MEASURING THE EVOLUTION OF THE MASS-TO-LIGHT RATIO FROM $z = 0$ TO $z = 0.6$ FROM THE FUNDAMENTAL PLANE

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Abstract. Galaxy evolution is probably a complex process. Mergers, infall, and starbursts may change galaxy properties systematically with time. As a result, the interpretation of the luminosity function is ambiguous, and information on the mass evolution of galaxies is needed. Such information can be retrieved from the evolution of the Tully-Fisher relation, Faber-Jackson relation, or the Fundamental Plane with redshift.

Observations of this kind have recently become possible. We present the Fundamental Plane relation measured for galaxies in the rich clusters out to $z = 0.58$. The galaxies satisfy a tight Fundamental Plane, with relatively low scatter (17%). The M/L ratio evolves slowly with redshift, $\ln M/L_V \propto 0.8z$. This result is consistent with simple evolutionary models if the bulk of the stellar population formed at high redshift.

It is not clear yet how these results can be made consistent with the rapid evolution of galaxies in intermediate redshift clusters as indicated by the Butcher-Oemler effect. Observations of post-starburst galaxies ("E+A" galaxies) indicate that these systems are dominated by disks. They may evolve into galaxies which are underrepresented in most "normal" Fundamental Plane samples.

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1. Measuring the evolution of mass: $F(M_*, z)$ or $F(v_c, z)$

Galaxy evolution may be a complex process, with possibly a large role for mergers, interactions, infall, and starbursts triggered by these events. Such processes complicate the interpretation of observations of high redshift galaxies, as galaxies can change rapidly in luminosity (due to starbursts), and can change morphology due to mergers, infall of gas, and enhanced star formation. The progenitors of certain types of galaxies at some redshift may be of different type at some other redshift, and their luminosities may be quite different.

In order to quantify these effects, more information is needed than the evolution of luminosity and color of galaxies, such as measured by the evolution of the luminosity function. Detailed information on the morphological evolution, and the evolution of the mass function is essential. The evolution of the mass function is possibly the most important, as it gives direct insight into the mass evolution of individual galaxies, and can directly determine when typical galaxies were assembled.

Unfortunately, the total masses of galaxies are notoriously difficult to measure. However, there exist good relations between circular velocity, and velocity dispersion, and photometric parameters: the Tully-Fisher relation for spirals (Tully & Fisher 1977), the Faber-Jackson relation (Faber & Jackson 1976), and the Fundamental Plane for early-types (Djorgovski & Davis 1987, Dressler et al. 1987). These relations are very suitable for evolutionary studies, because their intrinsic scatter is low at $z = 0$.

The general purpose of such observational studies will be a measurement of the evolution of the Tully-Fisher relation, Faber-Jackson relation, and Fundamental Plane with redshift. The combination of the observations with the evolution of the luminosity function of galaxies, can be used to constrain the evolution of the distribution of circular velocities $F(v_c, z)$, which is less sensitive to starbursts than the equivalent $F(L, z)$. Similarly, the stellar mass locked up in early type galaxies can be measured in a similar way. Such results will provide direct constraints on theories of galaxy formation and evolution.

2. Evolution of the Fundamental Plane

Here we present new results on a program to measure the evolution of the Fundamental Plane relation with redshift. Early results can be found in Franx (1993a,b, 1995). The Fundamental Plane is a relation between effective radius r_e, effective surface brightness I_e, and central velocity dispersion σ of the form $r_e \propto \sigma^{1.24} I_e^{-0.82}$ (e.g., Bender et al. 1992, Jørgensen et al 1996, JFK). Its scatter is low, at 17% in r_e (Lucey et al. 1991, JFK). The implication of the Fundamental Plane is that the M/L ratio of galaxies is well

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behaved (e.g., Faber et al. 1987). Under the assumption that galaxies are a homologous family, the implied M/L scaling is $M/L \propto r_e^{0.22}\sigma^{0.49} \propto M^{0.24}$. Such scaling is sufficient for the existence of the Fundamental Plane, and vice versa. The cause of the variation in M/L with mass is not well understood, but it is thought to be mainly due to variations in metallicity (see also, e.g., Renzini & Ciotti 1993).

Observations at higher redshifts will yield the evolution of the M/L ratio as a function of redshift. Below we explore the expected variation of M/L.

2.1. MODELS FOR THE EVOLUTION OF THE M/L RATIO

The luminosity of a co-eval stellar population is expected to evolve with time. Tinsley (1980) showed that the luminosity evolves like

$$L \propto 1/(t - t_{\mathrm{form}})^{\kappa}$$

where $\kappa = 1.3 - 0.3x$, and x is the slope of the IMF. The Miller–Scalo IMF implies $x = 0.25$, and $\kappa \approx 1.2$. Recent studies indicate that the value of κ depend on passband and metallicity (Buzzoni 1989, Worthey 1994). These authors find $0.6 < \kappa < 0.95$ for the V band.

To first order, this evolution implies that the M/L ratio evolves like

$$\ln M/L(z) = \ln M/L(0) - \kappa(1 + q_0 + 1/z_{\mathrm{form}})z,$$

where z_{form} is the formation redshift (Franx 1995). Hence the logarithm of the M/L ratio is expected to decrease linearly with redshift, and the coefficient depends on κ(IMF), q_0, and z_{form}. This equation is valid for $q_0 \approx 0$, and high z_{form}. The equation implies that the rate at which the M/L ratio decreases is a function of several unknown variables, and a direct interpretation of the observed decrease of the M/L ratio may not be very straightforward.

Fig. 1a shows the expected evolution of the L/M ratio if all galaxies form at the same redshift. As can be seen, the evolution depends strongly on the formation redshift. It is unlikely that galaxies formed in such a simple way. For Fig. 1b we explored models in which galaxies form at a range of redshifts. As a result, scatter is introduced in the L/M ratio, which increases with look back time. This is due to the fact that the relative age difference increases with look back time.

2.2. COMPLEX EVOLUTION

Even the last model is probably an over–simplification of the formation of early types. There is no good reason to assume that all stars in an early-type galaxy formed in a very short burst. A single galaxy may have had a

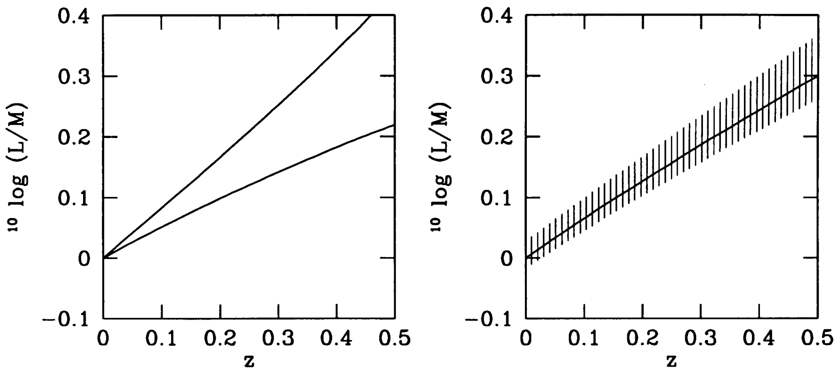

Figure 1. The evolution of galaxies with a simple star formation history. a) shows the luminosity evolution for galaxies with co-eval populations. Galaxies which formed recently evolve faster. b) the evolution of the mean L/M ratio for a sample of early-types which formed at a random time between $z = 1$ and $z = 2$. The scatter in the relation increases with redshift, as the relative age difference increases with lookback time.

complex formation history, with star formation extending over a long time. The evolution of the M/L ratio will be more complex if such age differences are taken into account.

We have created models in which early type galaxies form by transformation of galaxies with continuous star formation. It is assumed that the progenitors form stars in a continuous way, until a burst of star formation occurs, and the galaxies are transformed into non-star forming galaxies. These will appear as post starburst galaxies for another 1.5 Gyr, and then appear to be early types.

This type of evolution implies that the morphologies of galaxies evolve with time, from spiral, to post star burst galaxy, to early-type. This has important consequences, since the set of early-types at higher redshifts will be a special subset of the set of early-types at $z = 0$. If we select early-types at higher and higher redshift, we are selecting a subsample that is more and more biased towards the oldest early-types. In short, we may be selecting the oldest galaxies, and find that they are old.

The effect is illustrated in Fig. 2. Fig. 2a shows the typical evolution of 3 galaxies. The solid curve is the phase in which they appear as early-types. Clearly, the oldest early-types appear as early-type for the longest time. Fig. 2b demonstrates the effect on the observed L/M ratios of a large sample. At low redshifts, all galaxies appear as early types, and the evolution of the median L/M ratio remains normal. The scatter around the mean increases rapidly with redshift. Around $z = 0.2$, some of the galaxies appear as post star burst galaxies, and they would be excluded.

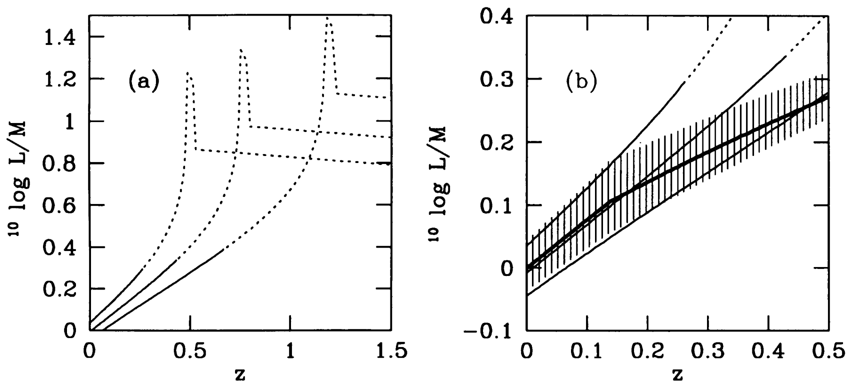

Figure 2. The evolution of galaxies which undergo three distinct phases: I — regular star formation in a disk, II — starburst, III — quiescent evolution. a) shows the luminosity evolution for three such galaxies. The galaxies are classified as regular early-types after 1.5 Gyr after the burst. This epoch is indicated by the solid curve. b) the evolution of the mean L/M ratio for a sample of early-types which formed in this complex way. The starburst is assumed to occur at a random time between $z = 0.5$ and $z = 2$. The thick line indicates the median L/M, the shaded area is bounded by the upper and lower quartile of the sample. The median L/M ratio bends at $z = 0.2$, as more and more galaxies drop out from the sample. The sample becomes more and more biased to the oldest early-types at higher redshifts.

The median L/M ratio is biased towards low values. This effects increases at higher redshifts. The bias is as strong as 30% at $z = 0.5$. As galaxies disappear from the sample, the scatter in the L/M ratio may decrease at higher redshifts.

2.3. THE FUNDAMENTAL PLANE IN CL0024+16 AT $z = 0.39$

CL0024 is a rich cluster at $z = 0.39$, and has been extensively observed (e.g., Dressler et al. 1985). We have obtained a deep, 19 hour integration at the MMT to measure the internal velocity dispersions of luminous galaxies in the cluster. *HST* images were used to measure the structural parameters of the galaxies. Full details of the observations and the analysis can be found in van Dokkum and Franx (1996).

Fig. 3a shows the resulting Fundamental Plane. There is a very clear relation, with relatively low scatter (15%). The slope is very similar to that for nearby cluster galaxies (e.g., JFK). In short, *early-type galaxies exist at $z = 0.4$ which are very similar to galaxies at $z = 0$.*

Fig. 3b shows the observed M/L ratios for Coma and CL0024 against the parameter $r_e^{0.22}\sigma^{0.49}$. The Fundamental Plane implies that galaxies lie along a line in the plot. We see a clear offset between the two data sets. The

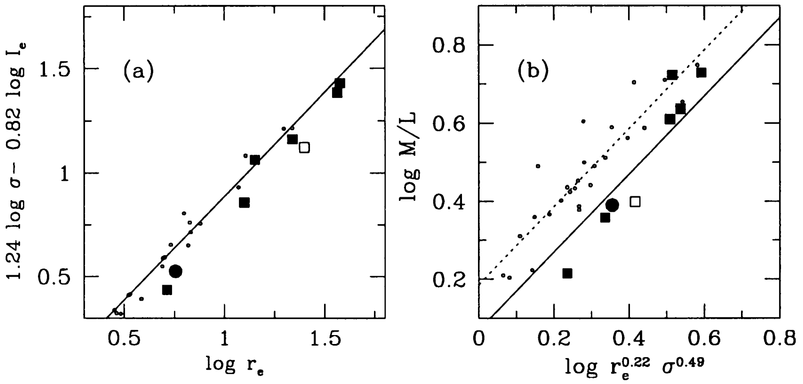

Figure 3. a) The Fundamental Plane for galaxies in CL0024+16 at $z = 0.391$ in the redshifted V band. The small symbols are galaxies in Coma. The Fundamental Plane in CL0024 is very similar to that in Coma, with similar low scatter (15%). b) The M/L ratio against $r_e^{0.22}\sigma^{0.49} \propto M^{0.24}$, for CL0024 and Coma. The lines are fits to the data points. The M/L ratio in CL0024 is lower by 31± 12%.

lines indicate fits to both data sets. The mean difference in the M/L ratio is 31%. The error is dominated by systematic effects, and is estimated at 12%. It is clear that the sample for CL0024 is biased towards the most massive galaxies, and this selection bias is partly the cause for the systematic uncertainty.

3. Using Keck to extend to $z = 0.58$

With modern telescopes and efficient instrumentation it is possible to extend the Fundamental Plane work out to higher redshifts. We have recently used Keck to measure the Fundamental Plane in two clusters at $z = 0.33$ and $z = 0.58$, CL 1358+65 and MS 2053-05 respectively. A full description can be found in Kelson et al. (1997). Typical integration times were 2 hours on the Keck telescope. Fig. 4a shows the resulting Fundamental Planes from $z = 0$ to $z = 0.58$. The figure demonstrates how well the relation is defined at each redshift interval.

Surprisingly, the scatter in the relation remains low. We have now 22 galaxies with Fundamental Plane parameters, and we find a scatter of 17%. This is quite comparable to the scatter in nearby rich clusters.

The evolution of the M/L_V ratio is shown in Fig. 4b. The data are consistent with a slow evolution of $\ln M/L_V \propto 0.8z$. Both the low evolution, and the small scatter are consistent with high formation redshifts for cluster early types ($z_{\rm form} > 2$).

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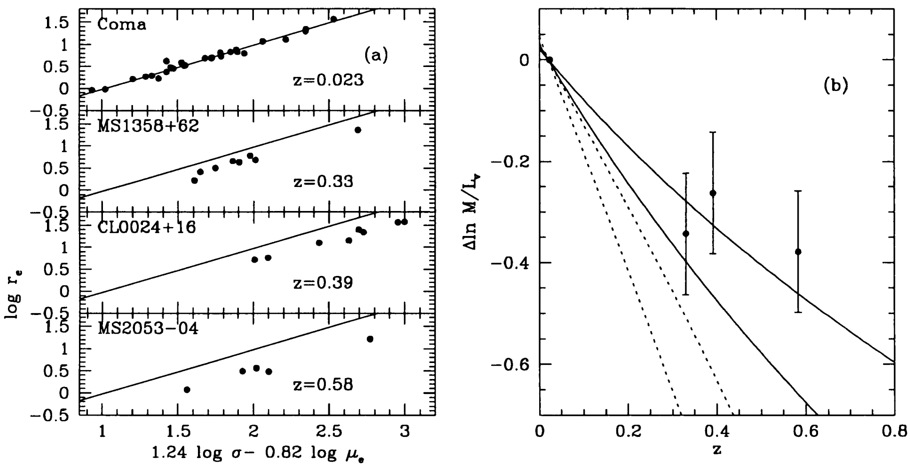

Figure 4. The evolution of the Fundamental Plane from $z = 0$ to $z = 0.58$, based on data from Kelson et al 1997. Panel a) shows the individual Fundamental Plane for the clusters. The solid line is the relation for Coma. The offset is mostly due to surface brightness dimming. Panel b) shows the evolution of the mean M/L_V ratio, after correction for surface brightness dimming ($q_0 = 0.5$). The M/L_V ratio decreases slowly with redshift. The solid lines indicate stellar population models with formation redshifts of ∞. The dashed lines indicates models with a formation redshift of 1. The data are consistent with high formation redshift. The datapoints move downward if lower values for q_0 are used.

4. How about the Butcher–Oemler effect and E+As?

It has been well established that distant clusters have a high proportion of blue members (Butcher & Oemler, 1984). Furthermore, some galaxies have post starburst spectra (Dressler and Gunn, 1983, 1992). These galaxies have spectra which can be modeled as the superposition of a young component and an old component, and were named "E+A" by Dressler and Gunn. The "E" stands for early type, and "A" for A-star. These galaxies were defined to have no emission lines, i.e., little or no star formation. The population models invoked a peak in the star formation rate 1 Gyr before their light was emitted, and a subsequent drop in the star formation rates.

The relatively high fraction of such post starburst galaxies in clusters, and the short lifetime of the phenomenon implies that many galaxies in clusters underwent such a phase at intermediate redshifts. Is this consistent with the slow evolution and high formation redshift indicated by the Fundamental Plane?

To answer this question, it is necessary to determine the morphologies of the "E+A" galaxies. This can be done on the basis of imaging and kinematics. We discuss two samples below.

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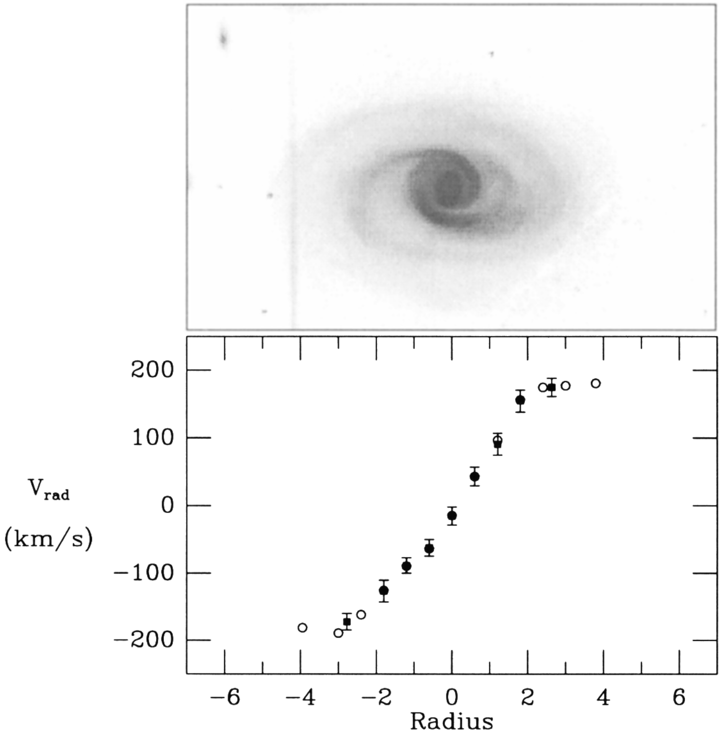

Figure 5. A bright E+A galaxy in Abell 665 at $z = 0.18$. The upper panel shows the *HST* image. The galaxy has smooth spiral arms, without regions of star formation. The lower panel shows the rotation curve of the galaxy, at the same scale. The galaxy is dominated by rotation at large radii. This E+A galaxy has virtually no bulge.

4.1. A GROUP OF E+A GALAXIES IN ABELL 665 AT $z = 0.18$?

Abell 665 contains a very bright, blue E+A galaxy. It was included by chance in the study of the kinematics of cluster members (Franx 1993a,b). The rotation curve of the galaxy proved that the galaxy was supported by rotation, and that it was likely a disk. Recent *HST* imaging has confirmed this. Fig. 5 shows the *HST* image, in combination with the rotation curve. The galaxy is strongly dominated by the disk, and has a very small bulge. It shows weak, smooth spiral arms, without any signs of star formation. The colors along the arms are also very smooth. The rotation curve is typical of a disk, and symmetric.

These data demonstrate that the galaxy is a disk. It will probably evolve into a disk dominated S0, given the lack of star formation. We notice that the optical morphology is very rare in the nearby universe: smooth spiral arms without star formation. This may be related to the recent cutoff in star formation.

There are two galaxies with the same morphology very close to the E+A in Abell 665. Furthermore, there is a fourth galaxy with strong star formation in the same area. This suggests that the other two galaxies might have similar E+A spectra, and that the fourth galaxy is still in the star forming stage – possibly shortly before the cutoff? Clearly, spectroscopic confirmation is required. The data are very suggestive that we are dealing with a small group of galaxies that are undergoing the transformation from the star formation phase into a early type phase.

The mechanism of the transformation is not clear: it could be triggered by the small group itself, or it could be triggered by infall into the rich cluster. It is clearly not triggered by a major merger, as such a merger would not produce disk dominated galaxies. Minor mergers, or tidal interactions, can certainly not be ruled out.

4.2. E+A GALAXIES IN CL 1358+65

We have obtained a large *HST* mosaic of 7x7 arcmin on the cluster CL 1358+65 at $z = 0.33$. We have spectra of 190 cluster members in the mosaic, and have selected E+A galaxies on the basis of this spectroscopy. Again, as in Abell 665, the E+A galaxies are disk dominated. Some of the galaxies have very strong Balmer lines, with a mean equivalent width of $\langle H_{\beta,\gamma,\delta} \rangle \approx 8$ Å. The colors are generally smooth across the galaxies, indicating that the young component is smoothly distributed. More detailed spectroscopy is needed to characterize the galaxies better. This will be presented in Franx et al, in preparation.

4.3. WHERE DO E+AS GO?

The above evidence implies that E+As may evolve into disk dominated S0s. We have to note that we cannot be certain about this: the E+As may also be in groups which merge to form ellipticals, or bulge dominated S0s. We can think of several ways to explain the low evolution and low scatter in the Fundamental Plane and the evidence for recent bursts and star formation from E+As:

1. The E+As may evolve into disk dominated S0s which are under-represented in the current sample for the Fundamental Plane.

2. The E+As may have generally low central dispersions, and such galaxies are usually excluded from Fundamental Plane analysis.

3. The stellar population models may need to be adapted.

4. The E+As may merge with older systems so that the influence of the burst is "diluted".

More studies based on larger samples are needed to distinguish between these possibilities. Such studies are now in progress.

5. Discussion

We have shown that it is possible to determine the Fundamental Plane at intermediate redshifts, all the way up to $z = 0.58$. The relation is well defined at these redshifts, with a relatively low scatter of 17%. The mean evolution of the M/L_V ratio is low, at about 45% at $z = 0.58$. This evolution is consistent with an early star formation epoch for our galaxies. We note, however, that the current measurement may be biased, mostly due to the fact that we only use non-star forming red galaxies. We may therefore exclude the star forming progenitors of current-day early type galaxies.

We have analyzed the structure of E+A galaxies in our program clusters. We find that most of our E+As are strongly disk dominated. They would likely evolve into strongly disk dominated S0s, unless they merge with other galaxies. It is still not quite clear how to explain the low scatter in the Fundamental Plane on the one hand, and the high fraction of E+As on the other hand. It is possible, however, that most of the E+As have a low central velocity dispersion, and are mostly omitted from Fundamental Plane samples in nearby clusters.

These observations demonstrate that information on galaxy masses can be obtained from deep, ground based spectroscopy. The next step is to extend this work to higher redshift, and to the field. Furthermore, similar studies have demonstrated that the Tully-Fisher relation can be used (Vogt et al 1996, Rix, Colless, & Guhathakurta 1996). The new generation optical telescopes will allow a rapid extension of this type of work to larger samples, higher redshifts, and lower galaxy masses.

Eventually, these observations can be used to determine the evolution of the distribution of circular velocities for galaxies $F(v_c, z)$, and the evolution of stellar masses locked up in early type galaxies $F(M_*, z)$. This requires accurate observations of the evolution of the luminosity function and the "mass relations" in the field. The final outcome of such a program can be expected to provide strong constraints on the models of galaxy formation and evolution.

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