FULL TITLE
*ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION***
NAMES OF EDITORS

Star Formation Histories and Stellar Mass Growth out to $z > 1$

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Abstract. The deepest multi-wavelength surveys now provide measurements of star formation in galaxies out to $z > 1$, and allow to reconstruct its history for large parts of the galaxy population. I review recent studies, which have consistently revealed a picture where galaxy star formation rates and their evolution are primarily determined by galaxy mass. Unless they undergo a quenching of their star formation, galaxies of similar masses have very similar star formation histories, which turn out to be relatively smooth: star formation rates decline with redshift in a primarily gradual manner, while typical starburst episodes have only a modest amplitude that barely evolves.

I discuss how the found relations and their redshift evolution can provide an observed reference star formation history as a function of galaxy mass.

The observed amplitudes and timescales of galaxy star formation are not fully reproduced by current theoretical models, and are a promising testbed to improve the assumed baryon physics. However, measurements of star formation rates in distant galaxies need to be treated with caution. Near-future data, methods and instruments will help us to improve on calibrations and sensitivities for high redshift star formation.

1. Star Formation and the Deep Multi-Wavelength Surveys

Star formation (SF) is responsible for most of those galaxy properties that we can currently measure out to high z: luminosities, spectral energy distributions, morphologies. Understanding the history and physics of SF is fundamental for the understanding of baryons in galaxies, and also for many other fields of astrophysics: the cosmic evolution of gas and metals, the extragalactic background light, and cosmological tests that rely on galaxies' clustering and number densities to illuminate the evolution of Dark Matter structure.

Studies of SF histories have been dramatically advanced by the recent arrival of deep, multi-wavelength surveys like GOODS, AEGIS and COSMOS. Their sensitivity allows to observe all galaxies down to masses below typical $L^\star$ systems out to $z > 1$, providing a comprehensive picture of their evolution. Their variety of multi-wavelength data, especially the Spitzer IRAC and MIPS $24\mu m$ data, have much improved the measurements of SF rates (SFR) and stellar masses ($M_\star$) in distant galaxies, where dust extinction corrections are challenging to measure (e.g. Daddi et al. (2007)).

In the following, I summarize the first broad-brushed, but comprehensive and new picture of SF in field galaxies that the deep surveys have just revealed: SF was predominantly not driven by an evolution of strong starbursts, but gradu-

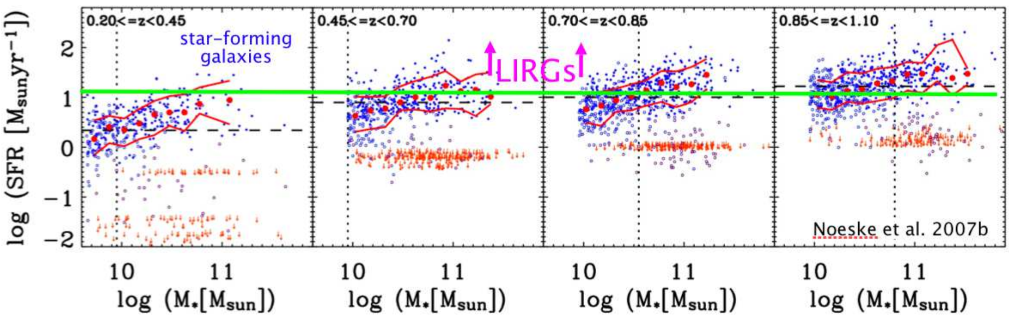

Figure 1 Log(SFR) vs log($M_\star$) for 2905 galaxies in AEGIS, in the $M_\star$ range where the data are $> 80\%$ complete. See Noeske et al. (2007a) for details. The *dotted vertical line* marks $> 95\%$ completeness. *Filled blue circles:* Combined SFR from MIPS 24μm and DEEP2 emission lines. *Open blue circles:* No 24μm detection, blue $U-B$ colors, SFR from extinction-corrected emission lines. *Purple circles:* as open blue circles, but red $U-B$ colors, mostly LINER/AGN candidates. *Orange down arrows:* No robust detection of $f(24\mu\text{m})$ or emission lines; conservative SFR upper limits shown. There is a distinct "Main Sequence" formed by fiducial SF galaxies (open and filled blue circles); galaxies with little or no SF lie below this sequence. Red circles: median of log(SFR) in mass bins of 0.15 dex for Main Sequence galaxies (blue circles). Red lines include 34% of Main Sequence galaxies above and 34% below the median of log(SFR), $\pm 1\sigma$ in the case of a normal distribution. *Horizontal black dashed line:* SFR corresponding to the 24μm 80% completeness limit at the center of each z bin. 24μm-detected galaxies above the *green line* are LIRGs.

ally declining on mass-dependent scales (Noeske et al. 2007a,b; Elbaz et al. 2007; Daddi et al. 2007). This picture ties together some separate key results of the preceding decade, that (i) the comoving SF rate (SFR) density of the Universe has decreased by about an order of magnitude since $z = 1$ (Madau et al. 1996; Hopkins 2004), (ii) that many distant galaxies had high SFR that are unusual today, and (iii) that the average SF history of galaxies is a strong function of their mass (Cowie et al. 1996; Heavens et al. 2004; Juneau et al. 2005), a phenomenon dubbed "Downsizing" (Cowie et al. 1996).

Most of the following discussion is based on the AEGIS survey (Davis et al. 2007). For more details, see (Noeske et al. 2007a,b).

2. A Star Formation Rate-Stellar Mass Relation ("Galaxy Main Sequence") out to $z \sim 2$

The evolution of SFR as a function of $M_\star$ and z is summarized in Figure 1, adapted from Noeske et al. (2007a). Shown are data from the AEGIS survey from $z = 0.2$ to 1.1. SFR are derived from Spitzer 24μm photometry and DEEP2 emission lines (Weiner et al. 2007), $M_\star$ from optical DEEP2 and NIR photometry (Bundy et al. 2006). For other SFR tracers and calibrations, the results are consistent, with small quantitative systematic differences.

The star-forming galaxies (blue symbols, predominantly late type morphologies, mostly blue $(U-B)$ colors) segregate from those with no measurable SF (red symbols; early types; red $(U-B)$ colors) and the galaxies with weak emission lines that are likely to have some residual SF (Schiminovich et al. 2007) or to be LINER/AGN-powered (purple; mostly early types; red $(U - B)$ colors). See the caption of Figure 1 or Noeske et al. (2007a).

Importantly, the SF galaxies form a defined relation between SFR and $M_\star$ over the whole z range, with a spread in SFR at a given $M_\star$ and z that is crudely log-normal with a 1σ width of $\lesssim 0.3$ dex (after correction for minimal estimates of SFR errors) at all z. Such a relation had been known at $z \sim 0.1$ (Brinchmann et al. 2004), and its existence to $z > 1$ (Noeske et al. 2007a) was confirmed by Elbaz et al. (2007). Recently, Daddi et al. (2007) reported this relation with a similar spread in SFR at $z \sim 2$ (cf. also e.g. Förster Schreiber et al. (2009)). Detailed studies at $z \sim 0.1$ are given in Schiminovich et al. (2007) and Salim et al. (2007). While the scatter in SF remains roughly constant at all observed z, the above authors find the SFR at a given $M_\star$ to decrease by a factor of $\sim 6(20)$ from $z = 1(2)$ to 0 (Noeske et al. 2007a; Elbaz et al. 2007; Daddi et al. 2007).

For reasons explained in Section 4., we nicknamed the SFR-$M_\star$ relation the "Galaxy Main Sequence (GMS)".

3. Implications of the Galaxy Main Sequence: A New Picture of Star Formation in Field Galaxies since $z \sim 2$.

The surprising persistence of an equally sharp relation between SFR and $M_\star$ out to $z \sim 2$, or over 10 Gyr in lookback time, has profound implications for SF in field galaxies over most of the cosmic time. These were first discussed in Noeske et al. (2007a) (and already in part in Zamojski et al. (2007)), and pertain only to star-forming galaxies on the SFR-$M_\star$ relation (and in the z-dependent $M_\star$ range where we are complete), not to those where SF was shut down by still debated processes (cf. Faber et al. (2007)).

1) Galaxies of equal mass must have had similar SF histories, else the scatter in SFR along the GMS would increase with time. The smoothness of the dependence of SFR on $M_\star$ suggests that we observe a generic mode of galaxy-wide star formation, possibly dominated by the same set of few physical processes over several decades in galaxy mass.

2) The 1σ spread of SFR at a given $M_\star$ and z is $\lesssim \pm 0.3$ in log(SFR), and remains roughly equally narrow out to $z \sim 2$. This finding limits the amplitude and duty cycles of typical variations in SFR that galaxies can have experienced over the past 10 Gyr: statistically, a galaxy spent 2/3 of its time within a factor of 2 of its typical SFR at that z. If some galaxies underwent stronger variations, causing much of the observed scatter, then the remaining majority of galaxies must have had even smoother SF histories. These limits on SFR variations constrain the effect of galaxy interactions on galaxy SFRs; they are consistent with theoretical predictions of the influence of frequent minor interactions (Somerville et al. 2001), and constrain the longer-term ($10^8 - 10^9$ yr) enhancement of SFR (e.g. Cox et al. (2006)) by major mergers to a modest factor.

3) The factor by which the SFR along the GMS have decreased since ~ 2 (see Section 2.) is much larger than the amplitude of typical SFR variations. The *dominant* process in the evolution of SF over the past 10 Gyr was hence *a gradual decline of SFR in individual galaxies*, with at most modest variations

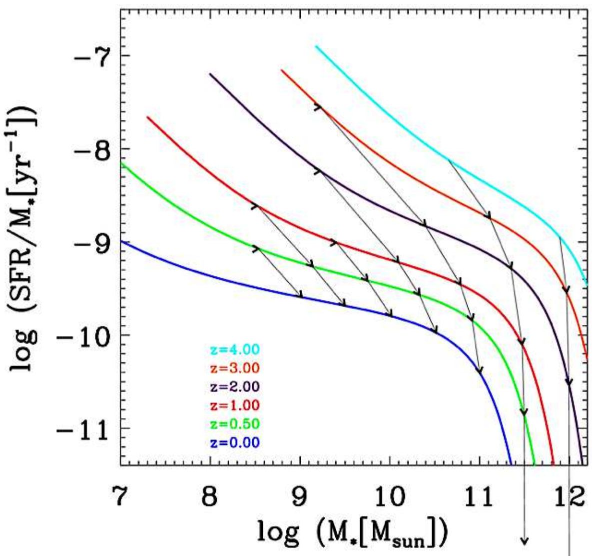

Figure 2 Isochrones in the log(specific SFR) - log(stellar mass) plane for the mass-dependent τ models presented in Noeske et al. (2007b). Isochrones range from $z = 0$ to 4 from bottom to top; the arrows are evolutionary tracks for galaxies of different masses. Note the substantial stellar mass growth due to SF over time: galaxy properties cannot simply be compared for galaxies of equal stellar mass at different z, but require corrections for this mass growth (Noeske et al. 2009, in preparation).

that were superposed on that smooth decline. It is especially noteworthy that these SFR variations seem to have the *same relative amplitude* (factor) at all z: out to $z \sim 2$, episodic SF variations or starbursts played a minor, barely evolving role in the SF history of the Universe, and of typical galaxies. This result is contrary to the formerly popular hypothesis that the evolution of SF might be driven by increasingly frequent strong starbursts at higher z.

The effect of galaxy interactions on SFR has now been measured for galaxies in major and minor mergers, and close pairs (Lin et al. (2007); Robaina et al. (2009), and this conference; Jogee et al. (2009), and this conference). These studies have consistently shown a mild enhancement of SFR: SFR distributions of interacting samples are shifted to $\lesssim 2\times$ larger values than those of isolated control samples. This limits the fraction of $M_\star$ formed at intermediate z to $\lesssim 10\%$ (Robaina et al. (2009), and this conference).

Finally, Figure 1 (green line) reveals the origin of the strong number density increase of Luminous Infrared Galaxies (LIRGs) with z: apparently, galaxies become IR-luminous due to their generic, gradual evolution of star formation, where SFR (and hence likely their dust extinction) increase with z. This supports studies (Bell et al. 2005; Melbourne et al. 2005) that found LIRGs at intermediate z to have mostly regular, disk-like morphologies and suggested that LIRGs are a universal phase in the intrinsic, gradual evolution of many galaxies.

4. The Galaxy Main Sequence: The Stellar Main Sequence - Equivalent for Galaxies

The results I summarized in Section 2. reveal a fundamental role of the SFR-$M_\star$ relation: because galaxies of equal mass have similar SF histories, they must evolve along similar tracks in the SFR - $M_\star$ plane. The SFR - $M_\star$ relation at a given z must therefore mark the point on each mass-dependent evolutionary track across the galaxy mass spectrum at that z: it is an *isochrone* cutting across the evolutionary tracks at a given time. See Figure 2, where this is shown for the equivalent case of specific SFR vs $M_\star$ at different z.

This is analog to another important isochrone in astrophysics - the Hertzsprung-Russell Diagram, which is a superposition of the mass-dependent stellar evolutionary tracks. In this picture, the galaxies' SFR-$M_\star$ relation is the analog of the stellar main sequence, where regular, active evolution, driven by the same set of physical processes in an undisturbed system, proceeds until a change in physics moves the object to its red late stages and passive end stadium (the "red and dead" galaxies). Incidentally, the galaxies' '"Main Sequence Turnoff" occurs systematically earlier for more massive galaxies (e.g. Bundy et al. (2006)), similar to stars.

These similarities led us to adopt the term "Galaxy Main Sequence", and the GMS is as fundamental to the understanding of galaxy evolution as the stellar MS to stellar physics: from the GMS at different z, we can recover the mass-dependent SF histories of galaxies. In Noeske et al. (2007b), we presented a first simple, parametric approach: The evolution of the GMS was modeled by simple, smooth model SF histories, justified by the dominance of the smoothly declining component of SF histories (Section 2.). We chose exponential SF histories ("τ models"), given their previous success for many applications; both parameters, the e-folding time τ and the "formation redshift" z_f where SF begins, were allowed to depend on the galaxies' "baryonic mass" as power laws [1]. This model reproduces the evolution of SFR and $M_\star$ on the GMS up to $z = 1.1$ remarkably well, and can attribute the scatter of SFR along the GMS to scatter in SF history parameters at a given mass (see Noeske et al. (2007b), Figure 1), suggesting an even smaller role of episodic or bursty SF. These τ models are the first parametrization of the mass-dependent SF histories of galaxies.

Figure 2 shows the τ models (colored lines) in the specific SFR (SFR normalized by $M_\star$) vs $M_\star$ plane. It is equivalent to the SFR-$M_\star$ plane, essentially with the MS rotated clockwise. For illustration, the model GMS is extrapolated out to $z = 4$; note that the models are only constrained by data to $z \sim 1$. The evolutionary tracks (black arrows) reveal substantial mass growth due to SF with redshift for all but the most massive galaxies, also found by independent methods (Conroy et al. 2007; Zheng et al. 2007). Comparing galaxies of equal $M_\star$ at different z is therefore generally not justified: one may compare very different objects. Instead, one needs to compare galaxies on the same evolutionary track, i.e. apply a mass correction that can for the first time be inferred from the τ models discussed above, or future refined parametrizations.

[1] Note that the mass in Noeske et al. (2007b) is the "baryonic mass" of a closed box model. Since galaxies are not closed boxes, this mass will depend in a complicated way on the galaxies' actual (baryonic/dark/total/dynamical) masses. This "mass" merely acts as a dummy parameter to generate evolutionary tracks that correctly reproduce the data on SFR and $M_\star$ vs z, by keeping track of the stellar mass growth due to a SF history. These tracks can however easily be linked to actual stellar masses at any observable z, through the $M_\star$ they generate at a given z.

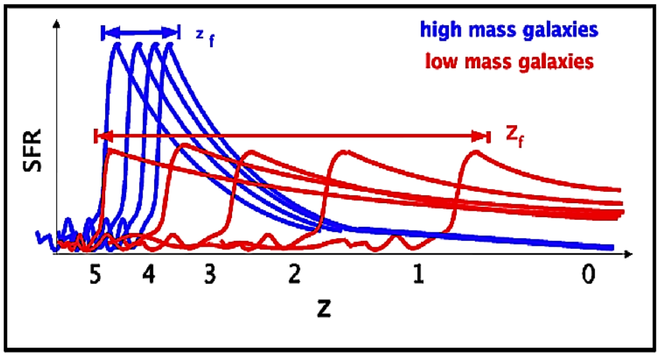

Figure 3 Simplified cartoon sketch of the concept of *"staged galaxy formation"* (Noeske et al. 2007b): In massive galaxies, SF declines on short timescales and begins to be efficient at high z. In less massive galaxies, SF declines not only more slowly; many low mass galaxies are also inefficient at forming stars at high z and attain sustained efficient SF only at lower z.

5. A Delayed Onset of Efficient Star Formation in Less Massive Galaxies

Interestingly, the τ model fits required both τ and z_f to be mass-dependent: Less massive galaxies had not only longer τ, i.e. a slower decline of SF, SF being less efficient and having lower initial SFRs; they also had systematically later z_f, equivalent to a later onset of SF. The observed "Downsizing" in SF galaxies is apparently a combination of both phenomena.

The late z_f are required to account for the high specific SFR (SFR/$M_\star$) of a majority of sub-$L_\star$ galaxies at $z \gg 0$ (see Figure 2 in Noeske et al. (2007b). These imply "doubling times" much shorter than the age of the Universe, i.e. these galaxies cannot have formed stars at their observed rate without overproducing their stellar mass. The usual explanation for high specific SFR, starburst events on top a lower SFR history, is not physical because a majority of all such galaxies would need to simultaneously undergo a stochastic event, and is also in contradiction with other observations - see Noeske et al. (2007a) for details. In a substantial fraction - but not necessarily all - of less massive galaxies, SF must hence have been inefficient at early times and only attained sustained efficiency later than in more massive galaxies (cf. Figure 3).

This mass-dependence of the onset of efficient SF, dubbed "Staged Galaxy Formation" (Noeske et al. 2007b), is consistent with the observed presence of very old stars — roughly a Hubble time — in the majority of Local Group dwarf galaxies and other resolved systems. Our data on SF to $z \sim 1$ only indicate that SF was inefficient, not absent, in less massive galaxies, allowing for some old stars; (ii) efficient SF only needs to delayed in the majority, but not all of such galaxies; (iii) our data do not probe galaxies down to true dwarf masses.

This systematic delay of efficient of SF in less massive galaxies is not likely to be an artifact of SFR measurement errors. It is consistent with statistical studies of galaxy SF histories from independent methods - the evolution of stellar mass functions and the fossil record in stellar populations of low z galaxies; cf. Conroy et al. (2007), especially Figure 6; Zheng et al. (2007); Panter et al. (2007).

6. Constraints to Galaxy Formation Models, and Uncertainties of SFR Measurements

The various data on SFR and $M_\star$ out to $z > 2$ have become an important testbed for theoretical work on galaxy formation, and help to improve the treatment of the complicated and numerically expensive baryon physics. Current models of galaxy populations do generally reproduce the SFR-$M_\star$ relation with a slope and scatter similar to the observed one (Elbaz et al. 2007; Daddi et al. 2007; Davé 2008).

Two types of discrepancies seem however to be universal between the data and models: On the one hand, models underpredict the redshift evolution of SFR for galaxies on the GMS. It is currently debated whether this results from systematic errors in SFR measurements at high z, problems of model physics, or both (Elbaz et al. 2007; Daddi et al. 2007; Davé 2008). On the other hand, the delay of efficient SF in less massive galaxies is not correctly reproduced by current models (Cirasuolo et al. 2008; Marchesini et al. 2008; Fontanot et al. 2009). Found from independent data and methods (Section 5.), this difference is probably physical and likely due to not yet fully understood baryonic physics (Neistein et al. 2006) that renders SF or its fueling processes inefficient at early times in low mass halos.

While observed galaxy SFR across most of the cosmic time have provided new key information for many purposes, considerable work is still necessary (and underway!) to improve their calibrations and systematics (see, e.g. Salim et al. (2009)), improve restframe IR coverage with Herschel, ALMA and JWST. In addition, systematics like the adopted stellar IMF and extinction curves can be tested from non-standard derivations of SFR (Conroy et al. 2007; Chen et al. 2009).

Acknowledgments. This work received funding through grants from the W.M. Keck Foundation, NASA and NSF and is based on observations with the W.M. Keck Telescope, the Hubble Space Telescope, the Spitzer Space Telescope, the Galaxy Evolution Explorer, the Canada France Hawaii Telescope, and the Palomar Observatory.

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