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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 $M_* \gtrsim 10^{10}\ M_\odot$ 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 (*τ models*), if less massive galaxies have systematically longer *e*-folding times τ, and a later onset of SF (z_f). Our model can provide a first parameterization of SFR as a function of M_* and z, and quantify mass dependences of τ and z_f, 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" 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 Multiband 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 SFR 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] λ3727), 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 <(>) 0.7, likely less.

We tested the effects of using different combinations of SFR and M_* measures, including *Galaxy Evolution Explorer* 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 τ 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 (τ models; eq. [1]) with mass-dependent parameters to quantify mass dependences of SF timescales and

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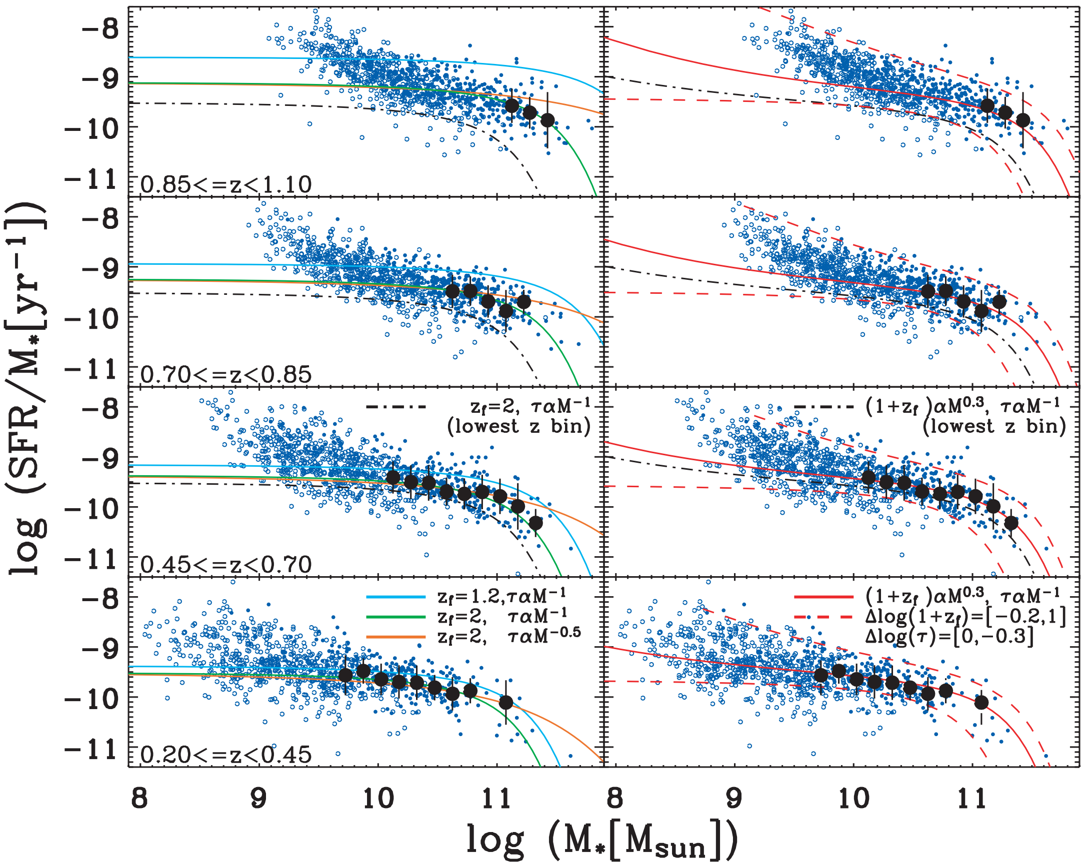

FIG. 1.—SSFR (yr^{-1}) vs. M_* for 3658 star-forming (main sequence; Paper I) AEGIS galaxies. *Filled blue circles*: SFRs from *Spitzer* MIPS 24 μm and DEEP2 emission lines (Paper I). *Open blue circles*: Blue galaxies without 24 μm detection, SFRs from extinction-corrected emission lines. Galaxies with 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 (SSFR) of the main-sequence galaxies, in the M_* range where the sample is >95% complete. The black dot-dashed line repeats the green (*left*) and red (*right*) models in the lowest z bin. *Left*: τ models with fixed formation redshift z_f and mass-dependent τ (*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 τ models (*red*), where both τ and z_f are mass-dependent. Red dashed lines show the effect of varying z_f and τ at a given $M_{\rm bar}$. The delayed onset of SF (lower z_f) in a fraction of less massive galaxies accounts for the increase of SSFRs at low M_* without requiring a large fraction of galaxies to simultaneously undergo starbursts.

to account for M_* growth. Previous authors have successfully employed τ models with different e-folding times τ 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 τ 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_b that is initially gaseous, later the sum of gas (M_g) and stellar mass M_*. For instantaneous recycling, with a recycled gas fraction $R = 0.5$ (Kroupa initial mass function [IMF]; Bell et al. 2005), and a SF efficiency ϵ such that the SFR $\Psi = \epsilon M_g$, one obtains

$$\Psi(M_b, z) = \Psi(z_f) \exp\left(-\frac{T}{\tau}\right), \qquad (1)$$

$$T = t(z) - t(z_f), \quad \tau = \frac{1}{\epsilon(1 - R)}, \qquad (2)$$

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

$$\tau(M_b) = c_\alpha M_b^\alpha. \qquad (3)$$

Figure 1 (*left column*) shows examples of equation (1) in the SSFR-M_* plane, compared to the median SSFR of the MS, for different z_f, c_α, and α.

3.1. *Staged τ Models*

Figure 1 (*left column*) shows that models with mass-dependent τ can crudely reproduce the median MS of SF galaxies and its redshift evolution for galaxies with $M_* \gtrsim 10^{10}\ M_\odot$ 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 $z_f < 1$, unphysical for massive galaxies. The reason is the monotonic decline of the SFR of τ models. Their present-to-past average SFR (Kennicutt et al. 2005),

$$b(t) = \frac{\Psi(t)}{\langle\Psi\rangle_T} = \frac{\Psi}{M_*}\frac{T}{1 - R}, \qquad (4)$$

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 ($\gtrsim$3). 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 τ 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 mass, similarly to τ, an approach we refer to as *staged* τ models:

$$1 + z_f(M_b) = c_\beta M_b^\beta. \quad (5)$$

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 τ models (Fig. 1, *right column*) provide a better description of the median of the MS than τ 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 τ at a given mass (*dashed red curves*) also reproduce the upper envelope of the MS, which is complete at all observed M_* and z, 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 τ model in Figure 1 (*right*) is given by

$$\tau = 10^{20.7}\left(\frac{M_b}{M_\odot}\right)^{-1}\ \text{yr}, \quad (1+z_f) = 10^{-2.7}\left(\frac{M_b}{M_\odot}\right)^{0.3}. \quad (6)$$

We calculated χ^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 χ^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. τ *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 τ and of the z_f. The mass dependences of τ and z_f, and M_* growth through SF, conspire to reproduce

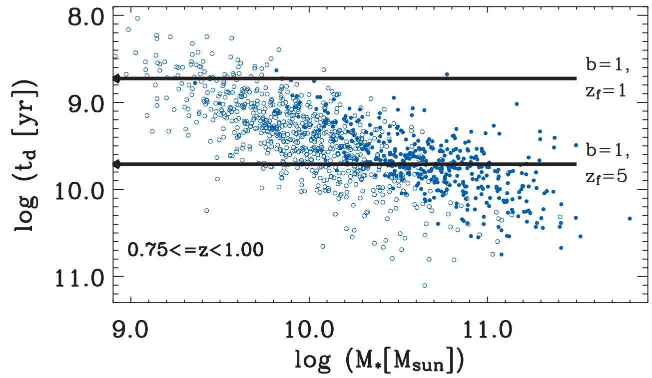

FIG. 2.—Stellar mass doubling times t_d (see § 4.2) as a function of M_*. Symbols are as in Fig. 1. Horizontal lines give the time between z_f and the center of the z bin shown, for z_f of 1 and 5. Galaxies above these lines would have t_d shorter than their adopted age, i.e., SFRs above their past-average level ($b>1$). Galaxies on the lines form stars at their past-average rate ($b = 1$).

the decline of SFRs that is similar over a wide M_* range (Paper I; Zheng et al. 2007).

Notably, τ 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 $\gtrsim 10^{10}\ M_\odot$ since $z \sim 1$.

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 τ 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 τ 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 $10^{12}\ M_\odot$ by $\dot{M}_h/M_h \approx 0.04\ \text{Gyr}^{-1}(1+z)^{2.25}$ (Birnboim et al. 2007), giving a factor of ~5 between $z \sim 1$ and $z \sim 0$, similar to the observed decline. The mean virial accretion in this mass range is predicted to vary as $\dot{M}_h \propto M_h^{1.15}$. If we adopt $M_*/M_h \propto V^2 \propto M_h^{2/3}$ (Dekel & Woo 2003 for SN feedback) and, naively, $\dot{M}_* \propto \dot{M}_h$, we obtain $\dot{M}_* \propto M_*^{0.69}$, 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 (see § 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*, $t_d = M_*/[(1-R)\Psi] = [(1-R)\mathrm{SSFR}]^{-1}$, within which the current SFR 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 $10^{10}\ M_\odot$, where the data are >80% complete. Incompleteness affects mostly red galaxies; hence, the plot shows >80% of the SF galaxies. Their current SFR would generate their observed M_* within t_d of 6×10^8 to 6×10^9 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 (∼5), 85% of the galaxies have a SFR above the past average ($b > 1$), and 57% a starburst ($b > 2$; Kennicutt et al. 2005).[10] 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 SFRs 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 ($\lesssim$1 Gyr) episode 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 $\lesssim 1 t_d$ after the onset of this epoch, suggesting $z_f \lesssim 2$ 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 τ models we use to approximate these SFHs parameterize both the decline timescales (τ), 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 (∼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.

[10] 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%).

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