Author: Hill, A.
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Chapter 1

INTRODUCTION

Understanding how galaxies grow and evolve is an important question whose relevance spans many sub-fields in astronomy and astrophysics. It is a massive undertaking, encompassing billions of years of time. Observationally one needs to explain how the minuscule initial density perturbations seen in the almost uniform microwave background radiation echoing from the big bang, grow into the complex, and diverse structure of galaxies we see in our own cosmic backyard. This work attempts to explain a little bit of what occurs in-between.

In this thesis, we use number density arguments to connect these galaxies to their low-redshift counterparts, and investigate when and where stellar mass is assembled. We also compare our results to state-of-the-art, cosmological simulations. By identifying in what way these galaxies change over time, we aim to inform the astrophysical processes which underly their evolution.

1.1 The Birth of Extra-Galactic Astronomy

At the time of writing, the field of extra-galactic astronomy is fast approaching its 100th year (or perhaps it has already elapsed - as with all things, it depends on how you count). Prior to the early 20th century, whether or not the stars, gas and dust that made up our Milky Way galaxy was the extent of our universe was an issue of considerable debate.

For over a thousand years, nebulae, or ‘clouds’ had been observed in the night sky. These nebulae turned out to be a diversity of objects including stellar nurseries, stellar remnants, and galaxies, with nebulae referring to an observational class of objects which appeared ‘fuzzy’ on the night sky. Several renowned figures from history including the astronomer William Herschel, and the philosopher Immanuel Kant had subscribed to the idea that some of these nebulae were not small clouds that were members of our ‘universe’, but instead were huge *island universes* existing outside our own.

However their extra-galactic nature remained hotly debated until Edwin Hubble surveyed variable Cepheid stars in two of these nebulae documented in the Messier catalogue, M31 and M33 (Hubble 1925). Using the tight period-luminosity relation known to this class of stars, he was able to prove conclusively that these ‘nebulae’ were much too distant to be a tiny component of our own galaxy, and instead were a massive arrangement of stars and gas, and galaxies in their own right. It was a paradigm shift on the scale of when Tycho Brahe’s observations of planetary motion confirmed the Copernican heliocentric model - the observable universe had just become a lot bigger, and our proximity to the centre of it was once again displaced.

Since Hubble’s first foray beyond the confines of our Galaxy, our understanding of the physical scale of the universe continues to expand; an expansion which is both literal, and figurative in nature. In 1929, Hubble noted a linear relationship between a galaxy’s distance to us and it’s recession speed, implying that the universe was getting bigger (Hubble 1929). The idea that the universe was expanding set the stage for a radical new view of cosmology, one in which our universe had a beginning from which to expand from. This cosmology invariably leads to a universe in which galaxies grown and evolve, which is a central tenant to the study of extra-galactic astronomy.

1.2 Tracing Galaxy Evolution Using Integrated Properties

In science, the best way to understand a physical, chemical, or biological process is to conduct an experiment in an environment where variables can be strictly controlled or accounted for to ferret out cause and effect. Results from experiment are noted, and used to develop and test theory. This is the heart of the scientific method. In astronomy and astrophysics, this is largely untenable. Astronomy is an observational science, with the time and physical scales involved practically infinite compared to the life-time and physical experience of the astronomer.

Fortunately, the invariability of the speed of light allows astronomers to effectively look back in time by observing galaxies at greater and greater distances. Although we cannot observe the billion year evolution of a single galaxy in even a thousand human lifetimes, we can look at how properties of galaxies change at different redshifts and infer evolution. The most famous example of this method is the measurement of the integrated star formation rate (SFR) of all galaxies at different epochs (Fig 1.1). From Fig. 1.1, we are able to infer that galaxies were forming stars at a much higher rate than at the present day, and that this rate peaked ~ 10 billion years ago.

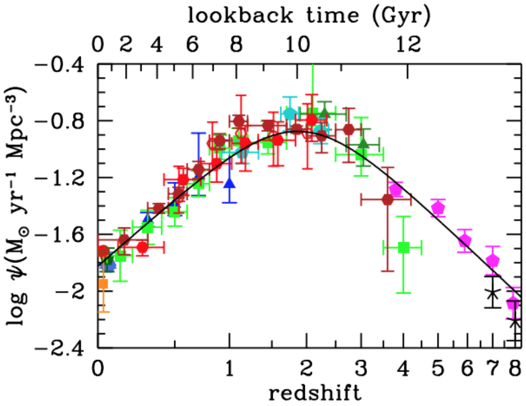

Figure 1.1 The comic star-formation rate density across cosmic time from Madau & Dickinson (2014). Here we we see the peak of cosmic star formation occurred at $z \sim 2$, or ~ 10 Gyr ago. This tells us that galaxies were forming stars at a higher rate in the past and this has been on a steady decline continuing through the present day.

Although the cosmic star formation history is informative, it is an integrated property across all galaxies. It does not specify where star formation is concentrated, in which galaxies most of the stellar mass is assembled, how the structure or morphology of galaxies change, the merger rates of galaxies, or whether these properties depend on stellar mass, dark-matter halo mass, gas fractions or any number of dependencies which might better explain the physics of what is driving evolution.

One way to achieve more specificity is to measure how the galaxy census evolves with redshift. In extra-galactic astronomy, the galaxy stellar mass function (GSMF) provides the relative abundance of galaxies as a function of mass in the form of number densities (e.g., Moustakas et al. 2013; Ilbert et al. 2013; Muzzin et al. 2013b). By measuring the GSMF at different redshifts, the changes in relative abundances can be determined (Fig. 1.2).

The evolution in the GSMF from Fig. 1.2 already reveals some interesting trends. It appears that the number density of the most massive galaxies ($\sim 10^{12}\mathrm{M}_{\odot}$)

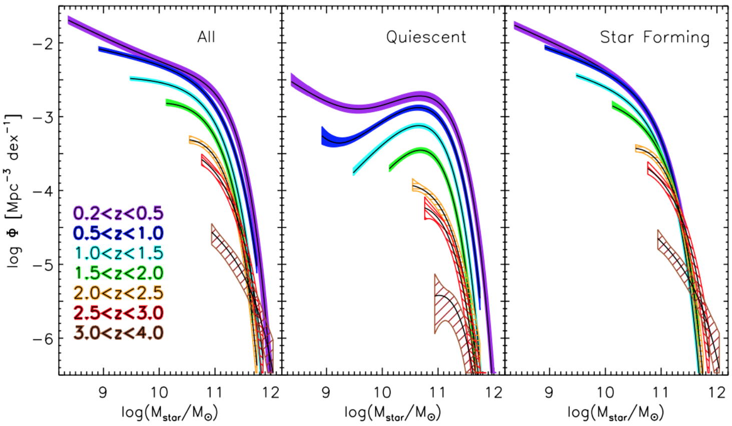

Figure 1.2 The evolution of the total (left), quiescent (centre) and star-forming (right) galaxy stellar mass functions from Muzzin et al. (2013b).

does not change significantly with redshift, suggesting these galaxies form at relatively early times. Muzzin et al. (2013b) also separated the GSMF based on galaxies which are quiescent (i.e. not actively forming stars or are forming them at insignificant rates), and those that are actively star-forming. We see the corollary in the center and right panels of Fig. 1.2 - there is a decrease in the number density of the most massive star-forming galaxies, with a corresponding increase in the number density of the most massive quiescent galaxies. This suggests that the most massive galaxies were actively forming stars at high redshift, and have since quenched.

Together, the conclusions drawn from Fig. 1.1 and Fig. 1.2 are significant, and already reveal salient truths about how galaxies evolve. However, the questions posed earlier still remain unanswered. The GSMF obfuscates much of the specific evolution and does not explain the underlying processes that drive evolution. For instance - why do the most massive galaxies quench at high redshifts? Do they exhaust their gas reservoirs? Does feedback play a role? Is the feedback driven by star-formation, or from quasars? In order to answer these questions, it is necessary to develop a method to connect progenitors to descendants.

1.3 Progenitor Selection

The most straight-forward way to look at galaxy evolution as a function of stellar mass is to choose a fixed stellar mass, and see how galaxy properties change as a function of redshift (we have already implicitly done this with the example of the evolution in the GSMF from Fig. 1.2 and the discussion in Sec. 1.2 when we examined the change in number density of galaxies with a stellar mass of $\sim 10^{12}\mathrm{M}_{\odot}$). This method is useful in determining what galaxies at a fixed mass looked like in the past, however it does not show how any one particular class of galaxy evolves.

If we were to infer an evolutionary link from fixed-mass analysis, we have implicitly assumed that in almost 10 billion years of cosmic time galaxies do not merge, and that they form no new stars. From Fig. 1.1 we already know that the assumption that galaxies do not form new stars is an unreasonable one, and it has been shown that galaxies do in fact merge, necessitating alternative methods to connect progenitor to descendant.

There are many methods which have been used to select progenitors and draw direct evolutionary connections in the literature; via fixed central velocity dispersion (e.g., Bezanson et al. 2012), the evolution of the SFR-stellar mass relation (e.g., Patel et al. 2013b), fixed central surface-mass density (e.g., van Dokkum et al. 2014; Williams et al. 2014) and more generally, number density arguments (e.g., Brammer et al. 2011; Papovich et al. 2011; van Dokkum et al. 2010, 2013; Muzzin et al. 2013a; Patel et al. 2013a; Marchesini et al. 2014; Ownsworth et al. 2014; Morishita et al. 2015). The required assumptions in some of the aforementioned methods are only applicable in specific regimes (i.e., massive elliptical galaxies, or field galaxies that have undergone no major merging). Since we wish to apply the method more generally, in this thesis we focus on number density selection arguments to choose progenitors.

The first example of using number density arguments to select progenitors was by van Dokkum et al. (2010), who used a constant number density to select the progenitors of today's massive ($\sim 10^{11.5} M_{\odot}$) galaxies out to $z = 2$. By using a constant number density, van Dokkum et al. (2010) assumed that galaxies maintain rank order across cosmic time, that is, the most massive galaxy at $z = 2$ is still the most massive galaxy at $z = 0$. This assumes that the two methods of mass growth, star formation, and merging, do not affect the number density across cosmic time. Mergers will certainly effect the number density, and the only way star formation will keep galaxies at the same rank order is if the specific star formation rate is independent of mass (which is not the case; Schreiber et al. 2015). One would expect the regime of validity of these assumptions to break down at flatter regions in the mass function (i.e., lower mass) as well as comparisons across large redshift ranges, where the errors associated with scatter in the mass accretion histories will begin to add up.

To account for the scatter in mass accretion histories, Behroozi et al. (2013) used abundance matching between galaxies and dark matter halos in simulations to convert *dark-matter* halo merger trees into *galaxy* merger trees. This correction allows one trace the *median* stellar mass evolution across cosmic time with the errors dominated primarily by the uncertainties in the observed stellar mass functions. This method has been shown in simulations to recover the median stellar mass evolution quite well, although it is unable to capture the diversity in galaxy progenitors of a given mass (Torrey et al. 2015; Clauwens et al. 2016; Wellons & Torrey 2017). As such, it is a statistical approach that is best suited for populations of galaxies, and is ideally suited for large surveys.

1.4 The Structural Evolution of Galaxy Progenitors

Using a constant number density selection, van Dokkum et al. (2010) investigated the structural and stellar mass evolution of the progenitors of today's massive galaxies ($10^{11.4}$) out to $z = 2$. The authors traced the stellar-mass growth as well as the structural evolution using stacking analysis from galaxies in the NEWFIRM survey, a NIR medium band survey designed to obtain accurate photometric redshifts from the rest-frame optical SED. From these stacks, surface brightness profiles were converted into surface mass density profiles to trace where mass was being accreted as a function of redshift. The most profound finding of this work was that the central regions in massive galaxies have undergone no appreciable mass evolution since $z = 2$, and all mass added has been in the outskirts, consistent with findings by other observationally driven studies (Hopkins et al. 2009; Bezanson et al. 2009). By comparing star-formation rates to the mass profile evolution, they conclude that star-formation was insufficient to explain the mass growth, and that minor mergers are the best candidate to explain the lack of self-similar growth between the interior regions and the outskirts; a viewpoint affirmed in subsequent studies (e.g., Hopkins et al. 2010; Trujillo et al. 2011; Newman et al. 2012; McLure et al. 2013; Hilz et al. 2013; Patel et al. 2013a). Sersic fits to the progenitor surface mass density profiles also show that the effective radius, and sersic index both decrease with increasing redshift, with a corresponding increase in the star-formation rate suggesting star-forming (and potentially disky) progenitors.

Using the abundance matching technique of Behroozi et al. (2013), Marchesini et al. (2014) re-visited the progenitors of massive galaxies. With a new selection, as well as the first data release of the deep, and wide (compared to surveys targeting similar redshift ranges, i.e. CANDELS) NIR UltraVISTA survey, Marchesini et al. (2014) targeted the more massive, and rarer ultra-massive galaxies ($M_* \sim 10^{11.8}$). In addition to the corrected cumulative number density selection, the authors also used a constant cumulative number density selection as a comparison between the two techniques. As expected, the mass evolution for an abundance matched number density selection is steeper than a constant cumulative number density. This means the progenitors are less massive than would have been selected in previous works, with the mass differences greater than the uncertainties in the mass functions at $z > 2$.

1.5 Galaxy Ages and Assembly Times

Arguably the most important ramification of the steeper mass evolution with redshift found using abundance matching (as opposed to a constant cumulative number density as discussed in the previous sections) is the effect this has on galaxy assembly times. If the progenitors at a given redshift are less massive than originally thought, this implies that massive galaxies assemble their mass more quickly at later times. This results in a different ages of assembly for massive galaxies.

Knowing when galaxies assemble their mass is necessary to fully understand

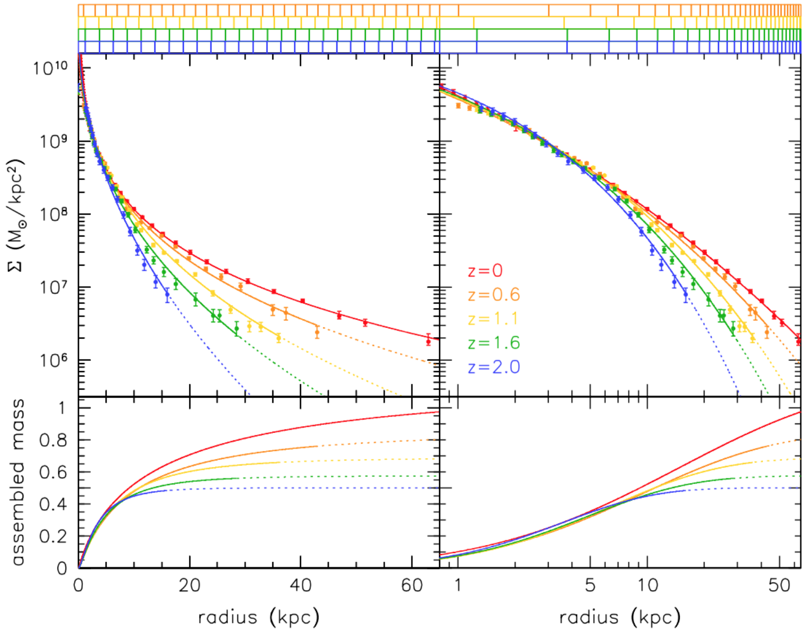

Figure 1.3 The stellar surface mass density profiles from van Dokkum et al. (2010) in linear (left) and log (right) units at redshifts spanning $0 < z < 2$. From this figure, it is evident that massive galaxies grow more substantially at larger radii since $z = 2$.

the mechanisms involved in galaxy growth and evolution. Equipped with a reliable progenitor selection, the assembly time scales of galaxies can be gleaned by simple inferrence from the stellar mass evolution over time. Although constant cumulative number density over-predicts the assembly age, a comparison of the stellar mass evolution of a diverse mass range of descendants in Muzzin et al. (2013b) implies that massive galaxies have an earlier mass assembly than less massive galaxies (Fig. 1.4), and less massive galaxies have more rapid recent assembly.

This notion of more massive galaxies assembling first is also verified in the galaxy ages. If we assume that galaxies only grow in mass through star formation (a poor assumption), then their assembly times will be equivalent to the measured ages of the stars within a particular galaxy, as the assembly time is simply the time at which the stars came into existence. Using optical spectroscpoy, the ages of the galaxies can be measured through age sensitive spectral indices. This has been done extensively for local galaxies (e.g., Kauffmann et al. 2003; Gallazzi et al. 2005; Thomas et al. 2010), with the consensus that massive galaxies are host to older stellar populations than less massive galaxies, and that massive galaxies were the first to form (an idea consistent with what is seen in the mass functions discussed above).

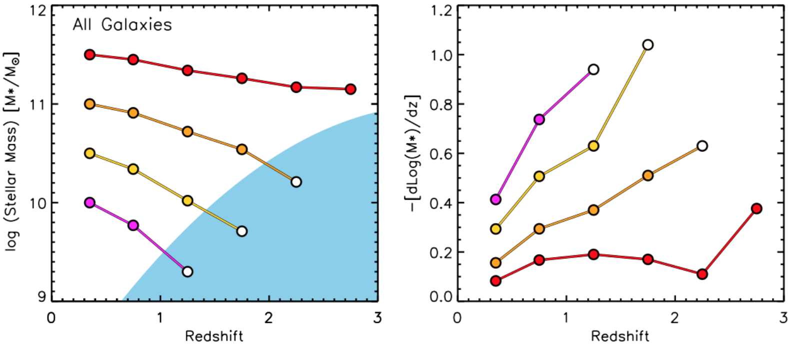

Figure 1.4 Left: the average stellar mass evolution of galaxies with progenitors chosen at a constant cumulative number density which shows that massive galaxies assembled the bulk of their stellar mass at earlier times than less massive galaxies. Right: the derivative of the stellar mass evolution from the left hand plot as a function of redshift. Here we see that less massive galaxies show more rapid recent assembly. (Fig. 14 from Muzzin et al. (2013b))

1.6 This Thesis

As much work as has been done, there remain some open questions which this thesis addresses. van Dokkum et al. (2010) found that the surface mass density profiles of massive galaxies remain essentially unchanged since $z = 2$, which begs the question, when do the interiors assemble, and what do the progenitors of massive galaxies look like at $z > 2$? Does the potential bias towards more massive progenitors in a fixed cumulative number density selection affect the median evolution in previous works? Does this bias also effect the inferred assembly times from Muzzin et al. (2013b)? We address these issues in Chapters 2 and 3.

The focus on the progenitors of $z = 0$ massive galaxies in the literature is partly out of accessibility. Massive galaxies are host to the oldest stars, and also tend to be more luminous making them ideal candidates to trace out to higher redshifts. They are also large, and can be resolved to within 1 r_e at higher-z than lower mass galaxies. As such there is currently a dearth of information regarding the evolution of galaxies with $M_* < 10^{11}$ at high-z $z > 2$. We attempt to bridge this divide in Chapters 3, 4 and 5.

Chapter 2

In this chapter, we used number density arguments to select the progenitors of today's massive galaxies in order to map their structural evolution out to $z = 5$. This work builds on the previous seminal work of van Dokkum et al. (2010) with an improved progenitor selection method, as well as the advantage of state-of-the-art NIR surveys which allow us to track progenitors out to higher redshift. We find the median progenitor stellar mass evolution to be steeper with redshift than selection using a fixed cumulative number density, however at $z < 2$, the stellar masses are consistent within the uncertainties in the mass function. In accordance with previous trends, we find that the progenitors of massive galaxies have smaller effective radii, as well as smaller sersic indices. In contrast to previous findings, our progenitor selection shows stellar mass continues to be accreted at all radii at $z < 2$, although the build-up is more significant at larger radii. At $z > 4$, we see evidence of significant mass growth in the central regions, probing an era of significant mass growth. We also compare our findings to the EAGLE simulation and find similar assembly at small radii. This work appeared in Hill et al. (2017)

Chapter 3

We use the same progenitor selection and mass functions of the previous chapter to measure the main progenitor stellar mass growth of galaxies as a function of stellar mass at $z \sim 0.1$, and measured the assembly time, which we defined as the time at which half the total mass of the descendent was assembled. We compare this assembly time to the light-weighted stellar ages from a sample of low-redshift SDSS galaxies from the literature. Our findings suggest that massive galaxies form a higher proportion of their mass ex-situ than lower-mass galaxies. We compare our timescales to the EAGLE simulation, as well as the semi-analytic models of Henriques et al. (2015). We find the semi-analytic models perform better than EAGLE in reproducing the observed stellar mass versus assembly time and light-weighted stellar ages. This work appeared in Hill et al. (2017b).

Chapter 4

In this chapter, we investigate the median flattening through the axis ratio of galaxies at $z < 0.5$ in the CANDELs fields, and its relationship to parameters such as stellar mass, sersic index, and size. We find that at at $z < 2$, quiescent galaxies are rounder than their star-forming counterparts, however at $z > 2$ the median apparent axis ratios are indistinguishable, suggesting the structure in star-forming and quiescent galaxies at high redshift are similar. We also find that in star-forming galaxies, at $z < 1$, the median axis ratio depends strongly on stellar mass, whereas quiescent galaxies do not show the same dependence. The strongest observable dependence for quiescent galaxies is sersic index. For star-forming galaxies, the size is the best predictor for flattening, with larger star-forming galaxies exhibiting smaller axis ratios. From our findings, we believe that the axis ratio is tracing the bulge-to-total galaxy mass ratio which would explain why smaller/more massive star-forming galaxies are rounder than their extended/less massive analogues, as well as why we do not observe strong mass and size dependencies in quiescent galaxies, as the majority of the quiescent population is not expected to have a strong disk complement. This work is to be submitted.

Chapter 5

In this chapter, we measure the stellar velocity dispersion for a strongly lensed, intermediate mass ($10^{5.9} M_{\odot}$) quiescent galaxy at $z = 2.8$. Because it is gravitationally lensed, we were able to obtain the equivalent of $\sim$ 200 hr of exposure time from only 9.8 hr on source, providing a first detailed look at red galaxies of this mass at $z \sim 3$. This object had been found serendipitously in the UltraVISTA survey, with a measured photometric redshift of $z = 2.4$ (Muzzin et al. 2012). From the discrepancy in the spectroscopic and photometric redshifts, we highlight the importance of spectroscopy for redshift determination for red objects with prominent rest-frame optical breaks. From the spectrum, we measure a stellar velocity dispersion and are able to determine a dynamical mass which is a more direct method and avoids the pitfalls of estimating mass than through the SED, with the associated uncertainties in the initial mass function and effects of dust. We are also able to confirm quiescence through strong Balmer absorption and the absence of any emission lines, as well as establish that intermediate mass galaxies do quench at these redshifts. This work appeared in Hill et al. (2016).

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