( M_* \) by \( \dot{M} = 0.04 \text{ Gyr}^{-1} (1 + z)^{2.25} \) (Birnboim et al. 2007), giving a factor of \( \sim 5 \) between \( z = 1 \) and \( z = 0 \), similar to the observed decline. The mean virial accretion in this mass range is predicted to vary as \( M_* \propto M_h^{1.5} \). If we adopt \( M_* \propto V^2 \propto M_h^{2.3} \) (Dekel & Woo 2003 for SN feedback) and, naively, \( M_* \propto M_h \), we obtain \( M_* \propto M_h^{0.69} \), compatible with the observed mass dependence (Paper I).

4.2. Staged Galaxy Formation

Figure 1 shows the previously described increase of the highest SSFRs toward lower \( M_* \). High SSFRs have been interpreted as episodes of SFR above the past-average level \((b > 1)\), based on the assumption that all galaxies had a relatively high \( z_f \), \( (z = 3) \); e.g., Bell et al. 2005; Juneau et al. 2005; Feulner et al. 2005).

Our data indicate that high SSFRs often do not represent
such irregular or periodic episodes late in the SFH of a galaxy. In Figure 2, we show SSFR versus $M_*$ as in Figure 1. We express the SSFR in terms of the doubling times, $t_d = M_*/[(1 - R)\Psi] = [(1 - R)/SSFR]^{-1}$, within which the current SSFR would produce the observed $M_*$. Small $t_d$ correspond to high SSFRs; for a declining SFH, a galaxy can be at most as old as $t_d$. Consider the galaxies at $0.75 < z < 1$ and $10^{10} < M_*/L_\odot$, where the data are $>80\%$ complete. Incompleteness affects mostly red galaxies; hence, the plot shows $>80\%$ of the SF galaxies. Their current SFH would generate their observed $M_*$ within $t_d$ of $6 \times 10^8$ to $6 \times 10^9$ yr, mostly $<3 \times 10^9$ yr. These $t_d$ are smaller than half of the age of the universe at $0.75 < z < 1$. If we assume a high $z_f$ ($\sim 5$), $85\%$ of the galaxies have a SFR above the past average ($b > 1$), and $57\%$ a starburst ($b > 2$; Kennicutt et al. 2005).\footnote{Even if all our diagnostics overestimated the SFR by a factor of 2, the fraction of galaxies with $b > 1(2)$ would still be $57\%(21\%)$.} At face value, this is contradictory; it should not be possible for a majority of galaxies to simultaneously undergo a starburst, which by definition should occupy a short part of a duty cycle.

However, these galaxies form the MS, and their SSFRs show a gradual decline on gigayear timescales since $z \sim 1$ (Paper I), likely even since $z = 1.4$, not an enhancement of SFRs in the $z$ range shown in Figure 2. These galaxies therefore do not seem to simultaneously undergo a brief ($\approx 1$ Gyr) epoch of elevated SFRs on top of lower level SFHs; instead, their high SSFRs represent the early, strongly star-forming phase of a SFH that smoothly declines on gigayear timescales to $z = 0$. Their high SSFRs (short $t_d$) imply (1) that this gradually declining epoch must form the bulk of their $M_*$, and (2) that the galaxies must be observed $\leq 1 t_d$ after the onset of this epoch, suggesting $z_f \leq 2$ for $>60\%$ of these galaxies; otherwise the produced $M_*$ would be higher than observed.

These lines of evidence suggest that the observed high SSFRs of many galaxies are not due to a periodic or irregular burst, late in their SFH. Instead, many such galaxies seem to be observed shortly after their “initial burst” phase, the early stage in their predominantly smooth SFH that forms most of their $M_*$. Moreover, the average SSFR increases smoothly to lower masses, at all $z$. This points to a smooth dependence of the average $z_f$ on galaxy mass. Based on this evidence, we propose a scenario of “staged galaxy formation,” where the average onset of the major SF ($z_f$) decreases smoothly with galaxy mass. This scenario achieves high SSFRs without requiring that a large fraction of galaxies at any epoch are elevated in SFR ($b > 1$) or starbursting ($b > 2$). Allowing lower $z_f$ for a fraction of less massive galaxies is the only possibility to avoid this contradiction between burst fraction and duty cycle. The staged $\tau$ models we use to approximate these SFHs parameterize both the decline timescales ($\tau_d$) and the onset ($z_f$) of the main SF episode as a function of mass.

The range of $t_d$ in Figure 2 shows that the staged scenario only requires a fraction of less massive galaxies to form later: the range of $z_f$ must reach to lower $z$ for less massive galaxies. In addition, the model does not exclude some low-level SF prior to the onset of the major SF episode, effectively the epoch of assembly. This allows it to be consistent with the presence of old ($\sim 10$ Gyr) stars in many low-mass local galaxies (e.g., Grebel 2004).

A relation between the galaxy mass and the onset time of the dominant SF episode is observationally and theoretically supported: see Heavens et al. (2004); Iwata et al. (2007); Thomas et al. (2005) for early-type galaxies; Feulner et al. (2005), Reddy et al. (2006), and Erb et al. (2006) report a systematic decrease of stellar age with $M_*$, up to $z = 3–5$. Cold dark matter structure formation provides a framework for a systematic relation between the dominant SF epoch and present-day galaxy mass (Neistein et al. 2006). Finally, insofar as downsizing means that a characteristic epoch of high SSFR occurs early in high-mass galaxies, while at low $z$ only low-mass galaxies exhibit high SSFRs (Cowie et al. 1996), a delayed onset of major SF in less massive galaxies is a natural part of this process.

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