The build-up of massive galaxies

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INTRODUCTION

1.1 Extragalactic Astronomy

THE Milky Way is one of the most impressive features of the night sky. The band of stars that we observe is in fact a projection of a galaxy that contains hundreds of billions of stars, including the sun. The stars are mostly confined to a thin disk, in which they form a multitude of spiral arms that are entwined with dust lanes. Such stellar systems are wide-spread in the universe, but this has only been known since the beginning of the last century. In the 1920's, Edwin Hubble discovered that some of the nebular structures he observed, were actually galaxies containing billions of stars. He discerned two classes: the spiral galaxies, which resembled the Milky Way and a second class of objects, less conspicuous in appearance, the elliptical galaxies (Fig. 1.1).

Based on his observations, Hubble constructed a galaxy classification scheme that is still in use today (Hubble, 1936). The basis for the classification is morphology, but this is not the only difference between the two main classes. Spiral and elliptical galaxies also differ in physical properties such as color (indicating a different stellar content), internal reddening (depending on the dust content), amount of interstellar gas, and star formation rate. Spiral galaxies are actively forming new stars, which results in a blue color. Elliptical galaxies consist mainly of old stars and are red. The stars in elliptical galaxies seem to be isotropically distributed. However, a closer look reveals a complicated sub-structure that can contain boxy forms and counter-rotating cores, indicating that eliptical galaxies are the product of complex evolutionary trajectories.

This dichotomy of the local galaxy population manifests itself also in mass. Star formation occurs primarily in blue spiral galaxies with low stellar mass ($M_* < 3 \cdot 10^{10} M_\odot$), whereas the more massive galaxies typically are red elliptical galaxies with old stellar populations. Both types of galaxy fill a

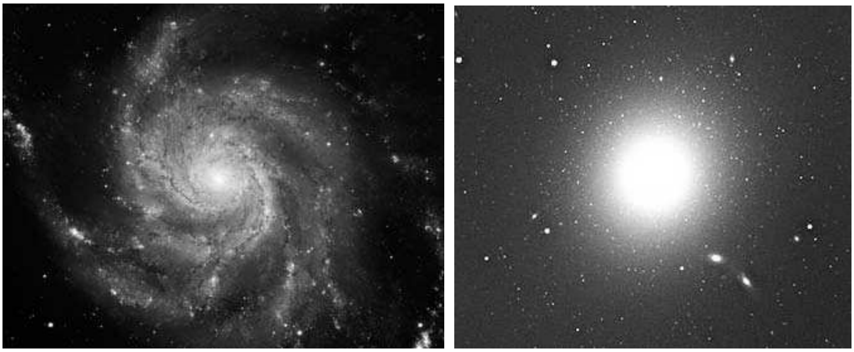

Figure 1.1 – The majority of the local galaxy population belongs to two classes: spiral and elliptical galaxies. *Left* - M101, an example of a spiral galaxy. The detailed spiral structure and blue color are the main characteristics of this class. Our Milky Way has a similar shape. *Right* - M87, a typical elliptical galaxy. The characteristic red color of elliptical galaxies indicates an old stellar population. *Images by the Anglo-Australian Observatory and Hubble Space Telescope.*

specific locus in a color-mass diagram (Fig. 1.2). The old massive ellipticals are concentrated along a red sequence, whereas the blue star forming galaxies form a blue cloud (Kauffmann et al. 2003; Blanton et al. 2005). These striking features of the nearby universe prompt some big questions. What is the origin of this color bimodality? What created the morphologies of local galaxies? And more general: How and when did galaxies form? When did they assemble their mass? To be able to answer such questions, one needs a picture of the galaxies at each stage of their evolution. Such pictures can be taken thanks to one particular characteristic of our universe: the finite speed of light.

1.2 The Distant Universe

To discover the conditions for galaxy formation and learn how galaxies evolved, we have to observe the distant universe. Due to the finite speed of light, an observation of a distant object is inevitably also a view into the past. In recent years our ability to find such distant (and thus dim) objects have improved immensely thanks to technological progress. Large telescopes and sensitive instruments have opened up a window to the distant universe, which means that today we can observe galaxies which emitted their light 13 billion years ago. In this way, we can study the evolution of galaxies throughout the past history of the universe, by simply registering and analyzing the galaxies found at different distance intervals.

Such look-back studies would not be possible if the universe were not expanding[1]. Practically all information on the distant universe is based on

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[1] One of the great discoveries of the 20th century is that the universe is expanding;

the analysis of electromagnetic radiation reaching us from faraway objects. As the light travels from its source to us, it feels the effect of the expanding universe and its wavelength is stretched (redshifted). This stretching is larger the longer the photon needs to travel and the amount of stretching is therefore an accurate measurement of the distance (redshift) to the light-emitting source. Helped by the finite speed of light and the expansion of the universe, astronomers can carry out look-back studies to assess empirically when and how galaxies formed.

The distant universe became a prominent field of astronomical research during the final decade of the twentieth century. At that time the Lyman break technique in combination with the new generation of 8- to 10-m telescopes made it possible to identify significant samples of high-redshift objects. Lyman Break Galaxies (LBGs) are color-selected, luminous, star forming galaxies that emitted their light more than 10 billion years ago, e.g., at a redshift $z > 2$. Since then, the bright ultraviolet (UV) radiation that is characteristic for young stars has been redshifted into the optical regime, making it available to large optical telescopes on earth. The galaxies are observed through carefully chosen filters in the UV, blue, and red spectral regions. The signature of an LBG is that its image should be bright in the two longer wavebands, but should not be present in the UV waveband (Steidel et al. 1996; 1998). The Lyman break technique has proven to be very successful and has identified hundreds of high-redshift galaxies. However, since it only targets the starforming galaxies, it does not give a complete census of the galaxy population at those redshifts.

When a star forming galaxy has exhausted its gas reservoir, it fades and becomes redder. The subsequent evolution is simply an aging of the existing stars, called passive evolution. Because young hot stars are absent in such systems, passively evolving galaxies show only little rest-frame UV radiation and are more prominent at longer wavelengths. As a result, these galaxies are not present in LBG-surveys. However, with the arrival of powerful (near-) infrared (NIR) detectors and ensuing NIR surveys, they were readily found. Samples of distant galaxies with red colors generally include both passively evolving objects and dust-reddened star-forming systems (Franx et al. 2003; van Dokkum et al. 2004; Förster-Schreiber et al. 2004; Labbé et al. 2005). In the case of the latter, the young and hot stars heat the surrounding dust, which re-processes the light at IR wavelengths. NIR surveys uncovered a significant population of massive high-redshift galaxies that were no longer forming stars. These galaxies were already old at $z \sim 2$, which means they must have formed the bulk of their stellar populations at even higher redshifts (Cimatti et al. 2002; Moustakas et al. 2004; Papovich et al. 2005; Treu et al. 2005).

With the wealth of NIR data currently available, it has become clear that

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the galaxies recede from each other, and from us. This is Hubble's second fundamental contribution to cosmology)

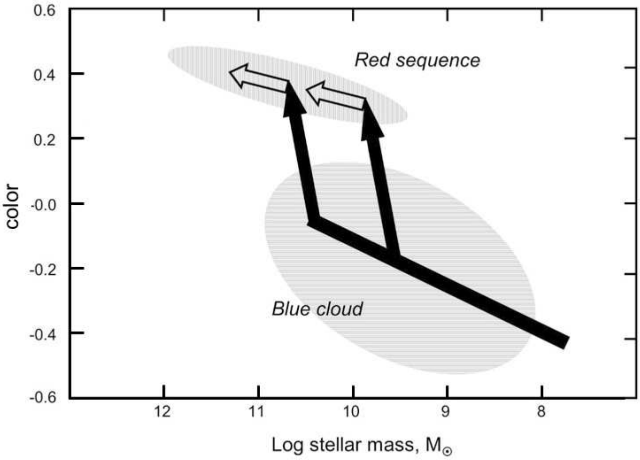

Figure 1.2 – The bimodality in the local galaxy population. Red galaxies form a tight sequence at the top of the diagram. They are typically more massive than blue galaxies, which loosely shape a blue cloud below. The blue galaxies can migrate to the red sequence through mergers in a way that is indicated by the arrows. Blue galaxies first acquire mass through star formation. The nearly vertical lines represent a merger event, during which star formation is quenched and the galaxy becomes red. Once a galaxy arrives on the red sequence it may still gain mass through a series of gas-poor "dry mergers" (*white arrows*). *Figure adapted from Faber et al. 2007.*

the red sequence we observe in the local universe was already in place at $z = 1$ (Bell et al. 2004; De Lucia et al. 2007) and probably even earlier than that (Kriek et al. 2008; Williams et al. 2009; Brammer et al. 2009). We know that since $z = 1$, the amount of stellar mass in the red sequence has approximately doubled (Bell et al. 2004; Faber et al. 2007), which cannot be explained by their low star formation rates (SFR). On the other hand, the amount of mass in the blue cloud stays constant over the same time interval, although these systems are actively forming stars. Somehow, blue galaxies seem to have traveled up to the red sequence, quenching their star formation on the way. The details of this mechanism are still unclear. Mergers of galaxies offer a possible explanation (see Fig. 1.2). The coalescence of two galaxies can result in remnants that are reddened through the loss of gas in the process and the subsequent slowing down of the star formation. Other processes can be repsonsible too, as long as they manage to shut down the star formation.

The SFR as a function of time and mass is clearly one of the key statistics that describes the evolution of the galaxy population. It is important to know when galaxies started to form stars and at what time and under what circumstances star formation was quenched again. In the last decade,

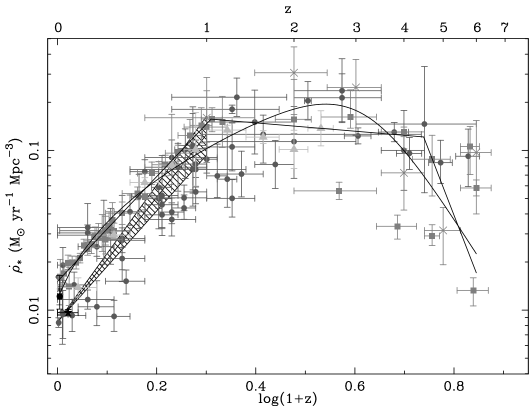

Figure 1.3 – Evolution of the star formation rate density with redshift. This diagram is a compilation of different star formation rate measurements indicated by different symbols. Solid lines represent parametric fits to the data. The cosmic star formation rate reaches a peak between redshifts $2 < z < 4$. It steeply declines at $z < 1$. *Figure taken from Hopkins et al. (2004).*

the advent of deep and/or wide galaxy surveys carried out at many different wavelengths has revolutionized our understanding in this aspect. One example of the achievements is the so-called Madau-diagram, which shows the evolution of the SFR density of the universe as a function of look-back time (Lilly 1996; Madau 1998). From inventories of the stellar content of the local universe (Cole et al. 2001; Bell et al. 2003) and surveys of star formation over its entire comic universe (e.g., Hopkins et al. 2004), it has become clear that the universe experienced a significant decrease (factor ∼10) in the rate at which new stars were created. Star formation was much more rapid in the past, reaching a gentle peak at $z \sim 2-4$ and falling off towards higher redshifts. Again, a number of physical processes may contribute to this decline, e.g., a declining rate of major galaxy mergers, a drop in the rate of minor tidal interactions, or the progressive consumption of gas. Yet, many empirical aspects of this declining cosmic SFR are still unclear.

The extensive results from observations of galaxies at high redshift might suggest that the formation and evolution of galaxies is quite well understood today. We are able to observe galaxies out to $z \sim 7$ (Bouwens et al. 2010) and therefore possess data of nearly all epochs of cosmic evolution. This seems to imply that we can study the evolution of galaxies directly. However, this is true only to a certain degree. Although we now have found a large number of galaxies at nearly every redshift, the relation between galaxies at different redshifts is not easily understood. We cannot suppose that galaxies seen at different redshifts represent various subsequent stages of evolution of the same kind of galaxy. The main reason for this difficulty is that different selection criteria need to be applied to find galaxies at different redshifts. Thus, it is difficult to trace the individual galaxy populations as they evolve into each other at different redshifts. This is the reason why our understanding of galaxy evolution is only possible within the framework of models, with the help of which the different observational results can be interpreted.

1.3 Galaxy Design

One of the most important developments in recent years is the establishment of a standard model of cosmology. In this model, the universe has evolved from an extremely dense and hot state, the Big Bang, 13.7 Gyr ago, expanding and cooling ever since. In the beginning, it consisted of an almost homogeneous plasma without heavy chemical elements and with only very tiny fluctuations in the density profile. It was very different from today's structured universe, which contains galaxies, stars, planets, and a multitude of chemical elements, including heavy elements which are the main constituents of our planet and of ourselves.

Even today, echoes of the Big Bang can be observed, in the form of cosmic microwave background (CMB) radiation. Accurate observations of this background radiation, emitted some 380,000 years after the Big Bang, have made an important contribution to what we know today about the composition of the Universe. All structure in the universe has evolved out of primordial density fluctuations. The seeds for structure formation must have already been present in the early phases of cosmic evolution and are in fact detected in the CMB. The technical progress of the last two decades has made it possible to directly observe this interesting cosmic transition period and to build a model that couples the homogeneous soup of the young universe to the rich structure we observe today.

1.3.1 A Standard Model

The observational results which have been accumulated during the past years provide important details and valuable constraints on the formation of galaxies. This information has been combined into a standard model. Astronomers believe that galaxies are formed by the accumulation of baryonic matter in halos of dark matter. The nature of dark matter (DM) is one of the biggest riddles of the universe. It is an invisible but omnipresent form of matter that fills 23% of the universe (which is almost 5 times as much as the total amount of visible matter).

The formation and evolution of the DM halos can be predicted by means of numerical simulations (Springel et al. 2005). The DM simulations provide quantitative predictions for various parameters of the DM distribution as a function of time and redshift. More difficult is the prediction of the evolution of the baryonic matter, e.g., the stuff galaxies are made of. In the early evolutionary stages, the gas density simply follows the dark matter distribution. Eventually, the gas becomes heated by compression and by the radiation of the first stars. From this point the theoretical predictions of the behavior of the gas become less certain. Feedback effects from star formation can strongly modify the baryonic matter distribution by ejecting gas from the affected halos, or even from neighboring low-mass halos. Moreover, the radiation field of the first stars modifies the conditions for star formation in the surrounding gas.

During the past years progress has been made in the theoretical understanding of these processes, and there are major ongoing efforts to further improve the theory. However, the present hydro-dynamical models do not yet include the full physics of the complex process of star-formation.

1.3.2 Semi-Analytic Models

Semi-analytic models (SAMs) were developed to introduce baryons in the DM simulations using prescriptive methods for star formation and feedback. The idea is to design simple parametrized models based either on observations or on more detailed simulations of individual systems and to implement these recipes in the structure formation framework provided by a dark matter simulation. This provides a powerful tool for studying the formation and evolution of the galaxy population. It is not resource-intensive and allows the treatment of large volumes and the exploration of a wide range of input parameters. In the most recent versions, elaborate physically-based models for feedback processes (Croton et al. 2006, Bower et al. 2006), galactic winds (Bertone et al. 2007), and gas stripping in clusters (Font et al. 2008) are being considered.

Simulations of the formation of stars and galaxies in dark halos using SAMs do give plausible results on the structure of the resulting stellar systems (Mo & White 1998). But, because of the approximations and the large number of free parameters, it is difficult to estimate the accuracy of the predictions based on the semi-analytic procedures. Comparing them to observational data can provide useful constraints.

1.4 Outlook

In the history of astronomy, scientific progress can in many cases be directly traced to new and powerful instrumentation. There is no doubt that future astronomical instruments will have a decisive impact on the field of galaxy formation and evolution. Most important for the progress in the field of high-redshift galaxies have been the observations of 8-10 m telescopes (GEMINI, Keck), combined with those from space (Hubble and Spitzer space telescopes). Many of the yet unsolved questions require the light collecting power and the angular resolution of even larger instruments. Coming up are some extraordinary observing facilities that will scan the universe when galaxies where only just emerging: the Giant Magellan Telescope (GMT; 24.5 m), the Thirty Meter Telescope (TMT; 30m), and the European Extremely Large Telescope (E-ELT; 42 m). An ambitious project at radio wavelengths is the Square Kilometre Array (SKA). It will be an array telescope with a collecting area of 10^6 m^2 operating in the wavelength range from 3 cm to 40 m. However, among all new instrumentation projects, the most promising tool for making significant progress in this field is undoubtedly the James Webb Space Telescope (JWST), a 6.5 m IR telescope (wavelengths ranging from 0.6-28μm) that will be launched into space (currently scheduled in 2014).

The programs carried out at those and other near-future facilities will aim at extending the available data base of high-redshift objects by means of new large surveys. The objective of these projects is to improve our knowledge by generating statistically more significant samples of galaxies of different types. One example is the recently started NEWFIRM medium band survey. Using a set of six medium-band NIR filters, the NEWFIRM survey obtains information and redshifts of IR-bright galaxies in the redshift range $1.5 < z < 3.5$. This survey is expected to provide for the first time a large sample of red high-redshift galaxies with accurate photometric redshifts (van Dokkum et al. 2009).

We are very close to observing luminous galaxies up to the distance at which they were formed for the first time. These are exciting times for observational cosmologists, as the first galaxies are most definitely within reach.

1.5 Thesis Summary

In light of the uncertainties that still exist in current models, observational constraints are required to further develop our understanding of what regulates star formation in massive galaxies. In particular, look-back studies to assess empirically when and how the red sequence emerged are crucial, and require sizeable samples of galaxies of known redshift, stellar mass, SFR, and morphology at epochs when massive galaxies are forming. In this thesis a new survey is presented that uses a combination of UV, optical and IR data to construct a sample of galaxies out to $z \sim 2$. The star formation history and consequent mass build-up of this sample is studied and ultimately compared to model predictions. The main results are summarized below.

In **Chapter 2** we present Spitzer's IRAC and MUSYC Public Legacy of the E-CDFS (SIMPLE), which is mainly based on observations from the Spitzer Space Telescope of one of the most popular fields in observational cosmology: the Extended Chandra Deep Field South (E-CDFS). Our data complement the set of data accumulated by the Multiwavelength Survey by Yale and Chile (MUSYC) which ranges from the near-UV to the near-IR. We provide a detailed description of the data reduction and the resulting catalog.

The catalog of the SIMPLE survey is a flux-limited sample of galaxies. This has to be taken into account when analyzing the data, since it introduces a bias. Luminosity-selected samples do not sample the same absolute magnitudes at each redshift, as they contain brighter galaxies toward higher redshifts. Such selection effects can severely affect results and in **Chapter 3**, we investigate how. We compare the properties of a rest-frame UV-, a rest-frame optical, and a mass-selected sample. We show that the most passive, compact galaxies typically have the highest optical M/L values and the lowest rest-frame UV luminosities. Applying a selection by luminosity will therefore affect known relations between size, mass, and specific star formation rate (sSFR). Sizes and sSFRs in luminosity-selected samples will be on average higher than in mass-selected samples, although an optically selected sample does recover the size-mass- and sSFR-mass-relation of a mass-selected sample at the high-mass end.

Chapter 4 describes the redshift evolution of the stellar mass assembly for a subsample of the SIMPLE survey. We characterize the stellar mass assembly by the specific star formation rate (SFR per unit mass). This is a useful quantity since it allows us to make a distinction between passively evolving and actively starforming galaxies. We find that at all redshifts the galaxies with higher masses have substantially lower specific star formation rates than lower mass galaxies. The average specific star formation rates increase with redshift, and the rate of incline is similar for all galaxies; it does not seem to be a strong function of galaxy mass. Using a subsample of galaxies with masses $M_* > 10^{11} M_\odot$, we measured the fraction of galaxies whose star formation is quenched. The fraction of quiescent galaxies decreases with redshift out to $z \sim 1.8$. We find that, at that redshift, ~30% of the massive galaxies are quiescent.

The evolution of the global SFR can be used as robust constraint on various simulations and SAMs of galaxy evolution. In **Chapter 5** we compare the build-up of massive galaxies as found through our own observations with SAM predictions. We also include deeper data from the FIREWORKS survey to extend the comparison to higher redshifts ($z \sim 3$). Both the model and the observations show a growth rate through star formation that increases with redshift. However, we find that for all masses, the inferred observed growth rates increase more rapidly with redshift than the model predictions. We discuss several possible observation-related causes for this discrepancy and find that none of them can solve it completely. The models need to be adapted to produce the steep increase in growth that is observed between $z = 0$ and $z = 1$.

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