Deep infrared studies of massive high redshift galaxies

Labbé, I.

Citation

Labbé, I. (2004, October 13). *Deep infrared studies of massive high redshift galaxies*. Retrieved from https://hdl.handle.net/1887/578

CHAPTER

ONE

Introduction and Summary

1 Introduction

1.1 Observational Cosmology

COSMOLOGICAL studies have resulted in a "standard" model: a flat, homogeneous, isotropic universe on large scales, composed of ordinary matter, non-baryonic cold dark matter, and dark energy (Spergel et al. 2003). In this model, the dozen or so of parameters that characterize the universe, most importantly the density of baryons, dark matter, and the expansion of the universe, successfully describe astronomical observations on scales from a few Mpc to several 1000 Mpc (Freedman et al. 2001; Efstathiou et al. 2002; Spergel et al. 2003). Large scale structure and galaxies grew gravitationally, from tiny, nearly scale-invariant adiabatic Gaussian fluctuations.

I remember vividly the first cosmology conference I attended at the start of this thesis work. I confess the discussions about cosmic microwave background fluctuations seemed endless, as were the discussions on the large scale structure seen in galaxy surveys. I realize now that I did not fully appreciate how much easier my life was going to be knowing that the universe was spatially flat and 13.7 Gyr old. I could focus for many years on questions that would have been much harder to address until these major issues were solved. Given the enormity of the subject in both distance and time, what cosmologists have learned in the last century, leading up to the arrival of this "standard model", is nothing short of an extraordinary success.

Leaving the mother of all questions "What is the the origin of the universe?" to the realm of literature and natural philosophy, there exist two major, widely recognized, unresolved issues in contemporary cosmology.

The first one relates to the seminal revelation by Fritz Zwicky who noted the existence of dark matter in the Coma cluster (Zwicky 1937), or the problem of missing mass, as it was then known. Zwicky measured the velocity dispersion of galaxies in the Coma cluster and used the virial theorem (Eddington 1916), which relates the total internal kinetic energy of the cluster to its gravitational potential, to argue that there was much more mass in the cluster than could be attributed to the stars in galaxies. In solar units, the ratio of mass to optical luminosity of a galaxy such as the Milky Way is $\sim 3M_{\odot}/L_{\odot}$, whereas for the Coma cluster the ratio was about 400. This implies that there must be about 100 times more hidden or "dark" matter as compared with matter in stars. The realization grew that all visible matter is only a minor constituent of the universe.

Dark matter has proved remarkably elusive and despite more than 70 years of observational astronomy and experimental physics – and a host of respectable and less-respectable candidates – there has been no confirmation of its nature, except that it is gravitating, does not emit or absorb light, is non-baryonic, and non-leptonic. Worse, since the rise of the standard cosmological model it has been joined by its even more elusive cousin, Vacuum or Dark Energy: the mysterious substance that apparently dominates the energy budget of the Universe, and is believed to fuel its accelerated expansion. Yet in contrast to the fundamentally impenetrable mist of the Big Bang, Dark Matter and Dark Energy are not so far removed that their effects cannot be measured with the present-day methods and technology. If anything, its presence challenges us towards new physics and promises to keep cosmology vibrant for quite some time.

The second great question in cosmology is the main inspiration of this thesis. How did galaxies, harboring most of the visible matter in the universe, form out of an almost perfectly smooth distribution of matter, 379.000 years after the Big Bang? In the standard model, the growth of structure with time on a range of scales, from the largest scale structure, to galaxies, and to perhaps even the first stars, is driven by the gradual hierarchical merging of Cold Dark Matter (CDM) Halos (White & Rees 1978). Cold intergalactic gas cooled onto these halos and was subsequently converted into the stars which shine as galaxies. Observation of galaxies can thus be used to trace the evolution of both normal and dark matter.

Given the theoretical foundation of structure formation and the general principles thought to govern the formation of galaxies, the formidable task is to understand the physics of star formation on galactic scales, the resultant feedback of energy and material into the interstellar and intergalactic medium, and the role of feedback from supermassive black holes that lurk in the center of galaxies. However formidable, the problem is likely one of complexity, but not in any sense a fundamental problem requiring new physics to be discovered.

1.2 Galaxy Formation

One of the most prominent and important clues to understanding galaxy evolution is the range and distribution of galaxy morphologies present in the local universe. These morphologies were first classified by Hubble (1930) and consist of four major classes: (i) elliptical galaxies (E), (ii) lenticular galaxies (S0), (iii) 'spiral' galaxies,

(iv) all remaining galaxies, considered ‘irregular’. Elucidating the origin of the “Hubble Sequence” is a crucial and necessary constraint on all models of galaxy formation.”

One of the strongest constraints comes from E+S0s galaxies, collectively called “early-type” galaxies, which are the most massive galaxies in the local universe. The standard CDM scenario prescribes that early-type galaxies formed by mergers of spiral galaxies at relatively recent times (Toomre & Toomre 1972; Toomre 1977; White & Rees 1978). In this scenario, the appearance of galaxies should reflect the growing and merging pattern of their dark matter halos, and as such galaxies should be growing through merging and/or star formation to the present day (e.g., White & Frenk 1991; Kauffmann & White 1993).

Strangely enough, extensive study of nearby early-type galaxies in clusters contradicts this picture. The massive early-type galaxies form an extremely homogeneous class, obeying tight relations in their properties, such as colors and luminosities (Sandage & Visvanathan 1978). Since the colors of stellar populations change with age, the small scatter in the color-magnitude relation constrains the scatter in age at a given magnitude. For ellipticals in the Coma Cluster, the estimated intrinsic scatter of 0.04 in $U-V$ colors implied a spread in age of less than 15% (Bower, Lucey, & Ellis 1992). The usual interpretation is that the stars in these galaxies formed at high redshift $z>2$. Detailed modelling of the spectra showed a similar picture (Trager et al. 2000).

The formation scenario of nearby early-type galaxies in clusters is closer to the classical picture of the monolithic collapse, the antipole of the hierarchichal galaxy formation. In the monolithic scenario, E+S0s assembled their mass and formed their stars in a rapid event, of much shorter duration than their average age (Eggen, Lynden-Bell, & Sandage 1962; Larson 1975; van Albada 1982). The formation process happened at high redshifts predicting that and the progenitors of todays massive early-type galaxies would be vigorously star-forming with star formation rates of much more than $100 M_{\odot}\mathrm{yr}^{-1}$

For decades, the chief way to make the distinction between these opposite formation scenarios was through minute observations of the colors and spectras of galaxies in the local universe. However, direct inference from the fossil evidence to explain its origin is impossible given the complexity of galaxy formation. Even with powerful computational solutions progressing at high pace, neither hydrodynamical simulations (e.g., Katz & Gunn 1991; Springel et.al. 2001; Steinmetz & Navarro 2002) nor state-of-the-art “semi-analytic” models (e.g., Kauffmann, White, & Guiderdoni 1993; Somerville & Primack 1999; Cole, Lacey, Baugh, & Frenk 2000) provide accurate predictions for the formation history of galaxies. The major problem still to hurdle is the correct description of galactic scale baryonic processes involved in stellar birth, evolution, and death. In contrast to the cosmic microwave background, where we were confident of the physics, were able to constructed elaborate deductive models, and test them observationally, the physics of galaxy formation is perhaps too complicated to consider from first principles.

Here, it is more robust to restrict our science to simple inferences from direct observations.

Clearly, observing galaxies *while they are forming* provides a powerful and complementary approach. Nature's gift to cosmologists, the finite speed of light, allows us to look back in time as we observe galaxies at increasing distance, as measured by their redshifts. This has been the corner-stone of the "look-back" approach to studying galaxy evolution. Observations of extremely distant and extremely faint galaxies at $z = 2$ and higher allow us a direct look into the process of their formation.

1.3 Massive High Redshift Galaxies

Answers to many of the questions are now becoming available from large statistical surveys of galaxies, using new instruments on the largest ground-based and space-based telescopes. Multicolor imaging is our most powerful tool for understanding galaxy evolution, as broadband filter measurements can go very deep and cover large areas. However, even the most ambitious apparent magnitude-selected surveys showed that simply observing fainter galaxies is a relatively inefficient means of assembling significant samples of galaxies at high redshift (e.g., Lilly et al. 1996; Ellis et al. 1996 Songaila et al. 1994; Cohen et al. 1996; Cowie et al. 1996). Most faint galaxies on the sky are in fact nearby.

The study of distant galaxies was revolutionized in the past decade, when the increased surveying power was coupled with advances in photometric pre-selection techniques. Of particularly importance was the identification of a large sample of high redshift galaxies from a specific color signature – red in $U - B$ colors, blue in $B - V$ colors. This color signature is produced when neutral hydrogen, from the intergalactic medium and within the galaxies, absorbs the flux of young hot stars ($t \lesssim 10^7$yr) shortward of Lyman 1216 Å and the 912 Å Lyman limit, which corresponds to the U-band at $z \sim 3$ (e.g., Guhathakurta, Tyson, & Majewski 1990; Songalia, Cowie, & Lilly 1990, Steidel & Hamilton (1992, Steidel, Pettini, & Hamilton 1995).

At the time this thesis work commenced, Lyman Break Galaxies (LBGs), as they are commonly called, were among the best studied classes of distant galaxies. Close to a 1000 had been spectroscopically confirmed (Steidel et al. 1996a,b, 2003) at $z \gtrsim 2$, and they were found to be a major constituent of the early universe, with space densities similar to local luminous galaxies. Could LBGs be the forerunners of todays massive ellipticals?

The strong clustering of LBGs indicated that they were luminous tracers of the underlying massive dark matter halos (Adelberger et al. 1998; Giavalisco et al. 1998; Giavalisco & Dickinson 2001) suggesting that they evolve into massive galaxies. Initially it was thought that they were very massive (Steidel et al. 1996b), but direct internal kinematic measurements revealed velocity dispersions of 60-100 kms^{-1} (Pettini et al. 2001; Shapley et al. 2001), which combined with their compact sizes of a few kiloparsecs (Giavalisco, Steidel, & Macchetto 1996) suggested virial masses of only $10^{10} M_{\odot}$, less than 1/10th of todays most massive galaxies. Their spectra were consistent with on-going star forming activity, resembling that of local star bursting galaxies, with only moderate extinction by dust (Adelberger & Steidel 2000). The estimated star formation rates were only $10 - 15\ M_{\odot}\mathrm{yr}^{-1}$, much lower than expected for the progenitors of local early-types in the monolithic scenario. Studies of the stellar composition, using optical and near-infrared broadband photometry, reinforced this picture of relatively low-mass, moderately star forming objects (Sawicki & Yee 1998; Shapley et al. 2001; Papovich, Dickinson, & Ferguson 2001). These properties are expected in the standard hierarchical scenario of galaxy formation, where LBGs are the low-mass building blocks that merge to become present-day massive galaxies in groups and clusters (e.g., Mo & Fukugita 1996; Baugh et al. 1998).

It was quickly realized that LBGs were selected in a very peculiar way. Galaxies that were dust-reddened by more than $E(B-V) \gtrsim 0.4$ were not selected(Adelberger & Steidel 2000). Could there still be a population of vigorously star forming galaxies that escaped detection because it was enshrouded in dust? We know that complementary samples of heavily obscured high-redshift galaxies are found in sub-mm, radio (Smail et al. 2000), and X-ray surveys (Cowie et al. 2001; Barger et al. 2001). Their number densities are much lower than LBGs, although their contribution to the total star formation rate can be significant (cf., Adelberger & Steidel 2000; Barger, Cowie, & Sanders 1999).

Even more important, have we overlooked a major population at $z > 2$ of evolved galaxies that resemble the present-day elliptical and spiral galaxies? None of the techniques described above would select those normal galaxies, whose light is dominated by evolved stars. Specifically, even the massive Milky Way would have never been selected with the Lyman Break technique if placed at $z \sim 3$, as it does not have the required high far-UV surface brightness.

It is much easier to detect evolved galaxies at $z > 2$ in the near-infrared (NIR), where one can access their rest-frame optical light, and where evolved stars emit the bulk of their light. The rest-frame optical light is also much less sensitive to the effects of dust obscuration and on-going star formation than the UV, and expected to be a better (yet imperfect) tracer of stellar mass.

Researchers had already begun using NIR data to look for evolved galaxies at $z > 1$. The techique relied on photometric pre-selection on the stellar Balmer and 4000 Å break. The Balmer discontinuity at 3650 Å is generally strong in stellar populations of age 10^8 to 10^9 yr, and is most pronounced in the photosphere of A-stars, while even older stellar populations show a charactaristic 4000 Å break due to the sudden onset below 4000 Å of metallic and molecular absorption in cool stars.

Evolved galaxies were targeted by selecting on red optical-NIR colors $R-K > 5$ or $I - K > 4$, which can be produced as the Balmer/4000 Å break redshifts out of the optical filters. Recent surveys yielded large samples of these so-called Extremely Red Objects at redshifts $0.8 < z < 1.8$ (EROs; e.g., Elston, Rieke, & Rieke 1988; Hu & Ridgway 1994; Thompson et al. 1999; Yan et al. 2000; Scodeggio & Silva 2000; Daddi et al. 2000; McCarthy et al. 2001; Smith et al. 2002, Moustakas et al. 2004), but their relation to the well-formed massive early-type galaxies at $z < 1$ has not been firmly established. Apparently, a minor fraction of 30% are strongly clustered and evolved galaxies (e.g., Cimatti et al 2002, Daddi et al. 2002), while the rest are believed to be dust reddened star-forming objects (e.g., Yan & Thompson 2003; Moustakas et al. 2004).

To observe evolved galaxies at even higher redshifts $z > 2$ one has to develop criteria to select the galaxies and at the same time go deep enough to overcome the cosmological effect of the $(1+z)^4$ surface brightness dimming. Normal evolved galaxies at $z \sim 3$ would be incredibly faint. In addition as the Balmer/4000Å break is less strong than the Lyman break, it requires a combination of extremely deep optical and NIR imaging to select them.

There were very few datasets that reached the required depths, most of them taken with the WFPC2 and NICMOS instruments on the Hubble Space Telescope (Thompson et al 2000; Dickinson et al 2000; Williams et al 2000). The largest survey to date is that of Dickinson et al. (2000), who imaged the Hubble Deep Field North (HDFN) WFPC2 field in J_{110} and H_{160} with NICMOS, finding that most high redshift galaxies would have been picked up by the Ly-break technique. Nevertheless, the total area studied is still very small, and the depth of the $K-$band data, which is important in constraining the constribution of evolved stars at $z \sim 3$, is not well matched to that of the rest of the NICMOS or WFPC2 imaging data.

To remedy this situation, we started the Faint InfraRed Extragalactic Survey: an ultradeep optical-to-infrared multicolor survey of high redshift galaxies.

1.4 The Faint InfraRed Extragalactic Survey

This dissertation is based on the Faint InfraRed Extragalactic Survey (FIRES; Franx et al. 2000) and its aims are intimately connected with the goals of this survey. FIRES is a large public program at the *Very Large Telescope* (VLT) consisting of very deep NIR imaging of two fields. The fields are the WPFC2-field of Hubble Deep Field South (HDFS), and the field around the $z = 0.83$ cluster MS1054-03, both selected for their exquisite, deep optical WFPC2 imaging with the HST.

The central question in this thesis is:

How did massive galaxies assemble over time?

This general question is addressed in the following chapters by analyzing the following specific issues:

1. **Have we overlooked a major population at high redshift perhaps resembling the present-day normal elliptical and spiral galaxies?**

2. **When did the Hubble Sequence of galaxies start manifesting?**

3. **How and when did galaxies assemble the bulk of their stellar mass?**

4. **Can we use the distribution of galaxy properties to constrain formation scenarios?**

5. **What is the detailed stellar composition of $z > 2$ galaxies: are there passively evolving galaxies at $z \sim 3$, and what is the role of dust?**

The body of this work deals with the properties of faint distant galaxies as observed in the HDFS, a small, otherwise undistinguished high-galactic latitude patch of sky. The HDFS and its counterpart in the north, the HDFN, constitute milestones in optical imaging, as the WFPC2 camera on the HST was pushed to its limits. The ultradeep imaging in four optical bands ($U_{300}, B_{450}, V_{606}, I_{814}$) of these "empty" fields, named after the absence of any large foreground galaxies, allowed an unprecedented deep look of the distant universe, and opened the door to the study of normal galaxies at $z > 2$.

It is often wondered whether such a small field presents us a fair view of the universe. Luckily, the universe seems not to be fractal or hierarchically structured beyond a few hundred Mpc, and voids and superclusters like the ones near us simply repeat. Therefore at large distances, even a pinhole survey such as the HDFS may sample enough volume as to obtain a representative picture. We should always remember, however, that the field size and volume of the HDFS is small.

Capitalizing on the advances in NIR detector capabilities, we took to the Infrared Spectrometer and Array Camera (ISAAC, Moorwood 1997) on the VLT, and observed this tiny field in the NIR J_s, H, and K_s filters for more than 100 hours total, and only under the best seeing conditions. The second field, centered on the $z = 0.83$ cluster MS1054-03, was observed for 80 hours (Förster Schreiber et al. 2004a). While not as spectacularly deep, the area surveyed in MS1054-03 is nearly five times larger, and turned out to be a crucial element for its ability to reinforce our findings in the HDFS.

A special asset in the deep imaging set was the K_s-band, the reddest band from the ground where achievable sensitivity and resolution were still somewhat comparable to the space-based optical data. At $z \sim 3$ it probes rest-frame wavelengths $\lambda \sim 5400$Å, comfortably redward of the Balmer/4000 Å break and therefore crucial to assess the build-up of evolved stars.

Aiming for evolved galaxies at $z > 2$, we experimented with simple color-selection criteria, analogous to those applied to EROs at lower redshift $1 < z < 2$. We selected high-redshift galaxies with the simple color criterion $J_s - K_s > 2.3$, specifically designed to target the Balmer/4000 Å breaks at redshifts between $2 < z < 4$. While candidate high-redshift galaxies with even redder $J - K$ colours have been reported by other authors as well (e.g. Scodeggio & Silva 2000; Hall et al. 2001; Totani et al. 2001; Saracco et al. 2001, 2003), the focus was usually on the objects with the most extreme colors. The $J_s - K_s > 2.3$ criterion, in fact, is not extreme at all as it corresponds to a $U - V$ color of 0.1 at $z = 2.7$. Such a selection would include all but the bluest present-day Hubble Sequence galaxies.

2 Outline and Summary

We present in **Chapter 2** the FIRES observations of the HDFS, the data reduction, the assembly of the photometric source catalogs, and the photometric redshifts. These data constitute the deepest groundbased NIR images to date, and the deepest K_s-band in any field, even from space (Labbé et al. 2003). We released the reduced data, catalog of sources, and photometric redshifts to the community, and they are now in use by many researchers worldwide.

One immediate scientific breakthrough was the identification of a significant population of galaxies with red $J_s - K_s > 2.3$ colors at $z > 2$. We find these Distant Red Galaxies, or DRGs as we shall now call them, in substantial numbers, with space densities about half of that of LBGs selected from ground-based imaging (Franx et al. 2003). Our follow-up studies suggested that DRGs, at a given rest-frame optical luminosity, have higher ages, contain more dust, and are more massive than LBGs (Franx et al. 2003; van Dokkum et al. 2004; Förster Schreiber et al. 2004),

These galaxies had been previously missed because they are extremely faint in the optical (rest-frame UV) and emit most of their light in the NIR (rest-frame optical). Surprisingly, galaxies with comparable colors at $2 < z < 3.5$ were almost absent in HDFN (cf., Labbé et al. 2003, Papovich, Dickinson, & Ferguson 2001) even though it was surveyed over a similar area and depth (Dickinson 2000). Clearly, cosmic variance due to large scale structure in the universe plays a role here, and the possibility existed that neither of the two fields was representative. Later, our findings in the HDFS were confirmed by the discovery of DRGs at similar densities in the much larger MS1054-03 field (see, e.g., van Dokkum et al. 2003; Förster Schreiber et al. 2004).

Another galaxy population that believed to be absent at high redshift, were large disk galaxies. Disk galaxies are thought to undergo a relatively simple formation process in which gas cools and contracts in dark matter halos to form rotationally supported disks with exponential light profiles (Fall & Efstathiou 1980; Mo, Mao, & White 1998). In the standard hierarchical model, large disks form relatively late $z < 1$, and very few of them are expected as early as $z \sim 2$.

In **Chapter 3** we report the discovery of 6 galaxies in the HDF-S at $1.5 \lesssim z \lesssim 3$ with colors, morphologies and sizes comparable to local spiral galaxies (Labbé et al. 2003b). The irregular optical WFPC2 (rest-frame far-UV) morphologies galaxies had previously been misinterpreted, because they traced the sites of unobscured star-formation rather than the underlying evolved population. Here, the combination of bandpass shifting and surface brightness dimming had given an exaggerated impression of evolution towards high redshift. In the NIR, however (rest-frame optical), the morphologies were much more regular than in the rest-frame far-UV, with *well resolved* exponential profiles as expected for rotating stellar disks. Models of disk formation in the standard CDM scenario (Mo, Mao, & White 1999) currently underpredict the number of large disks at high redshift by a factor of two. Only larger samples and kinematical studies, to establish the presence of rotating disks, can tell how serious this discrepancy is, and when classical Hubble sequence spiral galaxies came into existence.

In **Chapter 4** we analyze the cosmological growth of the stellar mass density from redshift $z \sim 3$ to $z = 0$, as traced by optically luminous galaxies in the HDFS. Measuring accurate stellar masses from broadband photometry is quite hard. We resorted to interpreting the mean cosmic colors $(U - B)_{rest}$ and $(B - V)_{rest}$ using stellar population synthesis models. We assumed an appropriate star formation history for the universe as a whole, and used the models to derive the global mass-to-light ratio M/L_V in the $V-$band.

We found that the universe at $z \sim 3$ had a ~ 10 times lower stellar mass density than it does today, and half of the stellar mass of the universe was formed by $z = 1 - 1.5$, broadly consistent with independent results obtained in the HDFN (Dickinson et al. 2003). Interestingly, the distant red galaxies discovered earlier in the survey may have contributed as much as $\sim 50\%$ to the cosmic stellar mass density at $z \sim 3$.

In **Chapter 5** we studied the rest-frame optical color-magnitude distribution of galaxies in the FIRES fields. We focused in particular on the redshift range $z \sim 3$, where observations in the HDFN showed that blue star-forming galaxies followed a clear trend, such that galaxies more luminous in the rest-frame $V-$band had slighly redder $U - V$ colors (Papovich, Dickinson, & Ferguson 2001; Papovich et al. 2004). The origin of this color-magnitude relation (CMR) for blue galaxies, or blue sequence, was not clearly understood, even at low redshift (cf., Peletier & de Grijs 1998; Tully et al. 1998; Zaritsky, Kennicutt, & Huchra 1994; Bell & De Jong 2001).

We analyzed spectra of nearby galaxies in the Nearby Field Galaxy Survey (Jansen, Fabricant, Franx, & Caldwell 2000; Jansen, Franx, Fabricant, & Caldwell 2000; Jansen, Franx, & Fabricant 2001), and found that the relation is mainly one of increasing dust-opacity with increasing luminosity. We also showed that the slope of this relation does not change with redshift, and may have a similar origin already at $z \sim 3$.

Similarly to studies of the red sequence cluster ellipticals (Bower, Lucey, & Ellis 1992; van Dokkum et al. 1998), we interpreted the scatter around the relation as the result of a spread in ages of the stellar populations. The blue-sequence scatter is fairly narrow, has a conspicuous blue envelope, and skew to red colors. After exploring a range of formation models for the galaxies, we concluded that models with episodic star formation explain most aspects of the $z = 3$ color-magnitude distribution. The episodic models cycle through periods of star formation and quiescence, rejuvenating the stellar population during each active episode. The result is that the luminosity weighted ages of the stars are smaller than the age of the galaxy, i.e., the time since the galaxy first started forming stars. They may provide a solution of the enigmatic observation that $z = 3$ galaxies are much bluer than expected if they were as old as the universe (e.g., Papovich, Dickinson, & Ferguson 2001).

Chapter 6 presents a study of the stellar composition of distant red galaxies and Lyman Break galaxies, using mid-IR imaging from IRAC on the Spitzer Space Telescope. Our previous studies indicated that DRGs have higher ages, contain more dust, and are more massive than LBGs at a given rest-frame optical luminosity (Franx et al. 2003; van Dokkum et al. 2004; Förster Schreiber et al. 2004), and may contribute comparably to the cosmic stellar mass density (Franx et al. 2003; Rudnick et al. 2003). Nevertheless, the nature of their red colors is still poorly understood, and the masses are somewhat uncertain. Are they all truly old, or are some also very young and very dusty? What is the fraction of passively, evolving "dead" systems? How much do the DRGs contribute to the stellar mass density in a mass-selected sample? And how do they relate to the blue Lyman break galaxies. Finally, what is their role in the formation and evolution of massive galaxies?

In this chapter, we present deep IRAC $3.6 - 8$ micron imaging of the HDFS field. The new IRAC data reached rest-frame NIR wavelengths, which were crucial in determining the nature of DRGs in comparison to LBGs. We uniquely identified 3 out of 11 DRGs as old passively evolving systems at $z \sim 2.5$. Others were heavily reddened star-forming galaxies, for which we are now better able to distinguish between the effects of age and dust. Furthermore, the rest-frame NIR data allowed more robust estimates of the stellar mass and stellar mass-to-light ratios (M/L_K). We found that in a mass-selected sample DRGs contribute $1.5 - 2$ times as much as the LBGs to the cosmic stellar mass density at $2 < z < 3.5$. Also, at a given rest-frame K luminosity the red galaxies are twice as massive with average stellar masses $\sim 10^{11}$ $M_\odot$, and their M/L_K mass-to-light ratios exhibit only a third of the scatter compared to the LBGs. This is consistent with a picture where DRGs are more massive, more evolved, and have started forming at higher redshift than most LBGs.

3 Conclusions and Outlook

We have presented evidence in this thesis that previous imaging surveys gave a biased view of the early universe. The immediate conclusions of the Faint InfraRed Extragalactic Survey are that large numbers of evolved and dust-obscured galaxies at $z = 2 - 3$ have been overlooked, that up to half of the stellar mass in the universe at $z = 2 - 3$ was unaccounted for, and that the morphologies of galaxies were misinterpreted.

With the newest optical-to-MIR multiwavelength surveys, we are for the first time obtaining a better census of the massive galaxies in the early universe. We are one step closer to tracing the assembly of massive galaxies directly, and it seems warranted now to interpolate between the properties of galaxies populations at different epochs. Ultimately, that approach will help us to understand how galaxies evolved from the cradle to the present-day.

Even so, for a full comparison with local samples, our data sets are still much too small. If we would dissect the galaxy population by redshift, luminosity, color, morphology, or environment, to analyze galaxy formation in all its complexity, we would be left with few galaxies in every subsample. A straightforward extension of the current work is thus to obtain much larger samples.

Apart from the obvious enlargement of the samples, it is now crucial to follow-up the current samples with high-resolution NIR imaging, and optical and NIR spectroscopy. High resolution NIR imaging allows to unambiguously determine the rest-frame optical morphologies of galaxies to high redshift. Unfortunately, given the limited availability of the Hubble Space Telecope, and the slow survey speed of the NICMOS camera in particular, we must await the arrival of next-generations of space telescopes (e.g., JWST or JDEM) or the maturing of ground-based solutions, such as active optics with laser guide stars. A dearth of high-resolution imaging of distant galaxies will continue to exist for some time to come.

On the other hand, new NIR spectroscopic instruments promise spectacular advances. In the coming years a number of multi-object NIR spectrographs will arrive at $8 - 10$ meter class telescopes. With these instruments we can obtain deep spectra for hundreds of distant galaxies at the same time. Spectroscopic redshifts constrain the space densities of the sources and allow to get accurate rest-frame colors. Kinematic measurements of nebular lines provide direct estimates of the dynamical masses involved, and reveal any ordered rotation. Finally, their emission line strengths provide independent constraints on star formation rates (SFRs) and dust extinction, helping to break the degeneracies inherent to modeling of the broadband SEDs (e.g., Papovich et al. 2001, Shapley et al 2001). Every topic discussed in this thesis, from the study of high-redshift disk galaxies, via the stellar populations of DRGs, to the origin of the high-redshift color-magnitude relation (and its scatter), benefits directly from deep spectra.

References

Adelberger, K. L., Steidel, C. C., Giavalisco, M., Dickinson, M., Pettini, M., & Kellogg, M. 1998, ApJ, 505, 18

Baugh,C. M., Cole, S., Frenk, C. S., & Lacey, C. G. 1998, ApJ, 498, 504

Bower, R. G., Lucey, J. R., & Ellis, R. S. 1992, MNRAS, 254, 601

Casertano, S. et al., AJ, 120, pp. 2747–2824, 2000

Cimatti, A., et al. 2002, A&A, 391, L1

Cohen, J. G., Cowie,L. L., Hogg, D. W., Songaila, A., Blandford, R., Hu, E. M., & Shopbell,P. 1996, ApJ, 471, L5

Cowie,L. L., Songaila, A., Hu, E. M., & Cohen, J. G. 1996, AJ, 112, 839

Daddi, E., Cimatti, A.,Pozzetti, L., Hoekstra, H., Röttgering, H. J. A., Renzini, A.,Zamorani, G., & Mannucci, F. 2000, A&A, 361, 535

Daddi, E., et al. 2003, ApJ, 588, 50

Dickinson, M., *Philos. Trans. R. Soc. London* **A 358**, p. 2001, 2000

Dickinson, M., Papovich, C., Ferguson,H. C., & Budavári, T. 2003, ApJ, 587, 25

Eddington, A. S. 1916, MNRAS, 76, 525

Efstathiou, G., et al. 2002, MNRAS, 330, L29

Eggen, Lynden-Bell, & Sandage 1962

Ellis, R. S., Colless,M., Broadhurst, T., Heyl, J., & Glazebrook, K. 1996, MNRAS, 280, 235

Elston, R.,Rieke, G. H., & Rieke, M. J. 1988, ApJ, 331, L77

Erb, D. K., Shapley, A. E., Steidel, C. C., Pettini, M., Adelberger, K. L., Hunt, M. P., Moorwood, A. F. M., & Cuby, J. 2003, ApJ, 591, 101

Fontana, A., Poli, F.,Menci, N., Nonino, M., Giallongo, E., Cristiani, S., & D'Odorico, S. 2003, ApJ, 587, 544

Fontana, A., et al. 2003, ApJ, 594, L9

Forster Schreiber et al. 2004,ApJ, accepted

Forster Schreiber et al. 2004, in preparation

Franx, M. et al., *The Messenger* **99**, pp. 20–22, 2000

Franx, M. et al. 2003, ApJ, 587, L79

Freedman, W. L., et al. 2001, ApJ, 553, 47

Giavalisco, M. & Dickinson, M. 2001, ApJ, 550, 177

Giavalisco, M., Steidel, C. C., Adelberger, K. L., Dickinson, M. E., Pettini, M., & Kellogg, M. 1998, ApJ, 503, 543

Guhathakurta, P., Tyson, J. A., & Majewski, S. R. 1990, ApJ, 357, L9

Hall, P. B., et al. 2001,AJ, 121, 1840

Hu, E. M. & Ridgway,S. E. 1994, AJ, 107, 1303

Hubble, E. P. 1930, ApJ, 71, 231

Ivison, R. J., Smail, I., Barger, A. J., Kneib, J.-P., Blain, A. W., Owen, F. N., Kerr, T. H., & Cowie, L. L. 2000, MNRAS, 315, 209

Katz, N. & Gunn, J. E. 1991, ApJ, 377, 365

Kauffmann, G., Charlot, S., & White, S. D. M. 1996, MNRAS, 283,

Kauffmann, G. & White, S. D. M. 1993, MNRAS, 261, 921

Kauffmann, G., White, S. D. M., & Guiderdoni, B. 1993, MNRAS, 264, 201

Labbé, I., et al. 2003, AJ, 125, 1107

Labbé et al 2004, in preparation

Larson, R. B. 1975, MNRAS, 173, 671

Lilly, S. J., Le Fevre, O., Hammer, F., & Crampton, D. 1996, ApJ, 460,L1

Lowenthal, J. D. et al. 1997, ApJ, 481, 673

Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., & Fruchter, A., MNRAS283, pp. 1388–1404, 1996

McCarthy, P. J., etal. 2001, ApJ, 560, L131

Mo, H. J. & Fukugita,M. 1996, ApJ, 467, L9

Moorwood, A. F. 1997, Proc. SPIE, 2871, 1146

Moorwood, A. F. M., van der Werf, P. P., Cuby, J. G., & Oliva, E. 2000,A&A, 362, 9

Papovich, C., Dickinson, M., & Ferguson, H. C. 2001, ApJ, 559, 620

Pettini, M., Kellogg, M., Steidel, C. C., Dickinson, M., Adelberger, K. L., & Giavalisco, M. 1998, ApJ, 508, 539

Pettini, M., Shapley, A. E., Steidel, C. C., Cuby, J., Dickinson, M., Moorwood, A. F. M., Adelberger, K. L., & Giavalisco, M. 2001, ApJ, 554, 981

Pettini, M., Shapley, A. E., Steidel, C. C., Cuby, J., Dickinson, M., Moorwood, A. F. M., Adelberger, K. L., & Giavalisco, M. 2001, ApJ, 554, 981

Rudnick, G. et al. 2001, AJ, 122, 2205

Rudnick, G., et al. 2003, ApJ, 599, 847

Sandage, A. & Visvanathan, N. 1978, ApJ, 223, 707

Saracco, P., D'Odorico, S., Moorwood, A., & Cuby, J. G. 2001, Ap&SS, 276,991

Saracco, P., et al. 2003, A&A, 398, 127

Sawicki, M. & Yee, H. K. C. 1998, AJ, 115, 1329

Scodeggio, M. &Silva, D. R. 2000, A&A, 359, 953

Shapley, A. E., Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., & Pettini, M. 2001, ApJ, 562, 95

Smail, I., Ivison, R. J., Owen, F. N., Blain, A. W., & Kneib, J.-P. 2000, ApJ, 528, 612

Smith, N. 2002, MNRAS, 337,1252

Smith, V. V., et al. 2002, AJ, 124, 3241

Somerville, R. S. & Primack, J. R. 1999, MNRAS, 310, 1087

Songaila, A., Cowie, L. L., Hu, E. M., & Gardner, J. P. 1994, ApJS, 94,461

Songaila,A., Cowie, L. L., & Lilly, S. J. 1990, ApJ, 348, 371

Spergel, D. N., et al. 2003, ApJS, 148, 175

Steidel, C. C., Giavalisco, M., Dickinson, M., & Adelberger, K. L. 1996, AJ, 112, 352

Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17

Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1

Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2003, ApJ, 592, 72

Steidel, C. C. & Hamilton, D. 1992, AJ, 104, 941

Steidel, C. C., Pettini, M., & Hamilton, D. 1995, AJ, 110, 2519

Steinmetz, M. & Navarro, J. F. 2002, New Astronomy, 7, 155

Thompson, R. I.,Storrie-Lombardi, L. J., Weymann, R. J., Rieke, M. J., Schneider, G., Stobie, E., & Lytle, D. 1999, AJ, 117, 17

Totani, T., Yoshii, Y.,Maihara, T., Iwamuro, F., & Motohara, K. 2001, ApJ, 559, 592

Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 120, 165

van Albada, T. S. 1982, MNRAS, 201, 939

van Dokkum, P. G., Franx, M., Kelson, D. D., Illingworth, G. D., Fisher, D., & Fabricant, D. 1998, ApJ, 500, 714

van Dokkum, P. G., Franx, M., Fabricant, D., Illingworth, G. D., & Kelson, D. D. 2000, ApJ, 541, 95

van Dokkum, P. G. et al. 2003, ApJ, 587, L83
van Dokkum, P. G., et al. 2004, ApJ, 611, 703
White, S. D. M. & Frenk, C. S. 1991, ApJ, 379, 52
White, S. D. M. & Rees, M. J. 1978, MNRAS, 183, 341
Williams, R. E. et al. 1996, AJ, 112, 1335
Williams, R. E. et al. 2000, AJ, 120, 2735
Yan, L., McCarthy, P. J.,Weymann, R. J., Malkan, M. A., Teplitz, H. I., Storrie-Lombardi, L. J.,Smith, M., & Dressler, A. 2000, AJ, 120, 575
Zwicky, F. 1937, ApJ, 86, 217