Red Galaxies at High Redshift

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Chapter 1

Introduction

1.1 Large-scale structure formation

STANDARD Cold Dark Matter (CDM) theory explains the formation of large-scale structure from a nearly homogeneous soup to the cosmic web observed today by gravitational instabilities that grow over time (Press & Schechter 1974). Cold Dark Matter dominates the mass content of the universe and clumps into so-called halos. Primordial gas will sink to the bottom of the potential wells outlined by the dark matter halos, where it can cool and form small units of stars. As time evolves, CDM halos, and with it their baryonic content, will merge to build up larger structures (White & Rees 1978). Eventually, this results in a web-like structure where filaments of young galaxies and ionized gas are surrounded by large, nearly empty voids. Large clusters of galaxies reside where the filaments meet. The bottom-up fashion of structure formation stems from the fact that the initial density fluctuations had most power at small scales.

Observations of the large-scale structure by the Sloan Digital Sky Survey (SDSS, York et al. 2000; Tegmark et al. 2004) and the 2 degree Field Galaxy Redshift Survey (2dFGRS, Colless et al. 2001; Sánchez et al. 2006) show a remarkable agreement with theoretical predictions and state-of-the-art simulations based thereupon (Springel et al. 2005). The evolution of the baryonic content, however, depends on complex dissipational processes that are far from understood.

1.2 Galaxy formation

What is the number of galaxy collisions, if any, needed to build up an M_* galaxy in the local universe? When in the history of the universe did most of the hierarchical build-up take place? What fraction of stars was formed in merger-triggered starbursts as opposed to quiescent episodes of star formation? What role do supermassive black holes at the centers of galaxies play in their evolution? How can the wide range in galaxy colors, from blue to red, be explained? These are all questions that astronomers are just beginning to address.

Observed scaling relations between galaxy properties provide stringent constraints in this quest for evolutionary scenarios. Apart from explaining the local color-magnitude relation (e.g., Sandage 1972; Bower, Lucey,& Ellis 1992), the Fundamental Plane (Djorgovski & Davis 1987; Dressler et al. 1987) and the correlation between the mass of supermassive black holes and their hosts (Magorrian et al. 1998), any model for galaxy formation should also account for the evolution of these scaling relations with redshift (e.g., Holden et al. 2004; van Dokkum & van der Marel 2007; Peng et al. 2006). Other observations that need to be reproduced are the wide range of galaxy colors at low and high redshift, and their correlation with mass, morphology and environment.

The local universe

In the local universe, the bimodal color distribution of galaxies is well established (e.g., Stateva et al. 2001; Blanton et al. 2003; Baldry et al. 2004; Balogh et al. 2004). Blue galaxies are more abundant in numbers than red galaxies, but since the latter tend to be more massive, it is the population of red galaxies that contributes most (50% - 75%) to the total stellar mass in the nearby universe (e.g., Bell et al. 2003). Nearby blue galaxies generally have a disk-like morphology with spiral arms, whereas red galaxies show elliptical shapes. The morphological classification of galaxies into spirals and ellipticals goes back to Hubble (1926). The fraction of red, elliptical galaxies increases significantly as we probe denser environments (Oemler 1974; Davis & Geller 1976; Dressler 1980).

The distant universe

Determining if and how the described trends and scaling relations are present at high redshift, is a challenging task. First of all, it is crucial to obtain unbiased samples of distant galaxies.

Until the 1990s, radio galaxies and quasars were the only objects known at $z > 2$ (e.g., Schmidt 1974). Their extremely high luminosities are believed to be powered by an accreting central supermassive black hole. The searches for 'normal' distant galaxies, with a stellar origin of the light, have only been successful since the 1990s. Brute force spectroscopic surveys of all objects brighter than an optical magnitude limit in a field are not an efficient means of constructing representative high redshift galaxy samples. First, because only a small fraction of such a magnitude-limited sample will lie at high redshift. For example, less than 5% of the I-band limited $m_I < 24$ sample by Le Fèvre et al. (2005) has a redshift $z > 2.5$. Second, because distant galaxies with considerable mass but largely devoid of rest-frame UV emission would be missed by such surveys.

Over the past decade, several color selection criteria have been designed, often aided by technological developments, to identify galaxies in the redshift range $1.5 < z < 3.5$. Steidel and collaborators (e.g., Steidel et al. 1996) were the first to efficiently select distant galaxies with relatively unobscured star formation using the state-of-the-art optical observatories (probing the rest-frame UV light). With the advent of first near-infrared and then mid-infrared instruments on ground- and space-based telescopes, new selection methods became possible to select $z \sim 2$ galaxies (e.g., Franx et al. 2003; Daddi et al. 2004; Yan et al. 2004), resulting in samples that were often complementary to the optically selected objects.

Each of these color-selected samples is subject to its own biases. Small amounts of unobscured star formation may shift galaxies into or out of the selection window. Furthermore, due to the range in redshifts and galaxy types, the observed-frame colors used for their selection alone are not uniquely related to the physical properties of the galaxies. In view of a grand theory of galaxy evolution, it is important to understand the physical conditions such as mass, age and dust extinction for the various color-selected samples. Ideally, we want to go beyond selecting galaxies by color, and characterize the stellar population properties for a sample of galaxies that is complete above a certain mass limit, since mass is a more fundamental parameter than (observed-frame) color.

The nature of distant galaxies

The measurement of dynamical masses, used for the study of cluster early-types up to $z = 0.83$ in Chapter 2 of this thesis, becomes increasingly more difficult above $z \gtrsim 1$ (e.g., van Dokkum & Stanford 2003; Holden et al. 2005). We therefore rely on stellar mass estimates derived by modeling the broad-band spectral energy distributions (SEDs) over a wide wavelength range with stellar population synthesis codes (e.g., Bruzual & Charlot 2003; Maraston 2005).

Likewise, determining spectroscopic redshifts, although requiring less signal-to-noise than the measurement of velocity dispersions, becomes increasingly demanding in terms of telescope time as we move to higher redshifts and fainter sources. Instead, the study of mass-limited samples at high redshift relies mostly on photometric redshift estimates.

A reliable interpretation of the multi-wavelength views of distant galaxies in terms of physical properties such as mass, age, and dust content, is the key to a robust test of galaxy formation models.

1.3 This thesis

In this thesis, we measure the masses, ages, and dust extinctions of high redshift galaxies, with an emphasis on red galaxies. We aim to establish the accuracy with which these properties can be determined and identify biases that may occur. Finally, we use our observations to build a mass-limited sample of $1.5 < z < 3$ galaxies and test a model that explains the formation of red galaxies by collisions of gas-rich disk galaxies, during which a quasar phase is triggered (Hopkins et al. 2006).

Chapter 2

In Chapter 2, we examine the fundamental plane (FP) of early-type galaxies in two high-redshift clusters: MS 2053–04 at $z = 0.58$ and MS 1054–03 at $z = 0.83$. In particular, we focus on the zero point and scatter of this scaling relation between galaxy size, velocity dispersion and surface brightness, and its evolution with redshift between $z = 0$ and $z = 0.83$. We study the residuals from the FP as a function of color, mass, $H\beta$ linestrength and position within the cluster. We find that the residuals from the FP of MS 2053–04 are correlated with the residuals from the $H\beta - \sigma$ relation, suggesting that stellar populations are playing a role in shaping the FP. Considering only massive ($M > 10^{11}\ M_\odot$) early-type galaxies to avoid selection biases in our magnitude limited sample, we conclude that their B-band mass-to-light ratio evolves as $\log M/L_B \sim -0.47z$ and we find a formation redshift $z_{form} \sim 2.95$.

Chapter 3

Chapter 3 consists of two parts. First, we describe the construction of a B-to-24 μm multi-wavelength catalog for the GOODS Chandra Deep Field South (CDFS). The catalog contains optical, near-infrared and mid-infrared photometry for sources over an area of 138 arcmin^2 down to $K_{s,AB}^{tot} \lesssim 24.3$ (5σ). The photometry is based on observations with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST), the ISAAC camera on the Very Large Telescope (VLT) and the IRAC and MIPS instruments on board the Spitzer Space Telescope. We cross-correlate our catalog with the 1 Ms X-ray observations (Giacconi et al. 2002) and with a large database of spectroscopic redshifts in the field. The latter allows us to quantify the reliability of photometric redshift estimates.

Next, we exploit the multi-wavelength data to estimate total IR luminosities for K_s-selected galaxies at $1.5 < z < 2.5$. We investigate which galaxies have the brightest total IR luminosities and which galaxies contribute most to the integrated total IR emission. We conclude that galaxies with red colors in the rest-frame UV, rest-frame optical, and rest-frame optical-to-NIR are dominating in the IR. However, at the reddest rest-frame optical colors, there also exists a population of galaxies that is undetected at 24 μm and therefore has low estimates for the total IR luminosity.

Chapter 4

Chapter 4 describes the optical spectroscopic follow-up of a sample of Distant Red Galaxies (DRGs, Franx et al. 2003) with $K_{s,Vega}^{tot} < 22.5$, selected by the simple color criterion $J - K > 2.3$. All the successful redshift determinations (22% of the targeted sample) were based on emission lines. With 15 spectroscopic redshifts identified with only 2 at $z < 2$, we confirm the efficiency of this simple criterion to select red galaxies at high redshift. The two lower redshift sources are best fitted by a dusty stellar population. Two other DRGs show CIV in emission, indicative of the presence of an active galactic nucleus (AGN). We find that the photometric redshift code by Rudnick et al. (2003) is able to determine redshifts for DRGs (or at least the subclass with emission lines) to an accuracy of $\Delta z/(1 + z) \sim 0.06$. Including DRGs with photometric redshifts, we find that $z < 2$ DRGs are more extincted than $z > 2$ DRGs by 2 mag in A_V.

Chapter 5

In Chapter 5, we address the question what new insights the IRAC camera on board Spitzer can reveal on the nature of galaxies at $2 < z < 3.5$. We approach this question by modeling the spectral energy distributions of distant galaxies in the Hubble Deep Field South (HDFS) up to very faint magnitudes ($K_{s,AB}^{tot} = 25$), including and excluding the IRAC photometric data points. We find that for blue galaxies in a field where deep NIR data is already available, the addition of IRAC offers little improvement. For red galaxies, on the other hand, the uncertainties in the estimated stellar mass decrease by a factor ~ 3 by adding IRAC. We caution however that significant systematic uncertainties in stellar mass estimates remain due to the differences between stellar population synthesis codes. Furthermore, IRAC helps to break the degeneracy between star-forming and quiescent red galaxies. Finally, we find that, as in the local universe, the most massive galaxies at high redshift are redder than lower mass galaxies, even when allowing for complex star formation histories.

Chapter 6

A problem with addressing the quality of estimated stellar population properties of observed galaxies is that the 'true answer' is often not available. Therefore, we test the standard SED modeling using simulated galaxies for which we know exactly the ages and masses of its stellar components and the distribution of gas and dust in between. In order to do this, we derived synthetic broad-band photometry from snapshots of hydrodynamical merger simulations by Robertson et al. (2006) as they would be observed when placed at redshifts $1.5 < z < 3$. The choice for merger simulations allows us to test the performance of standard SED modeling for different types of galaxies: from disks to mergers and eventually ellipticals. We discuss the impact of the star formation history, dust distribution, metallicity and AGN activity on the recovered mass, age, dust reddening and extinction. Systematic underestimates in all these parameters occur during the star-forming episodes. The properties of red quiescent merger remnants, on the other hand, are recovered very well.

Chapter 7

Multi-wavelength studies of deep fields have revealed a large variety of galaxy types in the early universe: from relatively unobscured star-forming galaxies to dusty starbursts to quiescent massive red galaxies. Especially the existence of the latter population, whose strongly suppressed star formation has been confirmed by spectroscopic identifications of their Balmer/4000Å breaks (Kriek et al. 2006), poses a strong constraint on galaxy formation models.

In the final chapter of this thesis, we combine the observations of three deep fields (HDFS, MS 1054–03, and CDFS) to test a model by Hopkins et al. (2006) that aims to explain the formation of red galaxies. Briefly, the model assumes that every observed quasar is triggered by the collision between two gas-rich disk galaxies. Starting from that assumption, it is then possible to translate the observed quasar luminosity function at a range of redshifts (e.g., Ueda et al. 2003; Hasinger, Miyaji,& Schmidt 2005; Richards et al. 2005) to the demographics of galaxies expected in a particular redshift interval. Using the same simulations as described in Chapter 6, we compute the colors, number and mass densities of massive galaxies at $1.5 < z < 3$ predicted by this model and compare it to observed samples subject to identical selection criteria.

We find that post-quasar galaxies have similar colors as red quiescent galaxies. The observed number and mass densities of quiescent galaxies are consistent with the model predictions. The model is also able to account for the abundance of star-forming galaxies, albeit with large uncertainties. However, the color distribution of star-forming galaxies is not well reproduced, in particular the observed dusty starbursts have no counterparts in the model predictions. Several possible reasons for this discrepancy are discussed.

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