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The Star Formation History and Stellar Assembly of High Redshift Galaxies

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Abstract. I discuss current observational constraints on the star-formation and stellar-assembly histories of galaxies at high redshifts. The data on massive galaxies at $z < 1$ implies that their stellar populations formed at $z > 2$, and that their morphological configuration was in place soon thereafter. *Spitzer* Space Telescope 24 μm observations indicate that a substantial fraction of massive galaxies at $z \sim 1.5$–3 have high IR luminosities, suggesting they are rapidly forming stars, accreting material onto supermassive black holes, or both. I compare how observations of these IR–active phases in the histories of massive galaxies constrain current galaxy–formation models.

Keywords. galaxies: evolution, galaxies: formation, galaxies: high-redshift, infrared: galaxies

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Most (~50%) of the stellar mass in galaxies today formed during the short time between $z \sim 3$ and 1 (e.g., Dickinson *et al.* 2003, Rudnick *et al.* 2006). Much of this stellar mass density resides in massive galaxies, which appear at epochs prior to $z \sim 1$–2 (see, e.g., McCarthy 2004, Renzini 2006). The fashionable scenario is that galaxies "downsize", with massive galaxies forming most of their stars at early cosmological times, with less–massive galaxies continuing to form stars to the present (e.g., Juneau *et al.* 2005). However, it is still unclear when and where the stars in these galaxies formed. For example, it may be that stars form predominantly in low–mass galaxies at high redshifts, which then assemble over time to form large, present–day massive galaxies (e.g., Kauffmann & Charlot 1998).

At $z \lesssim 1$ massive galaxies exist on a fairly prominent red sequence (e.g., Blanton *et al.* 2003, Bell *et al.* 2004, Willmer *et al.* 2006), are largely devoid of star formation and evolve passively. Forming such a red sequence is a challenge for contemporary hierarchical galaxy formation models (e.g., Davé *et al.* 2005) without including some agent to suppress star formation (the favorable mechanism is feedback from AGN; e.g., Croton *et al.* 2006, Hopkins *et al.* 2006). In hierachical models, the most massive galaxies continue to grow via satellite accretion. To maintain the red sequence this growth must occur without continued star–formation (so–called "dry" merging), but so far observational evidence is inconclusive and conflicting (e.g., van Dokkum 2005; Bell *et al.* 2006; Faber *et al.* 2005).

Understanding galaxy formation boils down to two questions: When did galaxies form their stars? And, when did they assemble into their present–day configurations? In these proceedings, I discuss constraints on star formation in massive galaxies at $z \sim 1.5$–3. In particular I focus on observations of the IR activity in high redshift galaxies using *Spitzer* 24 μm observations, and what this means for the galaxies' assembly and evolution.

Star Formation in High–z Massive Galaxies

Deep *Spitzer* surveys at 24 μm show that IR luminous galaxies evolved very rapidly (Papovich *et al.* 2004), dominating the SFR density at $z \sim 1$ (e.g., Le Floc'h *et al.* 2005). Several studies of the 24 μm emission of higher redshift galaxies ($1.5 < z < 3$) show very high detection rates ($\gtrsim 50\%$; Daddi *et al.* 2005; Papovich *et al.* 2006; Reddy *et al.*

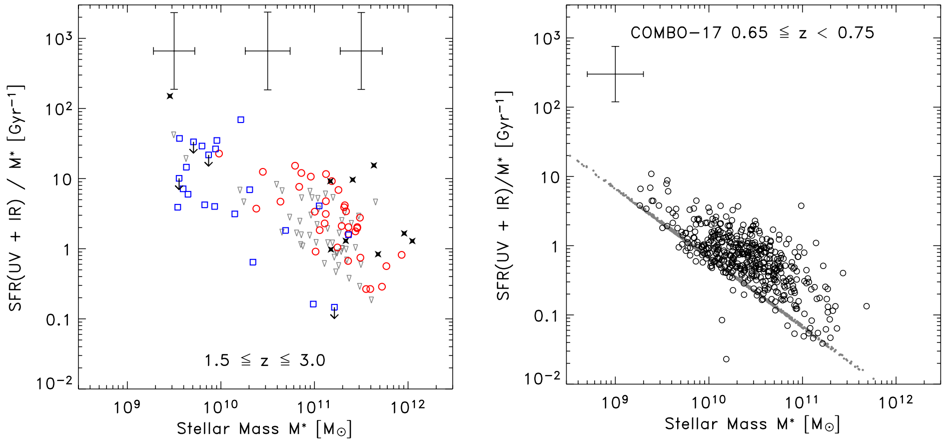

Figure 1. Specific SFR as a function of stellar mass for high redshift galaxies (from Papovich *et al.* 2006). The left panel shows galaxies at $1.5 < z < 3.0$. Red circles correspond to DRGs; gray triangles denote SFR upper limits. Blue squares show galaxies from the HDF–N. Stars show X–ray sources. The right panel shows galaxies from COMBO–17 at $0.65 < z < 0.75$. Dots denote SFR upper limits.

2006; Webb *et al.* 2006), suggesting that the majority of high–redshift galaxies emit in the thermal IR — *they are either actively forming stars, supermassive blackholes, or both at this epoch.*

For example, figure 1 shows the specific SFRs ($\Psi/\mathcal{M}$) derived from the masses and SFRs for the galaxies in the GOODS fields at $1.5 < z < 3.0$ (from Papovich *et al.* 2006), where the SFRs are derived from the summed UV and IR emission based on the *Spitzer* 24 μm data. The figure also shows the specific SFRs for $0.65 < z < 0.75$ galaxies from COMBO–17 (Wolf *et al.* 2003), derived also using *Spitzer* 24 μm data. Interestingly there is strong evolution in the specific SFRs, especially for massive galaxies. Galaxies with masses $\geqslant 10^{11}$ $\mathcal{M}_\odot$ at $1.5 \leqslant z \leqslant 3$ have high specific SFRs, $\Psi/\mathcal{M} \sim 0.2$–10 Gyr^{-1}, excluding X–ray sources. In contrast, at $z \lesssim 0.75$ galaxies with $\mathcal{M} \geqslant 10^{11}$ $\mathcal{M}_\odot$ have much lower specific SFRs, $\Psi/\mathcal{M} \sim 0.1$–1 Gyr^{-1}.

Papovich *et al.* (2006) defined the integrated specific SFR as the ratio of the sum of all galaxy SFRs, Ψ, to the sum of their stellar masses, $\mathcal{M}$. Figure 2 shows the integrated specific SFRs for galaxies selected from GOODS at $z \sim 1.5$–3.0 and COMBO–17 at $z \sim 0.4$ and 0.7, all with $\mathcal{M} \geqslant 10^{11}$ $\mathcal{M}_\odot$. The error box indicates the affect of assumptions in the SFRs and AGN activity (see further discussion below, and in Papovich *et al.* 2006). The integrated specific SFR in galaxies with $\mathcal{M} > 10^{11}$ $\mathcal{M}_\odot$ declines by more than an order of magnitude from $z \sim 1.5$–3 to $z \lesssim 0.7$. The curves in figure 2 show the specific SFR integrated over all galaxies, not just the most massive; this is the ratio of the cosmic SFR density to its integral, $\dot{\rho}_*/\int \dot{\rho}_*\, dt$. Although there is a decrease in the global specific SFR with decreasing redshift, the evolution in the integrated specific SFR in massive galaxies is accelerated. The implication is that at $z \gtrsim 1.5$, massive galaxies are rapidly forming their stars, whereas by $z \lesssim 1.5$ the specific SFRs of massive galaxies drops rapidly, and lower–mass galaxies dominate the cosmic SFR density.

If AGN contribute to the observed 24 μm emission in galaxies at $z \sim 1.5$–3, then they can affect the inferred IR luminosities. For example, using an IR template for Mrk 231 instead of a star–forming galaxy with $L_{\rm IR} \gtrsim 10^{13}$ $L_\odot$ would reduce the IR luminosity for $z \sim 1.5$–3 galaxies by a factor of $\sim$2–5. Many ($\sim$15%) of the massive galaxies at $z \sim 1.5$–3 are detected in the deep X–ray data (see Papovich *et al.* 2006), and these

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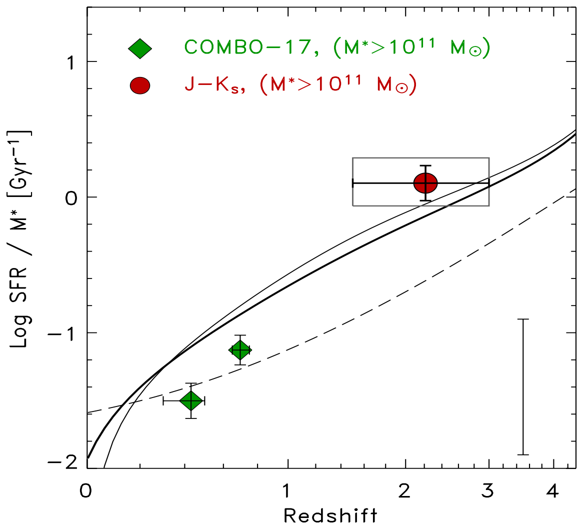

Figure 2. The integrated specific SFR as a function of redshift (from Papovich *et al.* 2006). The integrated specific SFR is the ratio of the sum of galaxy SFRs to the sum of galaxy stellar masses. The curves show the expected evolution from the global SFR density. Data points show results for galaxies with $\geqslant 10^{11}\ \mathcal{M}_{\odot}$. The inset error bar shows an estimate on the systematics.

objects tend to have high inferred specific SFRs (see figure 1). This obviously has an effect on the evolution of the integrated specific SFRs: the error box on the data point at $1.5 < z < 3$ in figure 2 shows how the result changes if the SFR for galaxies with putative AGN (based on X–ray detections, or rest–frame near–IR colors, see Stern *et al.* 2005; Alonso–Herrero *et al.* 2006) is set to zero. Interestingly, the high AGN occurrence in massive galaxies suggests that at $z \sim 1.5$–3 these objects are forming simultaneously their stars and supermassive black holes. This may provide the impetus for the present–day black-hole–bulge-mass relation and/or provide the feedback necessary to squelch star–formation in such galaxies, moving them onto the red sequence.

Confrontation with Models

Recent hierarchical galaxy–formation models predict a “downsizing” trend in the star formation rates of massive galaxies. De Lucia *et al.* (2006) show that within the semi-analytical galaxy–formation prescription coupled with feedback from AGN (Croton *et al.* 2006) that galaxies in the most massive dark matter haloes formed their stars at the earliest epochs. These models seem broadly consistent with observations. The “downsizing” jargon used by astronomers merely signifies that star–formation is accelerated in the most massive overdensities in current ΛCDM galaxy–formation models.

While encouraging, the details of star–formation in massive galaxies are not yet fully consistent with the *Spitzer* 24 μm observations. Assuming the galaxies at $1.5 < z < 3$ with observed masses $>10^{11}\ \mathcal{M}_{\odot}$ evolve to present–day galaxies with masses of *at least* this much, then the De Lucia *et al.* model predicts they should have observed specific SFRs $\sim$0.3 Gyr^{-1} on average. The observations instead suggest a specfic SFR value closer to 1 Gyr^{-1} (see figure 1). There may be a discrepancy at the factor $\sim$3 level, and this is likely discrepancy is likely greater because the observed galaxies presumably will continue to increase their stellar mass to $z \sim 0$. Admittedly the uncertainties of the IR–infered SFRs are at the factor $\sim$3 level, and to provide constraints on models of the star formation rates of massive galaxies will require lowering these observational uncertainties.

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A more serious challenge to hierarchical models is the existence of a substantial population of apparently passive galaxies on the red sequence by $z \sim 1$. The stellar mass density of galaxies on the red sequence is near its present–day value by $z \sim 0.7$ (e.g., Brown *et al.* 2006). Furthermore, Cimatti *et al.* (2006; see also Cimatti *et al.*, *these proceedings*) find that by using empirical color–evolution models the number of the most luminous galaxies ($>4\ L^*$) on the red sequence is nearly unchanged to $z \sim 1$. This is difficult for hierarchical models that predict the most massive present–day galaxies assembled into their current configurations at the lowest redshifts (e.g., Neistien *et al.* 2006; De Lucia *et al.* 2006). For example, both the Neistein *et al.* and De Lucia *et al.* show that the main progenitor (having $\gtrsim 50\%$ of the final mass) of massive galaxies with present–day $M > 10^{12}\ \mathcal{M}_\odot$ formed at $z \ll 1$. This is difficult to reconcile even with frequent "dry merging" on the red sequence (see also Faber *et al.* 2005).

We are witnessing a growing understanding (and even possible convergence) between observational and theoretical constraints on galaxy evolution, even though significant hurdles remain. It will be exciting to see the summary of our knowledge in this field at the next IAU General Assembly.

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