The intriguing life of massive galaxies
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Gas Accretion and Mergers in Massive Galaxies at $z \sim 2$

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Abstract. Galaxy assembly is an unsolved problem, with ΛCDM theoretical models unable to easily account for among other things, the abundances of massive galaxies, and the observed merger history. We show here how the problem of galaxy formation can be addressed in an empirical way without recourse to models. We discuss how galaxy assembly occurs at $1.5 < z < 3$ examining the role of major and minor mergers, and gas accretion from the intergalactic medium in forming massive galaxies with log $\mathrm{M}_* > 11$ found within the GOODS NICMOS Survey (GNS). We find that major mergers, minor mergers and gas accretion are roughly equally important in the galaxy formation process during this epoch, with 64% of the mass assembled through merging and 36% through accreted gas which is later converted to stars, while 58% of all new star formation during this epoch arises from gas accretion. We also discuss how the total gas accretion rate is measured as $\dot{M} = 90 \pm 40\ \mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ at this epoch, a value close to those found in some hydrodynamical simulations.

Keywords. galaxies: formation, galaxies: evolution

1. Introduction

The formation of galaxies is a difficult problem, and we are still debating the exact history and the physics responsible for establishing the modern galaxy population. One of the issues becoming clear is that this formation and evolution happens in a cosmological context, which ultimately implies that galaxy assembly involves the structure of the universe, as well as the properties of the dark matter and its relationship to baryons.

The major dominant paradigm for understanding galaxy formation theoretically is that the dark matter is cold. This idea when implement in simulations is successful at reproducing the large scale features of the Universe. There are now many simulations and models for how galaxies form within the Cold Dark matter paradigm, however most of these simulations to date have not been able to reproduce the abundances or the formation history of massive galaxies (e.g., Conselice *et al.* 2007; Bertone & Conselice 2009; Marchesini *et al.* 2010; Guo *et al.* 2011).

One example is that when examining the abundances of massive galaxies, typically those with $\mathrm{M}_* > 10^{11}\ \mathrm{M}_{\odot}$, the number densities up to $z \sim 1-2$ are similar to what is found in the local Universe (e.g., Conselice *et al.* 2011; Mortlock *et al.* 2011), yet significantly higher than what is predicted in CDM models (e.g., Conselice *et al.* 2007; Marchesini *et al.* 2010). While in CDM models galaxy formation happens hierarchically in the sense that galaxies form largely through mergers (both major and minor), the exact role of this process and its evolution is not yet clear.

To further investigate this problem requires that we examine directly how the formation process of galaxies occurs, and whether models can reproduce this, particularly features such as the merger and measured assembly history. For example, Bertone &

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Conselice (2009) compare the merger history of galaxies to the predictions from the CDM Millennium simulation. This comparison shows that this CDM simulation underpredicts the number of major mergers by a similar order of magnitude (factor of 10) that it underpredicts the abundances of galaxies. The reasons for this are unclear, but may relate to either the underlying cosmological assumptions, or the way in which baryons are implemented in these simulations. While this problem, and others, can be alleviated through e.g., radio mode feedback, a full understanding of galaxy assembly cannot be provided by simulations alone, and an empirical method is necessary.

Since the most massive galaxies with log $M_* > 11$ $M_\odot$ are largely in place by $z \sim 1$ to study their formation we must investigate these systems at higher redshifts, namely at $z > 1$. Recent studies have accomplished this by examining the most massive systems at $1.5 < z < 3$ with a Hubble Space Telescope survey of 80 massive galaxies with log $M_* > 11$ $M_\odot$, called the GOODS NICMOS Survey (GNS). Using the GNS we have recently made the first measurement of the minor merger history for massive galaxies (Bluck *et al.* 2012), and we have measured the major merger history previously (Bluck *et al.* 2009).

Using the merger history and the star formation history and distribution for the GNS sample (e.g., Bauer *et al.* 2011; Ownsworth *et al.* 2012) we calculate how much gas must be brought in through gas accretion outside of merging. This can be done by examining the imbalance between the amount of gas needed to sustain the star formation rates we observe, and the amount of gas present in-situ within the galaxy, plus that brought in from mergers. As discussed, we find that gas accretion is a necessary and major process in driving the formation of these massive galaxies at $1.5 < z < 3$.

We give a summary of these results here, including an outline for how these features are calculated. Overall we are starting to measure with some certainty how the most massive galaxies assembled during the important epoch $1.5 < z < 3$. A standard cosmology of $H_0 = 70$ km s^{-1} Mpc^{-1}, and $\Omega_m = 1 - \Omega_\lambda = 0.3$ is used through out, along with a Salpeter IMF.

2. The Role of Mergers up to $z = 3$

Galaxy assembly is a combination of at least three processes. These are merging with existing galaxies, the accretion of cold gas from the intergalactic medium, and the conversion of in-situ initial gas into stars in a galaxy over time. Understanding the role of these processes is one of the major goals of extragalactic astronomy.

We now have some idea about the role of mergers in galaxy assembly (e.g., Conselice *et al.* 2003). While mergers can dominate much of the assembly of galaxies, including triggering star formation, instigating morphological changes, etc., we are mainly interested here in how merging builds up the stellar masses of galaxies over time.

The amount of stellar mass added to a galaxy due to the merger process is given by the integral over the merger history, based on the fraction of galaxies merging, and the time-scale for mergers (e.g., Bluck *et al.* 2009; 2012). We carry out this integration using the observed merger history measured directly from the GNS sample of massive galaxies at $1.5 < z < 3$, and the modelled time-scale for mergers (e.g., Bluck *et al.* 2009; 2012). The total amount of stellar mass accreted is then a double integral over the redshift range of interest and over the stellar masses which we probe, which for the GNS, sensitive down to $M_* = 10^{9.5}$ $M_\odot$, can be expressed as,

$$\mathrm{M}_{*,\mathrm{M}} = \int_{z_1}^{z_2} \int_{M_1}^{M_2} M_* \times \frac{f_m'(z, M_*)}{\tau_\mathrm{m}(M_*)} dM_* dz, \tag{2.1}$$

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where $\tau_m(M_*)$ is the merger time-scale, which depends on the stellar mass of the merging pair (Bluck *et al.* 2012). The total integration of the amount of mass assembled through merging gives $M_{*,M}/M_*(0) = 0.53 \pm 0.24$, where $M_*(0)$ is the initial average mass of our sample. This is the fractional amount of stellar mass added due to both major and minor mergers for systems with stellar mass ratios down to 1:100 for the average massive GNS galaxy after following a merger adjusted constant co-moving density (Conselice *et al.* 2012).

However, to fully understand the total baryonic mass assembly of galaxies we need to also account for how much gas mass is brought into these systems through mergers. We calculate this by integrating the amount of gas in these merging systems using an empirical fit to the relationship between the gas mass fraction $\mu_{\rm gas}$ and the stellar mass found at $z = 2 - 3$. Overall we find that it is the lower mass galaxies that contribute the bulk of the gaseous mass, whereas most of the stellar mass accreted arises from higher mass mergers. We show this relative role of mergers in Figure 1. We can then use this relation to calculate for the GNS sample how much gas mass is added due to merging, finding $M_{g,M}/M_*(0) = M_{*,M}/M_*(0) \times f_g = 0.54 \pm 0.24$.

3. Gas Accretion

One important observation of high redshift massive galaxies with $\log M_* > 11\ M_\odot$ is that the average star formation rate for this population is around 100 $M_\odot$ year^{-1} and is constant over the epoch $1.5 < z < 2$ (Bauer *et al.* 2011). This is a large star formation rate, and the amount of gas mass accreted due to merging plus the original amount of gas is not enough to sustain this (Conselice *et al.* 2012).

We show from this that the amount of gas accreted into a massive GNS galaxy is (Conselice *et al.* 2012) $M_{g,A}/M_*(0) = 0.60 \pm 0.46$, such that an amount of mass of the order of the entire initial stellar mass of a massive galaxy is added over time outside of

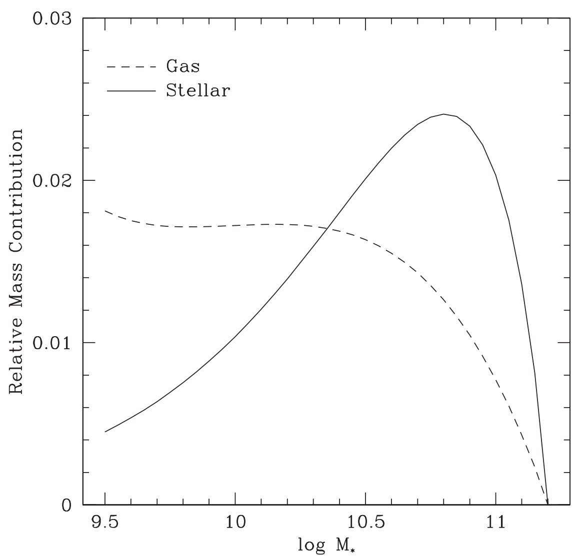

Figure 1. Figure showing the relative amount of gaseous vs. stellar matter accreted from mergers as a function of the merging galaxies stellar mass between $1.5 < z < 3$ for a typical central galaxy of $M_* = 10^{11.2}\ M_\odot$ (Conselice *et al.* 2012). The solid line shows the stellar mass contribution and the dashed line the gaseous contribution.

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mergers to form stars during $1.5 < z < 3$, a time span of 2.16 Gyr. This reveals a net gas accretion, which is then turned into stars of $55 \pm 40\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$.

We need to also consider that these galaxies have outflows (e.g., Weiner *et al.* 2009) that could easily double the amount of gas mass needed to be accreted from the IGM (e.g., Faucher-Giguere *et al.* 2011). Taking into account these outflows using empirical relations from Weiner *et al.* (2009) we find that the gross inflow rate is:

$$\dot{\mathrm{M}}_{\mathrm{acc}} = \dot{\mathrm{M}}_{\mathrm{outflow}} + \dot{\mathrm{M}}_{\mathrm{g,A}} = 90\,\mathrm{M}_\odot\,\mathrm{yr}^{-1},$$

The result of this is that gas accretion accounts for 36±31% of the stellar matter added to galaxies from $1.5 < z < 3$. Mergers account for the remainder of the mass assembly, with 1/3 of this minor mergers and 2/3 of this major mergers (Bluck *et al.* 2012). Gas accretion however is responsible for 58% of all new star formation during this epoch. Overall this implies that gas accretion into massive galaxies at early epochs is a major formation method, and dominates over mergers as a formation mechanism for new stars.

Our measured gas accretion rate is roughly consistent with theoretical calculations which predict a similar amount of gas accretion as we find (e.g., Murali *et al.* 2002; Dekel *et al.* 2009). Some of the first measurements of the gas accretion by Murali *et al.* (2002) predict a gas accretion rate of $\dot{M}_{\mathrm{g,A}} \sim 40\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$, while more recent work suggests higher rates of $\dot{M}_{\mathrm{g,A}} \sim 100\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$ (e.g., Dekel *et al.* 2009; Faucher-Giguere *et al.* 2011). Our results are in general agreement with these models.

4. Summary

While we are able to measure how gas accretion and mergers drives the assembly of log $\mathrm{M}_* > 11\ \mathrm{M}_\odot$ galaxies by using a deep near infrared HST survey, our results do not apply for all galaxies at all times, but only for these massive galaxies at the epoch $1.5 < z < 3$. The errors are also still large and can be reduced significantly by using larger samples of galaxies. In the future by using surveys such as CANDELS with WFC3 and larger area surveys with e.g., WFIRST we can start to make these kind of measurements for lower mass galaxies and for galaxies at even higher redshifts.

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