Star Formation and Merging in Massive Galaxies at $z < 2$

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**Abstract.** Observing massive galaxies at various redshifts is one of the most straightforward and direct approaches towards understanding galaxy formation. There is now largely a consensus that the massive galaxy ($M_* > 10^{11} M_\odot$) population is fully formed by $z \sim 1$, based on mass and luminosity functions. However, we argue that the latest data can only rule out number and mass density evolution of a factor of $> 2 - 3$ at $z < 1.5$. We furthermore show that the star formation history of $M_* > 10^{11} M_\odot$ galaxies reveals that $40\pm5\%$ of galaxies with $M_* > 10^{11} M_\odot$ at $z \sim 1$ are undergoing star formation that effectively doubles their stellar mass between $z = 0.4 - 1.4$. These massive galaxies also undergo $0.9_{-0.5}^{+0.7}$ major mergers during this same time period.

1. **Introduction**

Understanding when and how massive galaxies form is one of the most outstanding problems in cosmology and galaxy formation. Galaxies are predicted in Cold Dark Matter based models of structure formation to form gradually with time through the merging of smaller systems (e.g., Cole et al. 2001). While there is some evidence for this process, in terms of galaxies (e.g., Patton et al. 2002; Conselice et al. 2003; Bridge et al. 2007), many details are still lacking. Alternatively, massive galaxies, which are mostly ellipticals in today’s universe (e.g., Conselice 2006a), may have formed very rapidly in ‘monolithic’ collapses.

A such, massive galaxies are the dominant test-bed for galaxy models, and understanding their evolution observationally is an important goal. Most massive galaxies at $z < 1$ are red and passively evolving, yet star formation and merging activity have been seen in ellipticals from $z \sim 0$ to $z \sim 1$ (Stanford et al. 2004; Lin et al. 2004; Teplitz et al. 2006; Conselice et al. 2007a,b) - thus it is unclear when or how massive galaxies finally assembled. We must study this process at high redshift since the ages of stars in nearby galaxies cannot reveal their entire formation history, as the assembly of mass is likely decoupled from the formation of stars (e.g., Conselice 2006b; Trujillo et al. 2007).

Observational evidence suggests that passively evolving massive galaxies exist at $z \sim 1$, and likely at even early times, at $z > 2$ (Daddi et al. 2004; Saracco et al. 2005; Bundy et al. 2006; Conselice et al. 2007a). Recent claims also exist for the establishment of the full massive galaxy population by $z \sim 1$ (e.g., Drory et al. 2005; Bundy et al. 2006). However, what is not yet clear is if number densities measured in these surveys are able to rule out evolution at $z < 1$ after considering uncertainties in measuring stellar masses, number densities, and cosmic variance.

On the other hand, at $z > 1.5$ it appears that there are significantly fewer massive galaxies than at $z < 1.5$ (e.g., Drory et al. 2005). Observationally, the most massive galaxies at $z > 1.5$ are undergoing major mergers, which are
able to construct the stellar masses of massive galaxies rapidly (Conselice 2006b; Conselice et al. 2008a). The situation at $z < 1.5$ is not as clear, with observations inconclusive on whether there is evolution in the massive galaxy population at $z < 1$ (e.g., Brown et al. 2006). We argue here that by using a stellar mass selected sample of galaxies the number and mass densities of massive galaxies are consistent, within their errors, with no evolution at $z < 1.5$, yet there is observable evolution when examining in detail the physical processes occurring within these galaxies. Up to 50% of galaxies with $M_\star > 10^{11} M_\odot$ are undergoing star formation at $z \sim 1$, and roughly one major merger occurs within these systems at $z < 1.4$. We assume throughout a standard cosmology of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and $\Omega_m = 1 - \Omega_\Lambda = 0.3$.

2. Evolution of Massive Galaxy Number and Mass Densities

The most basic method for calculating the evolution of galaxies is measuring how their number densities and integrated stellar mass densities change as a function of time. Recent work on measuring densities suggests that within the measurement uncertainties galaxies with stellar masses $M_\star > 10^{11} M_\odot$, are largely in place at $z \sim 1$ (Bundy et al. 2005, 2006). Figure 1 shows the most up to date version of how the number and mass densities of galaxies with stellar masses $M_\star > 10^{11.5} M_\odot$ and $10^{11} M_\odot < M_\star < 10^{11.5} M_\odot$ evolve out to $z \sim 2$, as seen in the 1.5 deg$^2$ Palomar Observatory Wide-Field Infrared Survey (POWIR; Conselice et al. 2007a; Conselice et al. 2008b) covering the DEEP2 fields (Davis et al. 2007) from Conselice et al. (2007b) using a Chabrier IMF. The number
density evolution of these massive galaxies shows that statistically there is very little to no evolution at \( z < 1 \) for the \( M_\ast > 10^{11} \, M_\odot \) systems. This appears to support the idea that nearly all massive galaxies are present by \( z \sim 1 \) (e.g., Bundy et al. 2006).

However, as can be seen within the observational errors of Figure 1, there is potentially evolution in number densities for \( M_\ast > 10^{11} \, M_\odot \) selected galaxies between \( z \sim 1 - 1.5 \). Galaxies with \( M_\ast > 10^{11.5} \, M_\odot \) show an increase in number densities between \( z = 1.5 \) to 0.4 of a factor of \( 2.7^{+1.8}_{-1.7} \). This is however significant only at the \( < 2 \sigma \) level, considering all uncertainties (Conselice et al. 2007b). A similar result is found for the mass densities of galaxies with \( M_\ast > 10^{11.5} \, M_\odot \), and it is impossible to rule out that massive galaxies with \( M_\ast > 10^{11.5} \, M_\odot \) are all in place at \( z < 2 \) (Conselice et al. 2007b). However, as for the star-formation downsizing described in e.g., Bundy et al. (2006) there is also a stellar mass downsizing, such that lower mass galaxies are formed after higher mass ones. The number densities of systems with \( 10^{11} \, M_\odot < M_\ast < 10^{11.5} \, M_\odot \) increases by a factor of \( 2.2^{+0.57}_{-0.41} \) between \( z = 1.4 \) and \( z = 0.4 \), a result significant at \( > 4 \sigma \). Just as for the most massive systems, this evolution occurs completely at \( z > 1 \) (Conselice et al. 2007b). Taken as a whole, we calculate that the scenario whereby the stellar mass and number densities of massive galaxies does not evolve between \( z \sim 1.5 \) to \( z \sim 0.4 \) can be rejected at \( > 8 \sigma \) confidence. Through a careful analysis of number densities it does not appear that high mass galaxy formation, with the possible exception of \( M_\ast > 10^{11.5} \, M_\odot \) systems, is complete by \( z \sim 1.5 \). There could be a factor of \( 2 - 3 \) evolution in the mass and number densities for massive galaxies at \( z < 1 \) due to measurement uncertainties. We note that the Millennium simulation underpredicts the densities of these massive galaxies by a large factor (Figure 1), demonstrating how difficult it is to model these systems.

### 3. Star Formation in Massive Galaxies at \( z < 2 \)

One way to understand the star formation history of massive galaxies is to examine their position on color-magnitude diagrams. Conselice et al. (2007b) find that 35\pm4\% of galaxies with \( M_\ast > 10^{11} \, M_\odot \) at \( z \sim 1 \) are blue in color and not on the red sequence, and thus must be undergoing unobscured star formation. Previous studies have examined the increase in the amount of stellar mass on the red-sequence, finding as much as a factor of two increase since \( z \sim 1 \) (Faber et al. 2007; Brown et al. 2007). However, this increase is due to galaxies appearing on the red-sequence, which were previously blue, and not due to in-situ growth on the red-sequence itself due to e.g., dry mergers. This can be seen through massive galaxies gradually moving onto the red-sequence with time, as the number of blue massive galaxies declines at \( z < 1 \) (e.g., Bundy et al. 2006; Conselice et al. 2007b).

Quantifying the ongoing rate of star formation in massive galaxy samples can be done in several ways, including rest-frame UV emission, emission line fluxes, and Spitzer MIPS 24\,\mu m data. A surprisingly higher fraction of massive galaxies are detected in the mid-infrared compared with the fraction which are blue. Conselice et al. (2007b) find that \(~40\%\) of the \( M_\ast > 10^{11} \, M_\odot \) systems at \( 0.4 < z < 1.4 \) are detected in 24\,\mu m MIPS data after removing those systems.
Figure 2. The evolution in mass density for $M_*>10^{11}\ M_\odot$ galaxies as a function of redshift and stellar mass. The solid dots and open boxes represent the evolution of galaxies with stellar masses $M_*>10^{11.5}\ M_\odot$ and $10^{11}\ M_\odot<M_*<10^{11.5}\ M_\odot$, respectively, referenced to their stellar mass densities at $z\sim1.3$. The solid blue line shows the evolution in the amount of stellar mass added from the $z\sim1.3$ bin as a function of redshift from galaxies with stellar masses of $10^{11}\ M_\odot<M_*<10^{11.5}\ M_\odot$. The short-dashed line shows a similar increase in stellar mass due to star formation for the $M_*>10^{11.5}\ M_\odot$ systems. The long-dashed red line shows the relative increase in the stellar mass for the $M_*>10^{11.5}\ M_\odot$ systems due to stellar mass brought up from the $10^{11}\ M_\odot<M_*<10^{11.5}\ M_\odot$ bin due to star formation (Conselice et al. 2007b).

which are detected by Chandra. A total of $37\pm5\%$ of the systems at $M_*>10^{11.5}\ M_\odot$ are detected at 24 $\mu$m, with an average star formation rate of $70\ M_\odot\ yr^{-1}$.

Conselice et al. (2007b) find, similar to previous studies utilising IR star formation indicators, a decline with redshift in star formation occurring within the massive galaxy population. For systems with $M_*>10^{11.5}\ M_\odot$ the star formation rate declines as $(1+z)^{6.2\pm2.2}$, and for systems with $10^{11}\ M_\odot<M_*<10^{11.5}\ M_\odot$ as $(1+z)^{4.1\pm0.64}$. The overall decline in the entire galaxy population’s star formation history can be parameterised as $\sim(1+z)^{3-4}$. It appears that while the $10^{11}\ M_\odot<M_*<10^{11.5}\ M_\odot$ galaxies have a similar decline as the overall field, the highest mass galaxies decline at a faster rate.

4. Mergers in Massive Galaxies

The number and mass densities of the most massive galaxies are significantly lower at $z>2$ than at lower redshifts. While the star formation rate in these massive galaxies may be low (e.g., Krick et al. 2006), mergers are likely the major method for forming these galaxies. Examining the structural CAS and other parameters (Conselice et al. 2000,2002; Conselice 2003; Ravindranath et al. 2006) for galaxies at $2<z<3$ reveals that mergers produce the rapid growth in massive galaxies at $1.5<z<3$ (Conselice et al. 2003, 2005; Conselice 2006; Conselice et al. 2008).

What is not yet clear is the role mergers play in massive galaxy formation at $z<1.5$, particularly dry mergers that are not easily identifiable through
structure. One method of measuring the amount of merging is by examining changes in the number and mass densities of galaxies as a function of time after accounting for growth due to star formation (Figure 2; Conselice et al. 2007b). Conselice et al. (2007b) find that 12% of galaxies with $10^{11} \ M_\odot < M_\ast < 10^{11.5} \ M_\odot$ merge between $z \sim 1.2 - 1.4$, and enter the higher mass bin. At $z \sim 0.8 - 1.0$ this merger fraction drops to 8%. This is consistent with the CAS merger fractions (e.g., Conselice et al. 2003) for the same galaxies, and previous published results using smaller galaxy samples (e.g., Conselice et al. 2003; Lin et al. 2004; Bridge et al. 2007). This corresponds to a merger rate giving $N_m = 0.9^{+0.7}_{-0.5}$ mergers for $M_\ast > 10^{11} \ M_\odot$ systems at $0.4 < z < 1.4$, roughly doubling the mass of these galaxies during this time.

5. Summary

While massive galaxies can be identified up to $z \sim 3$ using deep NIR imaging, the evolution of these galaxies is difficult to measure within a factor of 2-3 using simply luminosity or mass functions. By examining the change in the mass function, and through structural parameters and MIPS 24 $\mu$m and [OII] line emission we show that massive galaxies are still undergoing some evolution, with at least as much as a factor of two increase in stellar mass at $z < 1.4$ from star formation and merging.

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