Evolution of Early-type Galaxies in Clusters

Bodo L. Ziegler

Universitäts-Sternwarte Göttingen
Geismarlandstraße 11, D-37083 Göttingen, Germany
bziegler@uni-sw.gwdg.de, http://www.uni-sw.gwdg.de/~bziegler

Abstract

This is a short review on the evolution of elliptical and lenticular/S0 galaxies in the dense environment of rich clusters for look-back times of more than half the age of the Universe. In addition, new data are presented for the cluster Abell 2218.

Scaling relations like the Fundamental Plane provide strong evidence that luminous ellipticals evolve purely passively up to redshifts of $z = 0.8$ *implying that no significant new stellar population was created during that time. This picture is supported by tight Mg-*σ *and colour-magnitude relations at various redshifts and age/metallicity diagnostic diagrams based on absorption lines. On the other hand, there is a strong decline in the frequency of S0 galaxies with redshift as was revealed by HST images of distant rich clusters. In the same clusters, however, a significant proportion of the galaxies have disturbed morphologies and signs of ongoing interaction/merging. Numerous post-starburst galaxies (like E+A galaxies) are found as well as passive spiral galaxies, while these galaxy types are less present in local clusters. This raises the question whether the spiral galaxies falling into the cluster from the surrounding field could be transformed into S0 galaxies. A possible scenario would be that the intracluster medium first deprives the spirals of all their gas leading to the end of star formation. The subsequent evolution within the tidal field of the cluster could then turn the spirals into S0 galaxies over the ages.*

The study of a great number of early-type galaxies per cluster including sub-L^* *galaxies reveals, however, that this picture needs some finetuning since the relations mentioned above have a larger spread than those based on the observation of just a few luminous galaxies. First results are presented for 48 early-type galaxies in the cluster Abell 2218 at a redshift of* $z = 0.18$.

1 Introduction

In the morphological scheme of Hubble's "Tuning Fork", the branch of early-type galaxies comprises the elliptical galaxies and the lenticular or S0 galaxies, which have a bulge and a disk component (Hubble 1936). Ellipticals can be further divided into boxy and disky ellipticals according to their isophote shapes (Kormendy & Bender 1996). Since disky ellipticals contain small stellar disks they may form a continuous sequence with the S0 galaxies. In a dynamical view, rotational support decreases from S0 to disky ellipticals whereas the random motion of the stars, measured by the velocity dispersion σ, gets more and more important. Another common feature of early-type galaxies is the lack of any significant amount of cold gas on global scales so that there is no significant ongoing star formation.

The currently favoured theory that combines cosmology and galaxy formation is the Cold Dark Matter model, which comes in various flavours. It predicts that galaxies merge hierarchically, i.e., smaller entities hit one against the other and gradually build up a large galaxy; the so-called mergertree scenario (Lacey & Cole 1993). Especially in the field, merging disks get heated up until they form a spheroidal, but at a later stage a disk can be formed again when the evaporated gas, which was trapped in the dark halo, is falling back onto the galaxy (Baugh et al. 1996). In this way, the mass of a galaxy is increased in jumps each time a merger occurs and a new stellar population may be created which dilutes the underlying older population and makes the mean stellar age younger. This is described by semi-analytic (Kauffmann & Charlot 1998) and hydrodynamic SPH (Steinmetz & Navarro 1999) models, which are able to incorporate star formation and feedback processes.

On the other hand, stellar population models, which predict the spectra and hence the colours and absorption lines of a galaxy for all time steps of its evolution based on the isochrones of the stellar content, assume just a certain time dependent star formation rate for a single metallicity and initial mass function. Most of them have not yet incorporated the superposition of different stellar populations having various ages and metallicities as the hierarchical merging picture implies (but see e. g. Sansom & Proctor 1998). Nevertheless, these passive evolution models are able to reproduce the observed properties of both local and distant galaxies (e. g., Bruzual & Charlot, 1993). The simplest model picks up a short burst of star formation in which all the stars of a galaxy are created, the so-called Simple Stellar Population model (SSP). It describes the observed evolution of early-type galaxies quite well. The main features are the rapid decline of the blue luminosity so that the red light is dominating after about 3 Gyrs, the rapid diminishing of the Balmer lines and the strengthening of the metal lines on the same timescale. However, stellar populations are degenerate between age and metallicity. Thus, the spectra of SSP's are nearly identical if the age is increased by a factor of 3 and, simultaneously, the metallicity decreased by a factor of 2 (Worthey 1994). For example, a spectrum at an age of 15 Gyrs and a metallicity of $[Fe/H] = -0.1$ looks the same as that at an age of 5 Gyrs and a metallicity of $[Fe/H] = +0.2$. This means that the colours and most absorption lines are degenerate, too, and can not be used to distinguish between age and metallicity effects. Only a few indexes like the Balmer lines are more dependent on age and the combinations of some metal lines like [MgFe] are more metallicity sensitive, so that they can be evaluated in an age/metallicity diagnostic diagram.

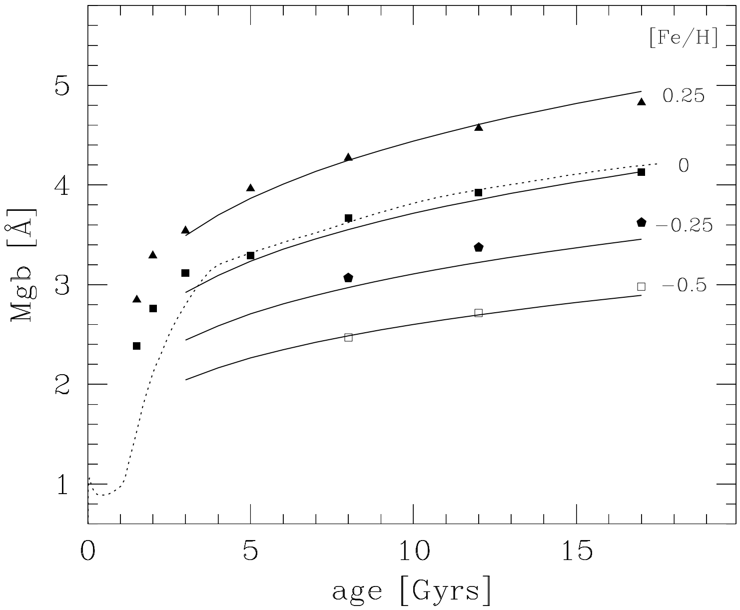

Figure 1: The dependence of the Mg_b absorption index on age and metallicity (from Ziegler & Bender 1997). Symbols are model data from Worthey (1994), the dotted line represents the SSP model of Bruzual & Charlot for solar metallicity and the solid lines follow Equation 1.

2 Evolution of elliptical galaxies

First evidence for an old age of ellipticals in clusters came from the observations of very tight colour-magnitude (Bower et al. 1992), Fundamental Plane (Bender et al. 1992) and Mg-σ (Bender et al. 1993) relations in local clusters. The Mg_b absorption index ($\lambda_0 \approx 5172$Å) follows Worthey's 3/2-rule (see Fig. 1) and from his SSP models the following time and metallicity dependence can be derived:

$$\Delta \log \mathrm{Mg}_b = 0.20 \Delta \log t + 0.31 \Delta \log Z/Z_o. \quad (1)$$

The observed narrow spread in the Mg_b–σ relation of ellipticals in the Virgo and Coma clusters (see Fig. 2), therefore, translates into small limits on the dispersion in age and metallicity at fixed velocity dispersion (Colless et al. 1999). For the most massive ellipticals in Coma, for example, relative age and relative metallicity are constrained to 17 % and 11 %, respectively (Ziegler & Bender 1997). This means in the picture of passive evolution (i. e. no merging), that when Mg_b line strengths of distant and, therefore, younger galaxies are compared with those of nearby ones at the same velocity dispersion σ, any difference can mostly be attributed to an age effect. In this sense, the Mg_b–σ relation breaks the age/metallicity degeneracy and is a powerful tool to investigate the evolution of elliptical galaxies.

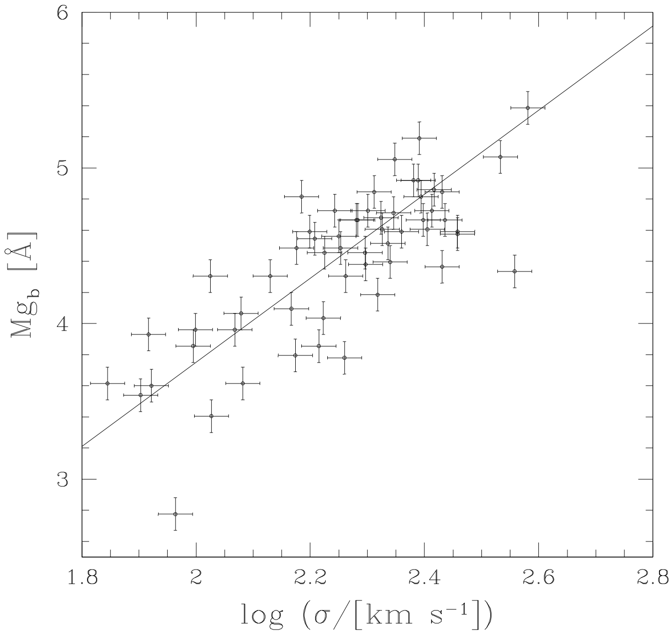

Figure 2: The Mg$_b$–σ relation of elliptical galaxies in the local Virgo and Coma clusters (data from Dressler et al. 1987, as transformed like in Ziegler & Bender 1997).

This age determination technique was first applied by us to early-type galaxies in three clusters at a redshift of $z \approx 0.4$: Abell 370 ($z = 0.375$), MS 1512+36 ($z = 0.372$) and Cl 0949+44 ($z = 0.377$) (Bender et al. 1996, Ziegler & Bender 1997). 28 nights at the Calar Alto 3.5 m-telescope, 9 nights at the ESO NTT and 2 nights at the ESO 3.6 m-telescope were spent to get 21 good quality spectra. Except from a few outliers (probably E+A galaxies), the reduction in the Mg$_b$ absorption is low and the mean offset from the local fit line is about 0.4Å (see Fig. 3). This means, that the distant galaxies must be quite old themselves, because the lookback time of about 5 Gyrs did not produce a higher difference in Mg$_b$ and that they indeed evolved only passively. Assuming the metallicity did not change at all during that time, Equation 1 can be transformed to predict the Mg$_b$ absorption for any given age. It depends, though, on the redshift of formation z_f and the cosmological parameters. In Fig. 3, hatched areas indicate the expected location of the Mg$_b$ absorption for two different formation redshifts and a range of plausible values of H_0 and q_0. The comparison with the data points leads to the conclusion, that the observed galaxies must have formed at $z_f > 2$, the most massive ones even at $z_f > 4$. But only the bulk of the stars must have come into existence at these epochs, the galaxies themselves could have been assembled at a later time if no new star formation took place during that process. These observations are still in agreement with CDM models, since these predict, that the last major merger of a galaxy in the cluster environment occurs at about $z = 2$ (Kauffmann 1996).

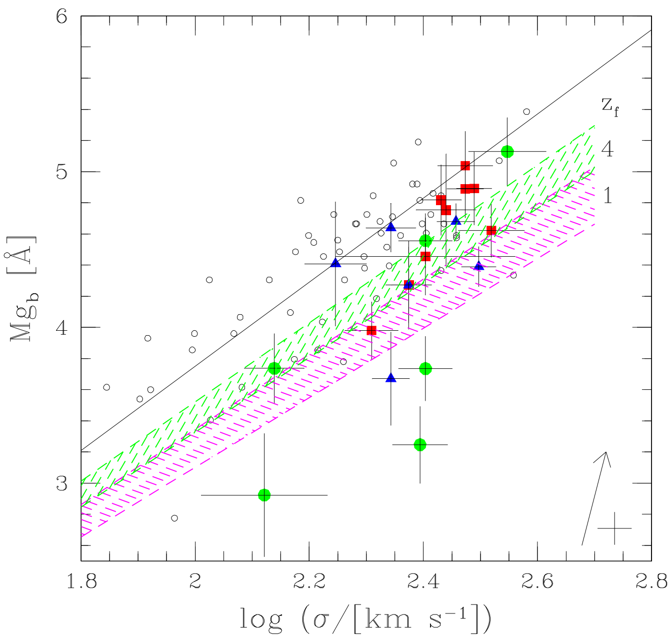

Figure 3: The Mg_b–σ relation of elliptical galaxies in three distant clusters at $z \approx 0.4$ (points with errorbars) compared to local cluster ellipticals (from Ziegler & Bender 1997). Hatched areas represent the expected range of Mg_b line strengths for redshifts of formation z_f of 1 and 4 for a variety of cosmological parameters. At the lower right corner, the arrow represents the aperture correction applied to the distant data points and the cross indicates the average error of the measurements of the local galaxies.

Another physical relationship of early-type galaxies is the Fundamental Plane (FP), which is set by the three observables velocity dispersion σ, effective or half-light radius R_e and the mean surface brightness $\langle\mu_e\rangle$ within R_e. It is a consequence of the virial theorem and a slight dependence of the mass-to-light ratio on the mass (e. g. Bender et al. 1992). Seen edge-on, the FP is very tight and both elliptical and S0 galaxies in the Coma cluster follow the same fit line although they are dynamically different (Bender et al. 1998). From the HST images of the three distant clusters we were able to derive accurately the photometric parameters (Saglia et al., 2000). Transforming the observed magnitudes into restframe B magnitudes, they can be compared to the Coma galaxies (see Fig. 4) and a mean brightening of about 0.5 mag for the distant galaxies is derived.

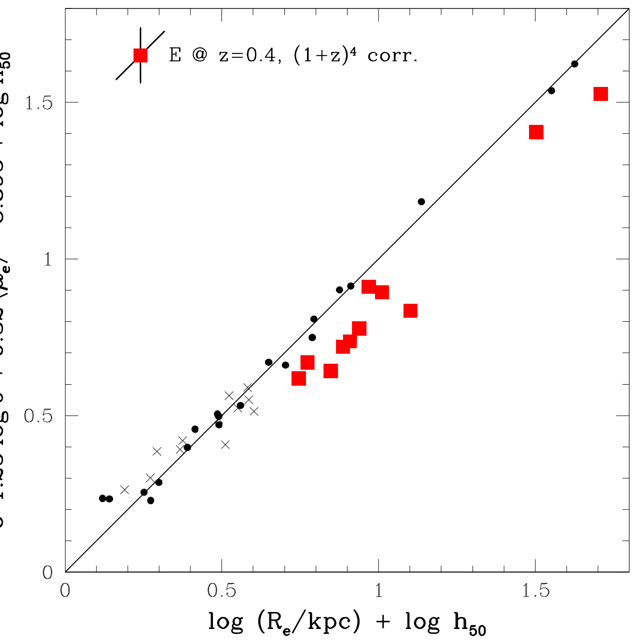

Figure 4: The Fundamental Plane seen edge-on for Coma ellipticals (small filled circles) and S0 galaxies (crosses) compared to early-type galaxies in three clusters at $z \approx 0.4$ (big filled squares) (adapted from Bender et al. 1998). The observed HST magnitudes of the distant galaxies were transformed to restframe B and corrected for surface brightness dimming. A typical error is plotted in the upper left corner.

In the meanwhile, other groups have used the FP as well to study the evolution of early-type galaxies in clusters at different redshifts: Abell 2218 at $z = 0.175$ (Jørgensen et al. 1999, Ziegler et al. 1999), Abell 665 $z = 0.181$ (Jørgensen et al. 1999), Abell 2390 $z = 0.24$ (Ziegler et al., 2000b), Cl 1358+62 $z = 0.33$ (Kelson et al. 1997), Cl 0024+16 $z = 0.39$ (van Dokkum & Franx 1996), MS 2053–04 $z = 0.58$ (Kelson et al. 1997) and MS 1054–03 $z = 0.83$ (van Dokkum et al. 1998). The combined results strongly favour a purely passive evolution of the stellar populations both in surface brightness and mass-to-light ratio (see for a summary Jørgensen et al. 1999). For open and λ-dominated cosmologies and a Salpeter IMF (Salpeter 1955), redshifts of formation greater than 2 are required to yield the corresponding old ages (Bender et al. 1998, van Dokkum et al. 1998a).

3 Evolution of S0 galaxies

In contrast to the elliptical galaxies, S0 or lenticular galaxies show a dramatic evolution with lookback time in the dense environment of rich clusters. But this was only recently discovered by images from the *Hubble Space Telescope*, whose *WFPC2* camera made it possible to resolve even the faint galaxies in distant clusters and determine their morphology (e. g., Dressler et al. 1997). Apart from the dwarf galaxies, the S0 galaxies form the dominant population in local rich clusters, followed by the ellipticals, whereas spirals contribute roughly only 10 %. This situation is very different in rich clusters at a redshift of $z \approx 0.5$. There, spiral and disturbed galaxies make up the major part of the luminous galaxies, whereas S0 galaxies are hardly found (10–20 %), see Fig. 5.

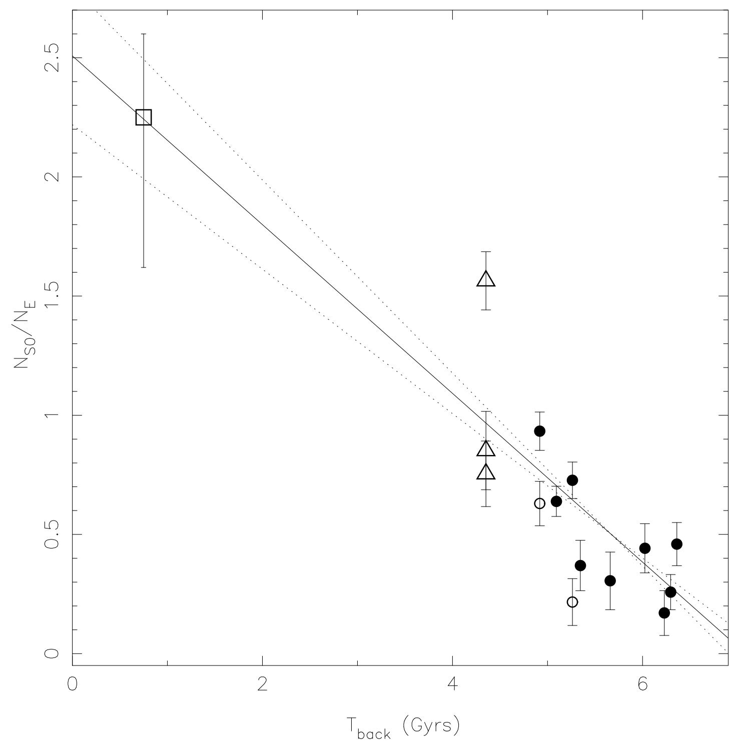

Figure 5: The proportion of bright S0 to elliptical galaxies in rich clusters as a function of lookback time (adapted from Dressler et al. 1997). The fit shown (with $\pm 1\sigma$ limits as dotted lines) was made to the MORPHS data (filled circles, Smail et al. 1997) and is compatible with clusters at $z = 0.3$ (open triangles, Couch et al. 1998) and the local reference (Dressler, 1980). The 2 open circles represent the outer regions of 2 clusters, which are not directly comparable to the other points.

On the other hand, Butcher & Oemler found a rapid increase in the “blue” galaxy population in rich clusters with redshift already twenty years ago

(Butcher & Oemler Jr. 1978, Butcher & Oemler Jr. 1984a). On average, the fraction of "blue" galaxies rises from 0.05 in local clusters to 0.25 in clusters at $z = 0.5$. Early spectroscopy of such BO-galaxies revealed in some cases a spectral energy distribution similar to normal ellipticals but with a stronger absorption of the Balmer lines, so that they were dubbed E+A galaxies (e. g. Butcher & Oemler 1984b). The idea behind that was that these post-starburst galaxies were ellipticals who had undergone a second burst of star formation in the recent past ($\leq$2 Gyrs), so that the newborn A stars were still responsible for the increased strength of the Balmer lines. But using high-resolution HST images, stellar disks were detected in most of these E+A galaxies indicating that spirals are the more probable progenitors rather than ellipticals (e. g., Couch et al. 1998). New spectroscopic observations have found in addition a number of dust-enshrouded starburst galaxies and a population of red, passive spiral galaxies with no significant emission lines (Poggianti et al. 1999). This study also revealed a population of red, passive spiral galaxies with no significant emission lines.

Many other galaxies in the distant clusters have a disturbed morphology and some show clear signatures of past or ongoing interaction or merging (Dressler et al. 1994, Smail et al. 1997). The majority of the E+A post-starburst galaxies are located at the rim of a cluster if it is regular or in between subcomponents (Balogh et al. 1997). In these regions, most of the spiral and irregular galaxies are found, too, whereas the early-type galaxies are concentrated to the core like in local clusters, see Fig. 6. S0 galaxies themselves were found to be bluer at the outskirts of a cluster than in the core (van Dokkum et al., 1998b).

All these findings give clear evidence that galaxy transformation is a common phenomenon in clusters so that the morphology of a galaxy can be changed. There are signs that galaxies interact with each other and even merge together. But the high velocity dispersion in rich clusters makes the effective cross section for such encounters small, so that the influence of the hot intracluster medium is much more important. This ICM was already detected by the first X-ray satellites, since its temperature is between 1 and 10 million degrees. In nearby clusters, H I studies revealed spiral galaxies deficient in H I and a displacement of the H I disk from the stellar disk, which is the larger the closer the galaxy is located to the center (Valluri & Jog 1991, Cayatte et al. 1994, Bravo-Alfaro et al. 1998). This could be caused by ram-pressure stripping of the ICM or tidal interactions between the galaxies.

Which mechanisms lead to the transformation into S0 galaxies is still unknown, so that the strong increase in the frequency of S0 galaxies during the past 5 Gyrs can not yet be explained. Spectroscopic observations have ruled out a simple fading of spiral galaxies (Couch & Sharples 1987, Balogh et al. 1997, van Dokkum et al. 1998b). The strengths of the Balmer absorption lines in some galaxies require that a truncation mechanism must act to cut off star formation very quickly and must also promote bursts of star formation (Barger et al. 1996). An appealing scenario is that spiral galaxies falling into the cluster from the surrounding field undergo a dusty starburst phase.

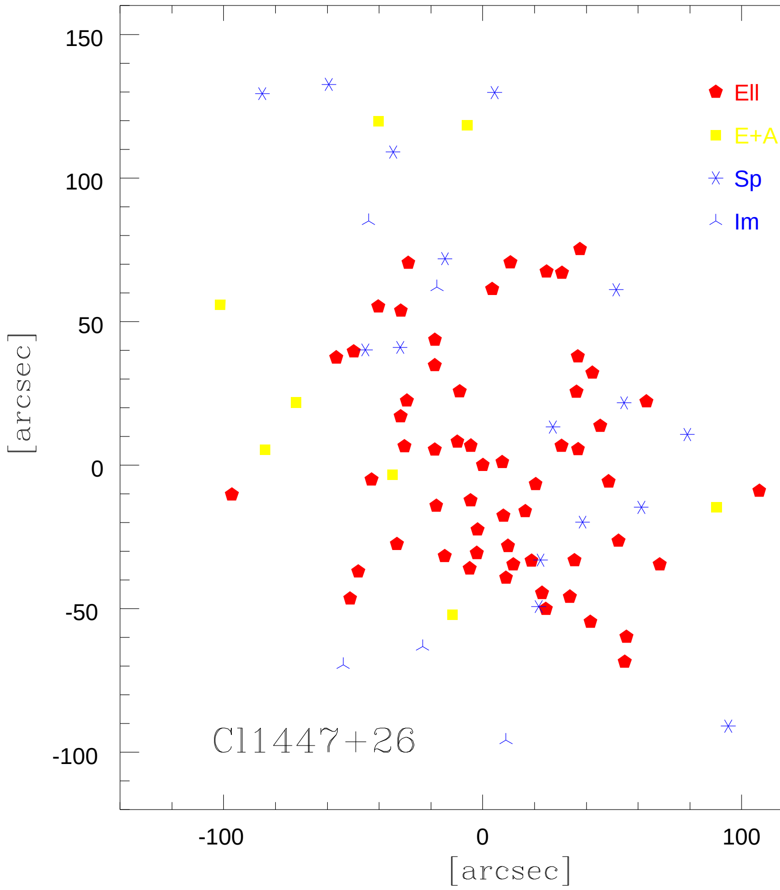

Figure 6: Radial distribution in the cluster Cl 1447+26 at $z = 0.37$ (from Belloni et al. 1997). Early-type galaxies (diamonds) are concentrated to the core, whereas spirals (stars), irregulars (crosses) and E+A galaxies (box) are located in the outer regions.

This increased activity causes the Butcher-Oemler effect. Ram-pressure stripping by the ICM then leads to a wide spread and rapid decline in the star formation rates resulting into the post-starburst galaxies and red, passive spirals. However, other processes may be equally important, such as tidal stripping (Governato et al. 1996) or galaxy-galaxy interactions (Lavery & Henry 1994). The timescale for the transformations described thus far is rather short (<1 Gyr, e. g., Barnes & Hernquist 1992). The subsequent evolution takes much longer and the permanent influence of the tidal field of the cluster as a whole (harassment) may cause a substantial removal of disk light (Moore et al. 1996). The end product of this scenario may then be an S0 galaxy (see the flowchart, Fig. 7 and Poggianti et al. 1999).

Galaxy Transformation:

infalling spiral galaxies ($z = 0.5$)

$\downarrow$

triggering of SF

$\Downarrow$

starburst

$\vdots$

stripping of gas by ICM

$\Downarrow$

post–starburst, red spirals

$\vdots$

tidal interactions (harassment)

$\Downarrow$

removal of disk–light

$\vdots$

fading through stellar evolution

$\downarrow$

S0 ($z = 0$)

Figure 7: Flow chart of a scenario for the transformation from spirals into S0 galaxies in rich clusters.

4 Evolutionary status of early-type galaxies in Abell 2218

The determination of morphology is increasingly difficult the more distant and, therefore, fainter the galaxies are, even on HST images (Smail et al. 1997). For example, the average size of L* galaxies at $z = 0.5$ is only $\approx$ 1–1.5 arcsec (Ziegler et al. 1999). But even in closer systems it is hard to detect disks and their visibility depends strongly on the inclination. A round S0 galaxy seen face-on may be classified as an elliptical. The MORPHS group has estimated that about 15 % of the S0 population may be misclassified as ellipticals independent of redshift. An additional problem of the past studies is the low number of observed galaxies. In most cases, spectra of only a handful or a dozen of the brightest cluster members were taken. Therefore, the evolution only of the more massive galaxies have been studied in FP analyses.

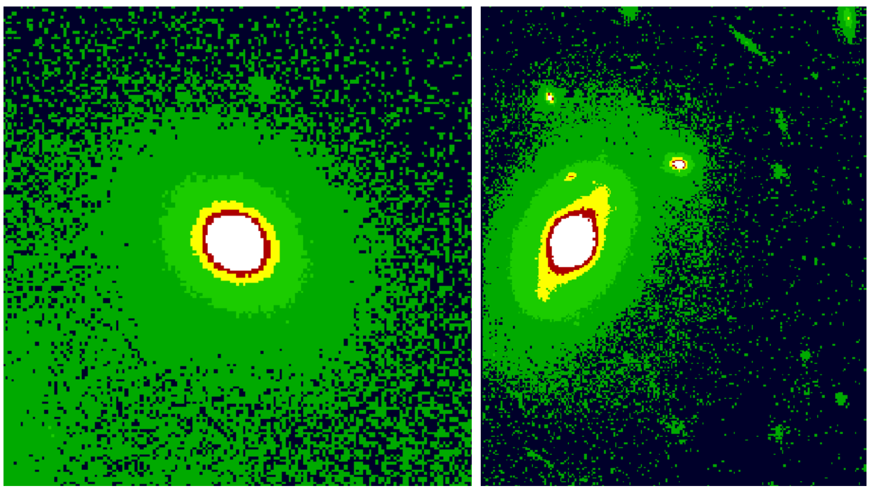

Figure 8: Bona-fide examples of an elliptical and an S0 galaxy in the cluster Abell 2218 ($z = 0.175$) extracted from an HST/WFPC2 image in the F702W filter. More examples can be found in Ziegler et al. 2000a.

To overcome this bias problem, we started a project in 1997 to observe for the first time a great number of early-type galaxies in the cluster Abell 2218 ($z = 0.175$). Multi-object spectroscopy was done using the LDSS2 spectrograph at the William Herschel telescope with three different masks (Ziegler et al. 2000a). Galaxies were selected by a colour criterion and encompass several sub-L* galaxies. The total exposure time of $\approx$ 5 hours allowed the extraction of high signal-to-noise spectra of 48 different early-type galaxies. The average size of these galaxies is $\approx$ 2–4 arcsec, which allows the accurate determination of the photometric parameters of the subsample of 20 galaxies contained in HST images. For the other galaxies they were measured from $UBVI$ photometry obtained at the Palomar 5 m-telescope. In the HST subsample, there are 9 S0/SB0 galaxies making up 50 % and 2 early spirals. Fig. 8 shows bona-fide examples of an elliptical and an S0 galaxy. Five of the galaxies outside the HST field have clear evidence for a disk component, too.

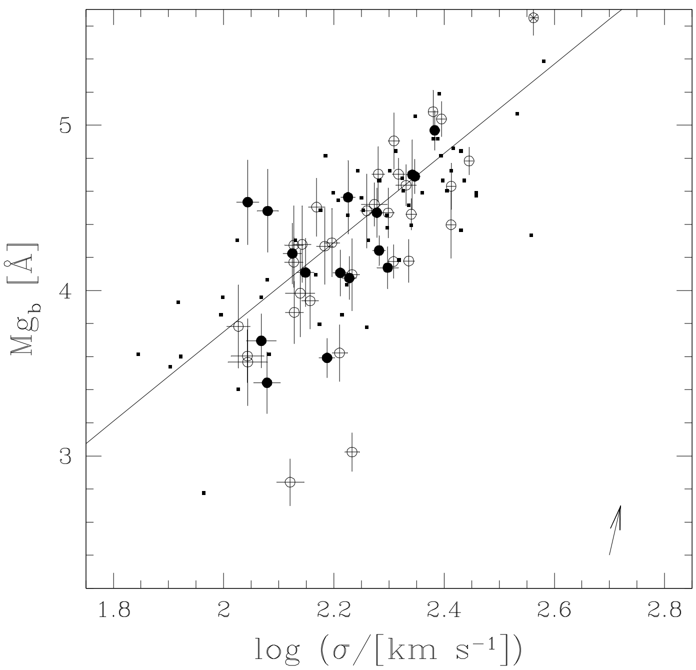

Figure 9: The Mg_b–σ relation of early-type galaxies in the cluster Abell 2218 at $z = 0.175$ (points with errorbars) compared to ellipticals in the local Coma and Virgo clusters (from Ziegler et al., 2000a). S0 galaxies are denoted by filled circles, ellipticals by open circles. The crossed circle marks a galaxy probably undergoing a merger. The arrow in the lower right corner represents the aperture correction applied to the A 2218 data points. The line represents the local Mg_b–σ relation.

The velocity dispersion σ and the line strengths of several absorption lines were measured like for the cluster galaxies at $z \approx 0.4$ (see Section 2). Fig. 9 compares the Mg_b–σ relation of A 2218 to the same local sample as in Figs. 2 and 3. The spread of the distant relationship is almost the same as of the local one and the zeropoints are nearly identical within the errors indicating a very old age for the early-type galaxies in A 2218. The slopes are also not very different from each other, so that the distant and local galaxy samples could have been drawn from the same population (KS statistics: $p = 0.016$). But the most striking result is that elliptical and S0 galaxies are equally distributed along the Mg_b–σ relation (KS statistics: $p = 0.61$) so that there exist S0 galaxies which are as old as ellipticals at a lookback time of ≈ 2.5 Gyrs for

A 2218. The two galaxies with very low Mg_b absorption have rather high Hβ values, and could, therefore, be post-starburst galaxies like E+As. It is not possible to detect any disk in these two galaxies in the ground-based images (FWHM $\geq$ 1.1 arcsec). Note also, that the two early spirals do not deviate significantly from the Mg_b–σ relation.

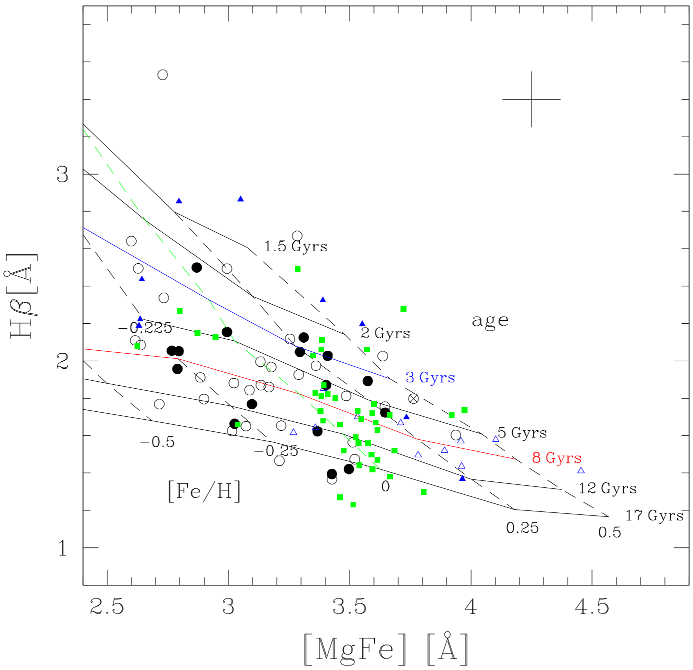

Figure 10: A line diagnostic diagram to disentangle age and metallicity effects (from Ziegler et al. 2000a). See text for explanation. S0 galaxies in A 2218: filled circles, ellipticals in A 2218: open circles, a typical error is shown in the upper right corner. The underlying grid of lines with constant age (solid; 1.5–17 Gyrs) and constant metallicity (dashed; [Fe/H]= $-0.5 - +0.5$) was derived from SSP models by Worthey (1994). For comparison, ellipticals (open triangles) and S0 galaxies (filled triangles) of the local Fornax cluster (Kuntschner & Davies 1998) are plotted as well as Gonzalez' sample (1993) of nearby field and Virgo ellipticals (boxes).

Although most of the absorption line indexes of SSP models are degenerate in age and metallicity (see Section 1), it is possible to construct line diagnostic diagrams. The reason is that some lines are more sensitive to age others more to metallicity. The Balmer lines like Hβ, e. g., depend very much on age, whereas the combination between Mg_b and Fe 5270, [MgFe], is a measurement of the metallicity (Worthey 1994). Such a diagram is shown in Fig. 10. The galaxies in A 2218 are spread out in age and metallicity with ellipticals and S0s being almost equally distributed. In particular, there are S0 galaxies whose mean age can be fitted both by models for a very old age and by a very young age. This is in contrast to the trend in the local poor Fornax cluster, where the lenticulars are more concentrated towards younger ages (Kuntschner & Davies 1998). There also seems to be a lack of very old and high metallicity galaxies in A 2218. But these galaxies are also missing in a sample of randomly selected nearby field and Virgo cluster early-type galaxies (González 1993).

We have determined the structural (R_e) and photometric parameter ($\langle \mu_e \rangle$) of the Fundamental Plane for the 20 early-type galaxies visible on the HST image of A 2218 according to Saglia et al. 1997. In Fig. 11, we compare the edge-on projection of the FP with that of Coma early-type galaxies (cf. with Fig. 4). The scatter is marginally larger than for Coma, and the slopes are not significantly different. There seems to be some difference between elliptical and S0 galaxies with the latter being brighter on average. If all of the offset is attributed purely to changes in luminosity, then the brightening is marginally consistent with pure passive stellar population models (e. g. BC98 models, cf. Bruzual & Charlot 1993).

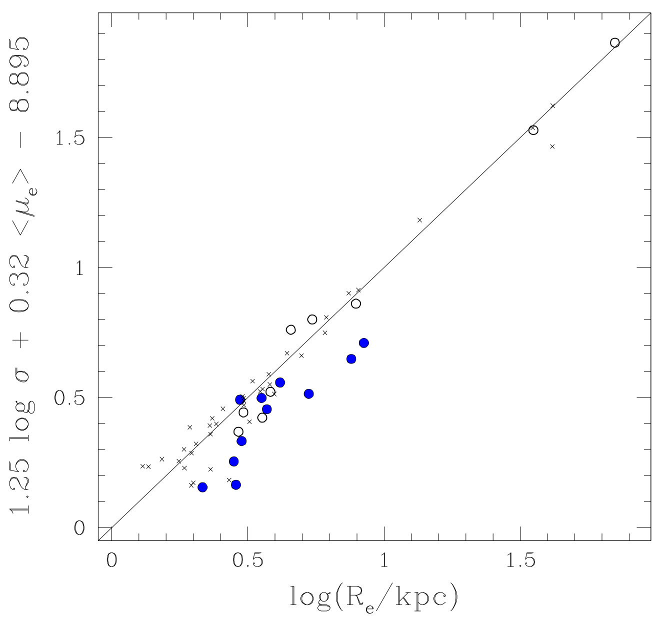

Figure 11: The Fundamental Plane seen edge-on for Coma early-type galaxies (crosses, fit line) compared to ellipticals (open circles) and lenticulars (filled circles) in Abell 2218 at $z = 0.175$ (from Ziegler et al. 2000a). The observed HST magnitudes of the distant galaxies were transformed to restframe B and corrected for surface brightness dimming.

5 Summary and future

In this short review it was shown, that luminous elliptial galaxies in rich clusters do evolve just passively according to the fading of their stellar content. The bulk of the stars must have been formed at high redshifts ($z_f > 2$), which is in line of predictions from CDM models in these dense environments. Most of the evidence comes from Fundamental Plane analyses of several clusters at redshifts from $z = 0$–0.8, which is augmented by the study of Mg_b–σ relations and age/metallicity diagrams.

In contrast to this smooth evolution, lenticular/S0 galaxies show a dramatic evolution in their frequency. While they form the dominant population of the bright galaxies in local rich clusters, their number diminishes to a few percent within a lookback time of about 5 Gyrs. To explain this phenomenon, a scenario was issued, in which spiral galaxies coming from the field surrounding a cluster are gradually transformed into S0 galaxies. An arriving galaxy does not change its morphology immediately, but first its star formation is truncated due to the quick removal of the gas, most probably by the ICM. Subsequently, the permanent tidal interaction with the cluster potential and other galaxies may change its appearance (bulge-to-disk ratio). Together with the fading of the stellar population these processes may then transform the spiral into an S0 galaxy as seen today.

The observation of a large sample of early-type galaxies in the cluster Abell 2218 at $z = 0.18$ revealed that a refined picture of galaxy evolution is necessary. Half of the 50 galaxies, which are made up by both luminous and sub-L* galaxies, are classified as ellipticals, the other half as lenticulars. Both galaxy types are almost equally distributed along the Fundamental Plane and Mg_b–σ relations. Modeling of the age sensitive Balmer lines showed that the mean age of the stellar population of both ellipticals and S0 galaxies varies between 2 and 20 Gyrs in A 2218.

Galaxy evolution certainly is science at the very frontier of astronomy and the determination of the kinematics of faint galaxies is only possible with observations at 10 m-class telescopes. With the advent of the VLTs we embarked on several projects aimed to further disentangle the phenomena connected to galaxy evolution. These projects encompass the Fundamental Plane and Mg_b–σ analysis of about 15 early-type galaxies in the cluster MS2053–04 at $z = 0.6$ as well as a detailed study of late-type galaxies in 6 different rich clusters at $z = 0.3$–0.6. Not only the star formation history of the galaxies located between the core and the very edge of the clusters, but also rotation curves and, thus, the mass and dynamics will be measured. As a complement, the same science will be made with a large sample of 170 field galaxies selected from the FORS Deep Field. The combined results will put strong constraints on CDM models.

To get a grip on the problem of galaxy transformation within clusters, we also started an intense campaign to observe poor X-ray detected clusters at $z = 0.2$–0.3 with ground-based optical (Calar Alto, HET, GEMINI) and radio telescopes (VLA) as well as with HST and XMM. The effectiveness of the competing processes invoked to explain galaxy transformation varies according to density and virial temperature of the local environment. For example, galaxy mergers are most effective in lower galaxy density environments where relative velocities are small; on the other hand, ram-pressure stripping is only effective at very high gas densities such as the cores of rich clusters. Therefore, by comparing galaxy evolution in clusters of different environments it is possible to separate the various physical processes that could contribute to the observed transformation in the galaxy population of clusters.

Acknowledgements: I would like to thank my partners in Durham, Drs. Bower, Davies, Kuntschner and Smail, as well as in Munich, Drs. Belloni, Bender, Greggio and Saglia, for the excellent collaboration, on which all the presented results are based.

References

Balogh, M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., and Ellingson, E., 1997, ApJ 488, L75

Barger, A. J., Aragón-Salamanca, A., Ellis, R. S., Couch, W. J., Smail, I., and Sharples, R. M., 1996, MNRAS 279, 1

Barnes, J. E. and Hernquist, L., 1992, ARAA 30, 705

Baugh, C. M., Cole, S., and Frenk, C. S., 1996, MNRAS 283, 1361

Belloni, P., Vuletić, B., and Röser, H.-J., 1997, in N. Tanvir, A. Aragón-Salamanca, and J. V. Wall (eds.), *HST and the High Redshift Universe*, 37th Herstmonceux Conference, p. 219, World Scientific

Bender, R., Burstein, D., and Faber, S. M., 1992, ApJ 399, 462

Bender, R., Burstein, D., and Faber, S. M., 1993, ApJ 411, 153

Bender, R., Saglia, R. P., Ziegler, B., Belloni, P., Bruzual, G., Greggio, L., and Hopp, U., 1998, ApJ 493, 529

Bender, R., Ziegler, B., and Bruzual, G., 1996, ApJ 463, L51

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

Bravo-Alfaro, H., Cayatte, V., Balkowski, C., and van Gorkom, J. H., 1998, in A. Mazure, F. Casoli, F. Durret, and D. Gerbal (eds.), *Untangling Coma Berenices: A New Vision of an Old Cluster*, p. 128, Word Scientific (see also astro-ph/9912405)

Bruzual, G. A. and Charlot, S., 1993, ApJ 405, 538

Butcher, H. and Oemler Jr., A., 1978, ApJ 219, 18

Butcher, H. and Oemler Jr., A., 1984a, ApJ 285, 426

Butcher, H. and Oemler Jr., A., 1984b, Nature 310, 31

Cayatte, V., Kotanyl, C., Balkowski, C., and van Gorkom, J. H., 1994, AJ 107, 1003

Colless, M., Burstein, D., Davies, R. L., McMahan, R. K., Saglia, R. P., and Wegner, G., 1999, MNRAS 303, 813

Couch, W., Barger, A., Smail, I., Ellis, R., and Sharples, R., 1998, ApJ 497, 188

Couch, W. J. and Sharples, R. M., 1987, MNRAS 229, 423

Dressler, A., 1980, ApJ 236, 351

Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich, R. J., and Wegner, G., 1987, ApJ 313, 42

Dressler, A., Oemler Jr., A., Couch, W. J., Smail, I., Ellis, R. S., Barger, A., Butcher, H., Poggianti, B. M., and Sharples, R. M., 1997, ApJ 490, 577

Dressler, A., Oemler Jr., A., Sparks, W. B., and Lucas, R. A., 1994, ApJ 435, L23

González-González, J. d. J., 1993, Ph.D. thesis, University of California, Santa Cruz

Governato, F., Tozzi, P., and Cavaliere, A., 1996, ApJ 458, 18

Hubble, E. P., 1936, The Realm of the Nebulae, Yale University Press, New Haven

Jørgensen, I., Franx, M., Hjorth, J., and van Dokkum, P. G., 1999, MNRAS 308, 833

Kauffmann, G., 1996, MNRAS 281, 487

Kauffmann, G. and Charlot, S., 1998, MNRAS 294, 705

Kelson, D. D., van Dokkum, P. G., Franx, M., Illingworth, G. D., and Fabricant, D., 1997, ApJ 478, L13

Kormendy, J. and Bender, R., 1996, ApJ 464, L123

Kuntschner, H. and Davies, R. L., 1998, MNRAS 295, L29

Lacey, C. and Cole, S., 1993, MNRAS 262, 627

Lavery, R. J. and Henry, J. P., 1994, ApJ 426, 524

Moore, B., Katz, N., Lake, G., Dressler, A., and Oemler, A., 1996, Nature 379, 613

Poggianti, B. M., Smail, I., Dressler, A., Couch, W. J., Barger, A., Butcher, H., Ellis, R. S., and Oemler Jr., A., 1999, ApJ 518, 576

Saglia, R. P., Bertschinger, E., Baggley, G., Burstein, D., Colless, M., Davies, R. L., McMahan Jr., R. K., and Wegner, G., 1997, ApJS 109, 79

Saglia, R. P., Maraston, C., Greggio, L., Bender, R., and Ziegler, B., 2000, A&A, submitted

Salpeter, E. E., 1955, ApJ 121, 161

Sansom, A. E. and Proctor, R. N., 1998, MNRAS 297, 953

Smail, I., Dressler, A., Couch, W. J., Ellis, R. S., Oemler Jr., A., Butcher, H., and Sharples, R. M., 1997, ApJS 110, 213

Steinmetz, M. and Navarro, J. F., 1999, ApJ 513, 555

Valluri, M. and Jog, C. J., 1991, ApJ 374, 103

van Dokkum, P. G. and Franx, M., 1996, MNRAS 281, 985

van Dokkum, P. G., Franx, M., Kelson, D. D., and Illingworth, G. D., 1998a, ApJ 504, L17, van Dokkum, P. G., Franx, M., Kelson, D. D., Illingworth, G. D., Fisher, D., and Fabricant, D., 1998b, ApJ 500, 714

Worthey, G., 1994, ApJS 95, 107

Ziegler, B. L., Saglia, R. P., Bender, R., Belloni, P., Greggio, L., and Seitz, S., 1999, A&A 346, 13

Ziegler, B. L. and Bender, R., 1997, MNRAS 291, 527

Ziegler, B. L., Bower, R. G., Smail, I. R., Davies, R. L., and Lee, D., 2000a, MNRAS, submitted

Ziegler, B. L., Bower, R. G., Smail, I. R., and Davies, R. L., 2000b, MNRAS, submitted