Formation and evolution of early-type galaxies
van Dokkum, Pieter Gerhardus

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
1999

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
ABSTRACT

Early-type galaxies are the dominant population in nearby rich clusters. In this thesis early-type galaxies in four clusters at $0.33 < z < 0.83$ are studied, to determine their star formation history and time of assembly. The evolution of the mean $M/L$ ratio of early-type galaxies is measured from the Fundamental Plane. The $M/L$ ratio evolves as $\Delta \log M/L_B \propto -0.40 z$, for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0$. From the slow luminosity evolution of massive early-types it is inferred that most of their stars were formed before $z = 2$. Early-type galaxies appear to have formed more recently than the stars within them. From a study of the cluster CL 1358+62 at $z = 0.33$ it is inferred that many low luminosity S0s in nearby clusters are probably dead remnants of star forming field galaxies, that suffered truncation of their star formation after entering the cluster environment. Furthermore, a population of luminous merging galaxies is discovered in the most distant cluster in the sample, MS 1054–03 at $z = 0.83$. It is estimated that more than half of present-day luminous ($\sim 2 L_\ast$) cluster ellipticals experienced a major merger at $z < 1$. The mergers already have evolved stellar populations, consistent with the homogeneity and old stars of low redshift ellipticals. The discovery of a high merger fraction in this young cluster is direct evidence against formation of massive galaxies in a “monolithic collapse” at high redshift, and in qualitative agreement with hierarchical models for structure formation.
1.1 Introduction

1.1.1 Galaxy Formation

One of the major questions in astronomy is how galaxies were formed and how they subsequently evolved. As far as we know, virtually all stars and metals in the Universe were formed inside galaxies; the subject of galaxy formation therefore has close ties with the star formation history of the Universe, and the evolution of its metal content. Furthermore, galaxy formation is a probe of structure formation. In the past ~15 Gyr the Universe evolved from the smooth Cosmic Microwave Background with variations ~10^{-5} on ~10^3 scales (Bandy et al. 1998) to the rich structure of stars, galaxies, clusters and superclusters seen today. Currently popular models assume this structuring process is driven by the evolution of dark matter halos (e.g., White & Rees 1978), but because dark matter is very difficult to observe, galaxies can serve as luminous probes of the evolution of these halos.

In recent years there has been tremendous progress in the fields of galaxy formation and evolution, largely because of advances in telescope design and instrumentation. Telescopes such as the Hubble Space Telescope (HST), the 10 m W. M. Keck telescope on Hawaii, and the Very Large Telescope in Chile provide the means to study galaxies at cosmological distances, enabling us to observe the young progenitors of today’s galaxies directly (e.g., Steidel et al. 1996). The study of galaxy formation has moved from extrapolating properties of nearby galaxies back in time to interpolating properties of galaxy populations at different epochs.

1.1.2 Properties of Early-Type Galaxies

This thesis deals with the formation and evolution of early-type galaxies, i.e., ellipticals and S0 galaxies. These galaxies form the dominant population in rich clusters such as the nearby Coma cluster (Dressler 1980). Early-type galaxies can be very luminous; the luminosities of giant ellipticals extend to \( M_B^{\ast} \sim -23 \). These properties make early-type galaxies very suitable for studies of galaxy evolution; they can be observed to large distances due to their high luminosities, and it is relatively easy to obtain a large sample at the same distance by observing high redshift rich clusters.

Early-type galaxies are very homogeneous in their properties. They obey tight relations between their luminosities, velocity dispersions, colors, and structural parameters (e.g., Bower, Lucey, & Ellis 1992, Djorgovski & Davis 1987, Dressler et al. 1987). The usual interpretation of this homogeneity is that the stellar populations of early-type galaxies formed in a short timespan at very high redshift. Age differences between galaxies lead to a spread in colors and \( M/L \) ratios, and the small scatter in these properties at a given mass implies a small scatter in luminosity weighted ages. As an example, the upper limit of \( \sigma_{U-V} < 0.035 \) on the scatter in the \( U-V \) color-magnitude relation of Coma ellipticals (Bower et al. 1992) implies an upper limit on the spread in luminosity weighted ages of \( \delta \tau / \langle \tau \rangle \lesssim 0.12 \). This upper limit indicates that most of the stars were formed at early times, and/or star formation in different galaxies was somehow synchronized.

Early-type galaxies can thus be considered relics of processes that took place in the early Universe, and studies of the evolution of early-type galaxies have been motivated by the desire to identify and quantify these processes.

1.1.3 Formation Theories

The homogeneity of early-type galaxies is consistent with the idea of galaxy formation in a “monolithic” collapse at high redshift. In these models, galaxies were formed in a single event
at very high redshift, from the collapse of proto-galactic gas clouds (Eggen, Lynden-Bell, & Sandage 1962; Searle, Sargent, & Bagnuolo 1973; Larson 1975; Rees & Ostriker 1977). Star formation in early-type galaxies ceased shortly after the collapse, followed by a smooth and regular dimming of the stellar light. These models naturally explain the homogeneity of early-type galaxies at \( z = 0 \), and predict little evolution in their properties or number density from the time of collapse to the present (see Jimenez et al. 1998).

A prediction of monolithic collapse models is the presence of massive star forming young galaxies at high redshift, with star formation rates of order \( 10^{2-3} M_{\odot} \text{yr}^{-1} \) (Jimenez et al. 1998). Star formation rates of galaxies at \( z > 3 \) selected by their continuum break at 912 Å are typically much lower (\( \sim 10 M_{\odot} \text{yr}^{-1} \); Steidel et al. 1996). However, massive star bursting systems at high redshift may have escaped detection in optical surveys if they are enshrouded in dust (e.g., Thompson et al. 1995). Dusty star bursting high redshift galaxies have been detected in the sub-mm (Blain et al. 1999), but it is difficult to determine their masses.

Massive star bursting young galaxies may be extremely rare. In semi-analytical models for galaxy formation in Cold Dark Matter (CDM) cosmologies (White & Frenk 1991; Cole 1991) the only objects that can form at \( z > 3 \) are of low mass. These low mass galaxies can merge as their dark halos merge, and high mass galaxies such as ellipticals and S0s are slowly built up in many generations of mergers. Mergers form bulges and ellipticals; spirals are formed by accretion of gas after a merger, which then settles into a disk (e.g., Kauffmann, White, & Guiderdoni 1993). In the hierarchical models explored until now early-type galaxies are relatively newcomers to the galaxy population (Kauffmann 1996; Baugh, Cole, & Frenk 1996); Baugh et al. (1996) predict 50% of present-day massive ellipticals experienced a major merger at \( z < 0.5 \).

These semi-analytical CDM models are currently unable to reproduce simultaneously the present-day luminosity function and the Tully-Fisher relation (Kauffmann et al. 1993; Cole et al. 1994; Heyl et al. 1995; Kauffmann et al. 1999). They also have difficulty explaining the homogeneity of early-type galaxies at \( z = 0 \); as an example, Baugh et al. (1996) predict a scatter in the \( U-V \) color-magnitude relation of \( \sigma_{U-V} = 0.074 \), a factor 2 larger than the observed upper limit \( \sigma_{U-V} < 0.035 \) (Bower et al. 1992).

On the other hand, observations and simulations of mergers and merger remnants in the field demonstrate that at least some ellipticals were formed in mergers (e.g., Schweizer & Seitzer 1992, Barnes 1999). Furthermore, the number fraction of galaxies in close pairs increases with redshift (Patton et al. 1997), indicating that mergers were more prevalent at earlier times. Similarly, many galaxies in the Hubble Deep Field are irregular and may be mergers in progress (Mobasher et al. 1996). Note that mergers are rare in present-day rich clusters, because the probability of a low velocity encounter is small. Therefore, if cluster ellipticals formed in mergers they must have occurred at early times, before or during the collapse of the cluster (Roos & Aarseth 1982; Merritt 1984).

### Testing Hierarchical Formation

Although the predictions of the monolithic collapse model are very different from those of hierarchical models it is at present unclear which provides a better description of galaxy formation. The fundamental difference between these models is the evolution of the mass function \( \phi(M) \) with time, but the mass function is very difficult to measure. It is relatively straightforward to measure the redshift evolution of the luminosity function (Lilly et al. 1995; Ellis et al. 1996). Although the evolution of the luminosity function depends on the evolution of the underlying mass function, it also depends on luminosity evolution of the galaxies. Even in the absence of star formation the luminosities of stellar populations are expected to evolve, because stars turn off the main sequence. Additional measurements are necessary to
disentangle the effects of mass evolution and luminosity evolution on the evolution of the luminosity function.

By measuring mass-to-light ratios of galaxies the evolution of the luminosity function can be corrected for the luminosity evolution of stellar populations. If it is established that mass-to-light ratios evolve as $M/L(z)$ luminosities of high redshift galaxies can be transformed to masses, and through the transformation

$$\phi(M,z) = M/L(z)\phi(L,z)$$

(1.1)

the evolution of the mass function can be obtained.

Furthermore, the measured evolution of $M/L$ ratios of galaxies provides important constraints on the properties of their stars, because it depends on the Initial Mass Function (IMF), and the formation redshift. The light of a young stellar population is dominated by massive stars which have a short lifetime on the main sequence. Therefore, the $M/L$ ratio of a young population evolves faster than the $M/L$ ratio of an old population. As illustrated in Fig. 1.1 the formation redshift of a stellar population can be determined from the measured evolution of its $M/L$ ratio (see Franx 1995).

## 1.2 Outline and Summary

In this thesis, two approaches are followed to constrain theories for the formation and evolution of early-type galaxies. Constraints on the ages of their stars are obtained from the observed evolution of their $M/L$ ratios (Chapter 2 – 4), and constraints on the time and process of their formation are obtained from morphological and spectral studies of large samples of galaxies in distant clusters (Chapter 5 – 7).
1.2.1 Ages of Stars in Early-Type Galaxies

In Chapters 2 – 4 the evolution of the $M/L$ ratio of early-type galaxies is determined from the evolution of the Fundamental Plane (FP) in clusters to $z = 0.83$ (corresponding to a time when the Universe was $\approx 45\%$ of its present age). The FP is a tight relation between the effective radii $r_e$ of galaxies, their surface brightness at the effective radii $I_e$, and their velocity dispersions $\sigma$, of the form

$$r_e \propto I_e^{-0.83} \sigma^{1.20}$$

in the $B$ band (Djorgovski & Davis 1987; Dressler et al. 1987; Jørgensen, Franx, & Kjærgaard 1996). The implication of the existence of the FP is that $M/L$ ratios of early-type galaxies are well behaved, and scale with the mass raised to a low power. Using $M \propto \sigma^2 r_e$ and $L \propto I_e r_e^2$, Eq. 1.2 can be rewritten as

$$M/L \propto M^{0.25}$$

(Faber et al. 1987). Therefore, the evolution of the FP traces the evolution of the $M/L$ ratios of early-type galaxies, and the evolution of the offset of the FP is proportional to the evolution of the mean $M/L$ ratio.

Determination of the high $z$ FP requires measurements of $r_e$, $I_e$, and $\sigma$ for samples of high redshift early-type galaxies. Because effective radii are typically $\sim 10$ kpc (or $\sim 1''$ for galaxies at high redshift) high resolution imaging with HST is required to determine $r_e$ and $I_e$. Velocity dispersions can be measured from the broadening of absorption lines in moderate resolution ($\sigma \lesssim 100$ km s$^{-1}$) spectra of early-type galaxies, obtained with high throughput spectrographs on large ground based telescopes.

These measurements were obtained for galaxies in four high redshift clusters. In Chapter 2 the methods for measuring $r_e$, $I_e$ and $\sigma$ of high redshift galaxies are described. Furthermore, these parameters are measured of galaxies in the cluster CL 0024+16 at $z = 0.39$. The Fundamental Plane is derived, and the evolution of the $M/L$ ratio is established to $z = 0.39$. In Chapter 3 $M/L$ ratios are measured of galaxies in CL 1358+62 at $z = 0.33$ and MS 2053+04 at $z = 0.58$. In Chapter 4, the analysis is extended to the cluster MS 1054–03 at $z = 0.83$ and these measurements are combined with those presented in Chapters 2 and 3. In this Chapter the implications for the formation redshift of the stars in early-type galaxies, the slope of the IMF, and $\sigma$ are discussed.

The $M/L$ ratio evolves as $\Delta \log M/L_B \propto -0.40z$, for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0$. The observed evolution provides a combined constraint on the formation redshift of the stars, the IMF, and cosmological parameters. The evolution is slow when compared to predictions from population synthesis models (e.g., Bruzual & Charlot 1999), indicating that the stars in early-type galaxies are very old. Furthermore, the data are inconsistent with $\Omega_m = 1$, unless the IMF is steeper than the standard Salpeter (1955) IMF. For a Salpeter IMF it is found that $z_{\text{form}} > 2.8$ and $\Omega_m < 0.86$ with 95% confidence. If the cosmological constant is non-zero lower formation redshifts are consistent with the data: $z_{\text{form}} > 1.7$ if $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

The luminosity evolution of massive early-type galaxies has now been determined with sufficient accuracy to place strong constraints on their epoch of star formation, and on cosmological models. The main uncertainty in the interpretation is the poor understanding of the IMF in the mass range around $1M_\odot$. Nevertheless, the current measurement can be used directly to correct the evolution of the luminosity function for the brightening of stellar populations with redshift. This can provide an important constraint on the mass evolution of galaxies.
1.2.2 Ages of Early-Type Galaxies

In chapters 5 – 7 morphologies and colors are studied of large samples of galaxies in two clusters, CL 1358+62 at $z = 0.33$ and MS 1054–03 at $z = 0.83$. Although the stars in massive early-types formed at high redshift, the formation of the early-type galaxies themselves did not necessarily coincide with the formation of their stars. If all early-type galaxies were formed at very high redshift, their number density and properties are expected to show little evolution at $z < 1$. However, if early-type galaxies were formed in mergers, or by stripping of spiral galaxies, their number density is expected to evolve. Furthermore, if early-types formed in mergers these mergers should be seen, even though the timescales are short (typically $\lesssim 1 \text{ Gyr}$; e.g., Barnes 1998). The approach in this thesis is to perform large field surveys of a few clusters at different redshifts using a combination of large HST mosaics in two passbands and extensive spectroscopy from the ground, with the aim to constrain the relevance of processes such as stripping and merging for the formation of early-type galaxies.

In Chapter 5 the color-magnitude relation in CL 1358+62 at $z = 0.33$ is presented and discussed, using a sample of 194 spectroscopically confirmed cluster members observed with HST. It is found that S0s in the outer parts of the cluster are bluer on average and have a larger scatter in their colors than S0s in the inner parts of the cluster, implying they have younger stellar populations. This result is consistent with the idea that clusters at $z = 0.33$ continue to accrete galaxies and groups from the field and that infall extinguishes star formation. It is inferred that the population of S0s in clusters probably evolves as star forming galaxies are converted into passively evolving galaxies, fully consistent with morphological studies of galaxies in clusters at slightly higher redshift (Dressler et al. 1998). The young S0s are of low luminosity; the most luminous galaxies in clusters are already in place at $z = 0.33$, and must have formed at higher redshift.

Chapter 6 and 7 discuss the morphological mix and color-magnitude relation in MS 1054–03 at $z = 0.83$. A spectroscopic and photometric survey of this cluster yielded a sample of 81 spectroscopically confirmed cluster galaxies observed with HST. The most striking result of this survey is the large fraction of luminous ongoing mergers in MS 1054–03. Properties of these mergers and implications of their existence are discussed in Chapter 6. Most of the mergers will likely evolve into luminous ($\sim 2L_\odot$) elliptical galaxies. From the number fractions of mergers and ellipticals in MS 1054–03 it is estimated that $\gtrsim 50\%$ of present-day cluster ellipticals experienced a major merger at $z < 1$. Morphologies, spectra and colors of the mergers show that the merging galaxies are E/S0s or early-type spirals, with stellar formation redshifts $z \gtrsim 1.7$. The high merger fraction in this young cluster is direct evidence against formation of massive ellipticals in a “monolithic” collapse at high redshift, and in qualitative agreement with hierarchical formation scenarios.

In Chapter 7 the color-magnitude relation of MS 1054–03 is presented. The scatter and slope of the color-magnitude relation of early-type galaxies are very similar to those of the nearby Coma cluster. No trend with radius in the cluster is seen, but the data are consistent with the weak trend observed for S0s in the cluster CL 1358+62 at $z = 0.33$. A model is described which explains both the rapid evolution of the early-type fraction in clusters and the roughly constant scatter in the color-magnitude relation. The model assumes that star forming galaxies are continuously transformed to passively evolving galaxies, with the transformation rate determined by the observed evolution of the early-type fraction. Furthermore, it is assumed early-type galaxies are not immediately recognized as such after star formation ceases. The model reproduces the observed evolution of the scatter in the color-magnitude relation and the zeropoint of the Fundamental Plane, provided that early-type galaxies are recognized as such $\sim 1 \text{ Gyr}$ after star formation ceases.
1.3 Conclusions and Prospects

In conclusion, evidence is presented that the stars of early-type galaxies in clusters are old, whereas the early-types themselves have been assembled relatively recently. Specifically, we have shown that most stars in massive early-types were formed before \( z \approx 2 \), whereas it is inferred that more than half of present-day massive ellipticals were assembled in mergers at \( z < 1 \). The discovery of a large population of luminous mergers with evolved stellar populations in the outskirts of the cluster MS 1054–03 at \( z = 0.83 \) has far reaching implications; their presence is direct evidence against galaxy formation in a “monolithic” collapse at high redshift, and in qualitative agreement with hierarchical theories for structure formation. More wide field studies of high redshift clusters are necessary to establish whether MS 1054–03 is typical for its redshift, and to determine whether the merger fraction in distant clusters correlates with the dynamical state of the cluster itself.

It is difficult, but not impossible, to extend the studies presented in this thesis to higher redshifts. Several clusters have been discovered at \( z > 1 \) (e.g., Deltorn et al. 1997, Stanford et al. 1997, Rosati et al. 1999). Because the 4000Å-break is redshifted to \( > 8000 \) Å the part of the spectrum of these galaxies that is usually observed is redshifted to the IR; IR imaging and spectroscopy will therefore be important aspects of studies of \( z > 1 \) early-types.

Furthermore, it is important to extend these studies to groups and the field at intermediate and high redshift. Currently popular hierarchical galaxy formation models predict that massive field ellipticals are several Gyr younger than cluster ellipticals, because galaxy formation is accelerated in dense environments (e.g., Kauffmann 1996). Therefore, comparison of the luminosity weighted ages and assembly time of field ellipticals and cluster ellipticals is an important test of these models.

References