Chapter 1

Introduction

1.1 Structure Formation

HIERARCHICAL structure formation theory provides us with a simple framework of how mass assembles into structures over cosmic time (e.g., White & Rees 1978). In combination with impressively accurate determinations of the fundamental cosmological parameters as derived from a variety of observations, this theory has recently resulted in a concordance cosmology. These observations include the cosmic microwave background fluctuations (e.g., Bennett et al. 2003; Spergel et al. 2007), as well as large scale structure studies (e.g., Tegmark et al. 2004; Eisenstein et al. 2005), and supernovae data showing the accelerating expansion of the universe (e.g., Riess et al. 1998; Perlmutter et al. 1999; Tonry et al. 2003).

In this concordance cosmology, structure originates from small fluctuations in the nearly-uniform density field of the early universe. As the universe expands and cools, these fluctuations grow by gravitational instability into galaxies and clusters of galaxies. The structure formation occurs hierarchically, such that small objects form first and subsequently merge to form larger structures.

It is not the visible matter, but rather the "cold dark matter" (CDM) which sets this framework. Although the nature of this CDM is currently a puzzle, gravitational interaction as measured by weak lensing provides definite evidence for its existence (e.g., Clowe et al. 2006; Bradac et al. 2006). Baryonic matter (i.e., the stars and gas that make up galaxies) constitutes only 4% of the total mass-energy density of the universe. In contrast to the simple evolution of the CDM, the baryonic component of the universe experiences a much more complicated growth. Due to the complex physics associated with star formation, nuclear activity, and various other processes, our understanding of the formation of baryonic structure is still far from complete. The following sections describe our current picture of the formation and evolution of galaxies.

1.2 Galaxy Properties

The appearance of galaxies in the local universe provides crucial clues to their evolution. Broadly speaking, low-redshift galaxies can be divided into two groups. Massive galaxies ($> 3 \times 10^{10} M_\odot$) predominantly have quiescent stellar populations, elliptical morphologies, and live in high-density environments, whereas less massive galaxies in general have more ongoing star formation, spiral structures, and reside in lower-density environments (e.g., Loveday et al. 1992; Marzke et al. 1994, 1998; Lin et al. 1996; Zucca et al. 1997; Kauffmann et al. 2003, 2004; Hogg et al. 2003; Blanton et al. 2005; Baldry et al. 2006). The relation between stellar mass and current star-formation activity implies that the bulk of the stars in massive galaxies is formed at higher redshift than the stars in less massive galaxies. Furthermore, each group forms a well-defined sequence in color-mass space and are denoted as the red and blue sequence respectively.

The origin of the observed galaxy trends is related to the following two key questions: first, which processes determine the formation redshift and early star formation history of galaxies; and second, what mechanisms are responsible for quenching star formation. This latter question concerns both the initial quenching of galaxies, and maintenance of the quiescent phase. CDM theory predicts halo mass and environment as the main drivers behind the formation time and strength of the initial burst. However, the second question is more difficult to address, and various studies propose different mechanisms.

Generally, three models are invoked to explain the suppression of star formation. Hopkins et al. (2006, 2007) suggest a model in which the star formation is initially quenched by a major gas-rich merger. For this specific case, the environment will be of major importance. Several other groups propose a critical halo mass above which star formation is precluded, for example by feedback processes from active galactic nuclei (AGNs; e.g., Croton et al. 2006; Cattaneo et al. 2006). In addition to initial quenching, this model also explains the maintenance of the quiescent phase. In a third theory, which is similar to the second, the stellar mass (and thus only internal galactic processes) determines the star formation history of a galaxy (e.g., Bower et al. 2006; Birnboim et al. 2007). For this model either AGN feedback (Bower et al. 2006) or shock accretion (Birnboim et al. 2007) prevents star formation. These three mechanisms are thought to contribute in different fashions to the origin of the fundamental relations between stellar mass, environment, morphology and star formation history.

1.3 Massive Galaxies over Cosmic Time

While detailed studies of low-redshift galaxies are essential, higher redshift studies provide a powerful and complementary approach to investigate the origin of the observed galaxy trends. First, it is crucial to assess if and how the relations between the star formation history, environment, stellar mass and morphology evolve over cosmic time. Second, galaxies assemble mass by merging even after their star formation is quenched (e.g., van Dokkum 2005; Bell et al. 2006), and this complicates the study of the stellar mass dependence of various properties for low-redshift galaxies. Third, as the quenching mechanism may be strongly dependent on halo or galaxy mass, we have to focus on the high-mass end of the galaxy distribution. However, massive galaxies in the local universe already have stopped forming stars. In order to directly witness the processes responsible for the initial quenching of massive galaxies, we have to push our studies to higher redshift.

Fortunately, massive galaxies are in general easier to study at high redshift than less massive galaxies. Large surveys allow statistical studies of the evolution of massive galaxies over cosmic time. However, observing fundamental properties, such as star formation rate (SFR), stellar mass, density and morphology is much more challenging at high redshift. Furthermore, the increasing redshift, and thus the changing accessibility to different rest-frame wavelength regimes complicates the ability to obtain comparable, un-biased, and in particular spectroscopic galaxy samples.

Nevertheless, much progress has been made in the past few years. There are strong indications that the bulk of the stars of early type galaxies at $0 < z < 1$ is formed at $z \sim 2$ or even higher (e.g., Thomas et al. 2005; van Dokkum & van der Marel 2007). Furthermore, the red sequence at $z \sim 1$ already hosts 50% of the stellar mass of the local red sequence (e.g., Bell et al. 2004). These findings motivated searches for massive, quiescent galaxies at even earlier epochs. This resulted in the identification of galaxies with quenched star formation up to $z \sim 2$ (e.g., Glazebrook et al. 2004; McCarthy et al. 2004; Daddi et al. 2005). Moreover, it was found that a red sequence was already in place at $1.5 < z < 2.0$ (e.g., Arnouts et al. 2007). This finding implies that the initial build-up of the red sequence occurs at even earlier times. In order to identify the epoch at which the first massive galaxies stop forming stars, this work needs to be extended to even higher redshift.

The high-redshift universe ($z > 2$) has long been thought to be dominated by galaxies with high SFRs. Relatively un-obscured star-forming galaxies are bright in the rest-frame UV and thus could be easily picked up in optical surveys. The strong Lyman breaks in these galaxies make their identification particularly easy (Steidel et al. 1996a,b). However, galaxies that are faint in the rest-frame UV will be missed using this technique. Consequently, this population of Lyman break galaxies may not be representative of the full population of high-redshift galaxies. The introduction of extremely deep near-infrared (NIR) surveys (e.g., Labbé et al. 2003) indeed showed that red galaxies already existed beyond $z > 2$ (e.g., Franx et al. 2003; van Dokkum et al. 2003). Moreover, these red galaxies dominate the high-mass end of the galaxy distribution at $2 < z < 3$ (van Dokkum 2005). Broadband photometric studies suggest that this red galaxy population consists of a mixture of galaxies with evolved stellar populations and dusty starburst galaxies (e.g., Förster Schreiber et al. 2004; Labbé et al. 2005; Reddy et al. 2005; Webb et al. 2006; Papovich et al. 2006).

Studies of the stellar populations of massive and in particular red galaxies beyond $z = 2$ are hampered by the lack of spectroscopic redshifts and independent spectroscopic constraints on galaxy properties. Broadband photometry may be difficult to interpret due to its inherent low resolution, especially when no spectroscopic redshifts are available. Dusty starbursts are hardly distinguishable from galaxies with evolved stellar populations, emission lines may affect the broadband fluxes, and a possible contribution by an AGN is difficult to quantify. Optical spectroscopy provided redshifts for a small sub-sample of these red galaxies (van Dokkum et al. 2003). However, the requirement that galaxies have emission lines or bright UV continua to derive redshifts resulted in samples which are biased toward star-forming galaxies.

As the typical massive galaxy at $z \sim 2.5$ is faint in the observed optical (van Dokkum 2006), spectroscopic studies should be shifted to longer wavelengths. Furthermore, quiescent galaxies are not expected to have nebular emission lines. Thus, a detailed understanding of the properties of massive galaxies at $z \sim 2.5$, and accordingly the identification of galaxies with quiescent stellar populations beyond $z = 2$, requires continuum spectroscopy at NIR wavelengths. This is the main motivation for starting a NIR spectroscopic survey for massive galaxies at $2 < z < 3$. In the next section we will introduce our survey and summarize the main results.

1.4 This Thesis

In **Chapter 2** we explore the possibilities offered by NIR spectroscopy for the study of massive, high redshift galaxies. We use NIR spectra, obtained with the Gemini near-infrared spectrograph (GNIRS), NIRSPEC on Keck and ISAAC on the VLT to examine the full rest-frame optical continua of three red massive $z > 2$ galaxies in detail. All three galaxy spectra show the Balmer/4000 Å break in the rest-frame optical. The continuum shapes allow us to determine accurate spectroscopic redshifts. This technique is particularly important for galaxies that are faint in the rest-frame UV, such as galaxies with quiescent stellar populations or dusty starburst galaxies. Furthermore, we use the break, continuum shape, and equivalent width of Hα, together with evolutionary synthesis models, to constrain the age, star formation timescale, dust content, stellar mass, and SFR of the galaxies. Inclusion of the NIR spectra in the stellar population fits greatly reduces the range of possible solutions for stellar population properties. We find that the stellar populations differ greatly among the three galaxies, ranging from a young dusty starburst with a small break and strong emission lines to an evolved galaxy with a strong break and no detected line emission.

In order to determine the relative frequency of both passive and star-forming galaxies, the analysis presented in Chapter 2 is applied to a larger sample of K-selected galaxies at $z = 2.0 - 2.7$ in **Chapter 3**. All galaxies are observed with GNIRS, which allows simultaneous detection of the whole rest-frame optical wavelength regime for $z \sim 2.3$ galaxies. Surprisingly, we detected no rest-frame optical emission lines, such as Hβ, [O III], Hα, [N II], for nine of the 20 galaxies in the targeted redshift range. The stellar continuum emission of these same nine galaxies is best fitted by evolved stellar population models. Thus, both the Hα measurements and the independent stellar continuum modeling imply that 45% of our K-selected galaxies are not forming stars intensively. This high fraction of galaxies without detected line emission and low SFRs may imply that the suppression of star formation in massive galaxies occurs at higher redshift than is predicted by CDM galaxy formation models.

Chapter 4 concerns the 11 galaxies with detected Hα emission and details our investigation into the origin of the line emission using the GNIRS spectra and follow-up observations with SINFONI on the VLT. Based on their [N II]/Hα ratios, the spatial extent of the line emission and several other diagnostics, we infer that 4 of the 11 emission-line galaxies host narrow-line AGNs. These host galaxies have stellar populations ranging from evolved to star-forming. Combining our sample with a UV-selected galaxy sample at the same redshift that spans a broader range in stellar mass, we find that black hole accretion is more effective at the high-mass end of the galaxy distribution ($\sim 2.9 \times 10^{11}\ M_\odot$) at $z \sim 2.3$. Furthermore, by comparing our results with SDSS data, we show that the AGN activity in massive galaxies has decreased significantly between $z \sim 2.3$ and 0. AGNs with similar normalized accretion rates as those detected in our K-selected galaxies reside in less massive galaxies ($\sim 4.0 \times 10^{10}\ M_\odot$) at low redshift. This is direct evidence for downsizing of AGN host galaxies. Finally, we speculate that the typical stellar mass scale of the actively accreting AGN host galaxies, both at low and at high redshift, might be similar to the mass scale at which star-forming galaxies seem to transform into red, passive systems.

In **Chapter 5** we present our complete NIR spectroscopic survey for K-bright galaxies at $z \sim 2.3$. The full sample consists of 36 massive galaxies, for which we successfully derived spectroscopic redshifts from emission lines or continuum shapes. We use this unique sample to determine, for the first time, how accurately redshifts and other properties of massive high-redshift galaxies can be determined from broadband photometric data alone. We find that the photometric redshifts of the galaxies in our sample have a systematic error of 0.08 and a random error of 0.13 in $\Delta z/(1+z)$. We show that the systematic error can be reduced by using optimal templates and deep photometry. Turning to stellar population parameters, we show that the spectra lead to significantly improved constraints. For most quantities this improvement is about equally driven by the higher spectral resolution and by the much reduced redshift uncertainty. We find that properties such as the age, A_V, current SFR, and the star formation history are generally very poorly constrained with broadband data alone. Interestingly, stellar masses and mass-to-light ratios are among the most stable parameters. Finally, we show that the spectroscopy supports the finding that red galaxies dominate the high mass end of the galaxy population at $z = 2 - 3$.

The existence of massive galaxies with strongly suppressed star formation at $z \sim 2.3$, identified in Chapter 3, suggests that a red sequence may already be in place beyond $z = 2$. In order to test this hypothesis, we study the rest-frame $U - B$ color distribution of massive galaxies at $2 < z < 3$ in **Chapter 6**. We find a statistically significant ($> 3\sigma$) red sequence in the color distribution, which hosts $\sim 60\%$ of the stellar mass at the high-mass end. The red-sequence galaxies have little or no ongoing star formation, as inferred from both emission-line diagnostics and the stellar continuum shapes. Their strong Balmer breaks and the location of the galaxies in the rest-frame $(U - B)$, $(B - V)$ plane indicate that the star formation in these galaxies has just recently been suppressed. In order to study the evolution of the red sequence, we compare our sample with samples at $0.02 < z < 0.045$ and $0.6 < z < 1.0$. Rest-frame $U - B$ evolves by only ~ 0.16 mag from $z \sim 2.3$ to 0.0 at a given mass. Over the same redshift interval, the number and stellar mass density on the high-mass end of the red sequence grows by factors of ~ 8 and ~ 6 respectively. We explore simple models to explain the observed evolution. Just aging of stellar populations predicts too strong $\Delta(U - B)$ and no evolution in the number density. More complicated models that include aging, quenching and red mergers provide reasonable fits to $\Delta(U - B)$ and the number density evolution. However, the effects of dust, which cannot be fully assessed with current data, complicate the interpretation.

1.5 Conclusions and Outlook

The findings presented in this thesis place important constraints on galaxy formation models. The main conclusion of this thesis is that a red sequence of galaxies with quiescent stellar populations is already in place at $z \sim 2.3$. This red sequence has just started to build up at this epoch. This implies that these galaxies formed their stars in a relatively short period at high redshift, followed by a quiescent phase. Nevertheless, not all massive galaxies in the local universe experienced this same star formation history. The number of galaxies on the high-mass end of the $z \sim 2.3$ red sequence is only $\sim$13% of the total number of massive galaxies on the local red sequence. Thus, many galaxies may quench their star formation at later times.

Furthermore, our results provide clues to a possible quenching mechanism. The significant fraction of red-sequence, post-starburst galaxies with actively accreting black holes suggests that AGNs may play a role in the migration of galaxies from the blue cloud to the red sequence. Nevertheless, the AGNs may as well co-evolve with star-formation, especially if both are fed by the same gas supply. Remarkably, the fraction of massive galaxies that lives on the red sequence at $z \sim 2.3$ is not so much lower than in the local universe. This result may suggest that mass is a fundamental property for the star formation history of a galaxy. Overall, our results do not strongly favor one quenching model.

Despite this significant progress, many urgent questions remain. First, it is clear that we need to understand why galaxies stop forming stars. One possible way to address this question, is to extend our study to lower stellar masses. If stellar or halo mass determines the time of initial quenching, we should not detect galaxies with quiescent stellar populations at lower stellar masses at these high redshifts. Also, more detailed studies of the co-evolution of star-formation and AGN activity may provide better constraints. A second important question is how these red galaxies will evolve to the present. Is the subsequent growth of massive galaxies mainly due to star formation or to mergers? Crucial clues can be obtained by studying their sizes. Recent studies found that massive galaxies are much smaller at $z > 2$ than in the local universe (Zirm et al. 2007; Toft et al. 2007). This implies that the $z \sim 2.3$ quiescent galaxies will accrete matter or redistribute their stars, possibly by mergers. Third, although our current studies suggest that the red-sequence has just started to build up at $z \sim 2.3$, direct evidence is still missing. Our result is supported by the work of Brammer & van Dokkum (2007), who found that in contrast to $z \sim 2.4$, red galaxies at $z \sim 3.7$ have significant UV emission and are thus still actively forming stars. However, spectroscopic evidence of the exact epoch of first quenching still has to be found.

Future advances in instrumentation will be of major importance for addressing the aforementioned three questions. Multi-object NIR spectrographs, which are currently becoming available, will provide dozens of spectra of high-redshift galaxies simultaneously. These instruments will make the study of fainter galaxies practical, and thus will help addressing the first, the third, and many more questions. For the future evolution of massive galaxies, and the build up of the red-sequence we need consistent samples over large areas at different redshift intervals. Obtaining spectroscopic redshifts for the required samples will not be feasible in the foreseeable future. Fortunately, there are alternate methods to increase the resolution of our photometric studies. A future project using medium-band filters on a wide-field NIR imager will provide more accurate photometric redshifts and rest-frame colors, and consequently will allow more detailed studies of the build-up of the red sequence.

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