Masses and Mass-to-Light Ratios of Early-Type Galaxies at High Redshift – The Impact of Ultradeep FORS2 Spectroscopy

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With FORS2 on the VLT we obtained ultradeep spectra of a sample of early-type galaxies at $z \sim 1$, which, together with high-resolution imaging from HST, provide dynamical masses. We study the evolution of the multi-wavelength photometric Fundamental Plane, including the rest-frame near-infrared, which places strong constraints on the formation and evolution of early-type galaxies as a function of mass and environment. Most prominently, we find that massive early-type galaxies formed early (at $z > 2$), independent of their large-scale environment.

Spectroscopy of distant galaxies is a major focus of today's large telescopes. For $z \approx 1$ or less, the exposure time to obtain a redshift measurement is typically less than an hour. Hence, with the currently available instruments, it is possible to measure redshifts of thousands of galaxies in order to determine galaxy number densities, luminosity functions and clustering properties, and the evolution thereof with cosmic time. Although redshift is a useful piece of information, it is insufficient to infer the physical properties of an individual galaxy. Arguably, the single most important quantity is mass, or mass-to-light ratio (M/L), which provides direct insight into the build-up of the galaxy mass-function over cosmic time. Mass-related quantities can be unambiguously compared with model predictions, contrary to luminosities and colours. In order to measure galaxy masses, high signal-to-noise ratio (S/N) spectra are required: from the spatial and dynamical structure of spectral features, information about the galaxies' gravitational potential can be inferred. This requires the selection of relatively bright galaxies at moderate redshifts ($z \approx 1$) and long integration times.

In this article we describe an observational programme at the VLT which was used to obtain 8–24-hour deep spectroscopic observations of early-type galaxies up to $z = 1.3$. These long integrations enabled us to obtain two new results. We measured the rate of luminosity evolution of early-type galaxies out to $z = 1.3$, constraining their formation epoch. We describe how this depends on environment and galaxy mass, and how this compares to model predictions. Second, we compared the evolution of optical colours and M/L with the evolution in the rest-frame near-infrared, derived from observations from the Spitzer Space Telescope. This provides insight into the applicability of IR light as a mass indicator and a test for stellar population models.

The Fundamental Plane at $z = 1$

The Fundamental Plane (FP) is a relation between size, surface brightness and stellar velocity dispersion for early-type galaxies (see Figure 1). From the virial theorem it can be seen that this scaling relation in fact represents an underlying relation between M and M/L. The evolution of M/L (or L) with redshift can therefore be traced by measuring the offsets of distant galaxies from the local FP. Since the scatter in the FP is relatively small, the offset can be determined accurately. For massive early-types in dense environments (i.e., clusters) it has been known for several years that they have decreased in luminosity since $z = 1$ by a little over 1 magnitude in the optical. Assuming that such galaxies have evolved passively between the epoch of observation and the present, this rate of luminosity evolution implies that their stars must have formed at rather high redshifts ($z > 2$).

An important issue is whether the epoch of early-type galaxy formation depends on large-scale environment, or whether it is driven by the intrinsic properties of the galaxies themselves and their immediate neighbourhood. Up to several years ago, galaxy formation models very generally suggested that early-type galaxies in low-density environments (the field) form their stars at later times than early-types in clusters. More recent models, on the other hand, indicate that the mass of a galaxy itself is a crucial parameter in describing its evolution and that no large differences between massive field and cluster galaxies are to be expected.

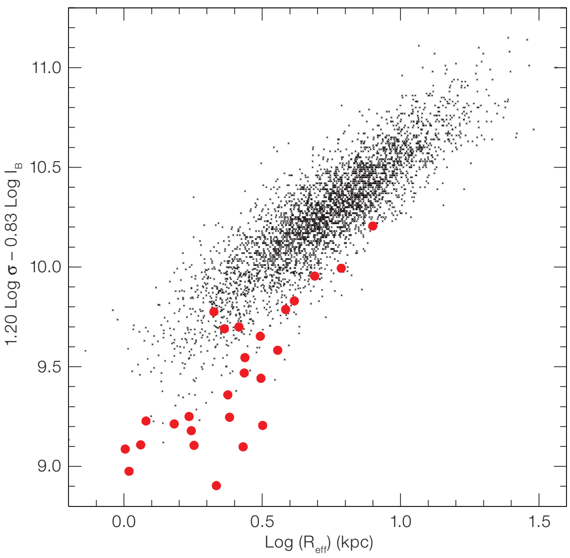

Figure 1: The edge-on projection of the FP of low-redshift early-type galaxies from SDSS (small black dots) and our sample of $z \sim 1$ early-types (large red dots). There is a clear offset between the two samples, indicating that there is significant luminosity evolution between $z = 1$ and the present.

A crucial test is to measure the rate of luminosity evolution for galaxies in different environments, as age differences manifest themselves in differential evolution. Before our observing programme was undertaken, it was unclear whether or not the luminosities of galaxies in the field evolve differently from the luminosities of galaxies in clusters. Our programme mainly aimed at measuring masses of field early-type galaxies at $z = 1$, because the field samples thus far had been of lesser quality (smaller numbers, lower data quality and lower redshift) than the cluster samples.

With FORS2 we targeted the Chandra Deep Field-South (CDF-S), which has been imaged by the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST). These imaging data are essential for selecting $z \sim 1$ galaxies with early-type morphologies, and to determine their sizes and surface brightnesses (two of the FP parameters). Besides the CDF-S, we also targeted a field containing the high-redshift ($z = 1.24$) cluster RDCS 1252.9-2927 (hereafter, CL1252). This field has been imaged by ACS as well.

The spectroscopic observations were carried out between September 2002 and October 2003, in a series of five runs. Since the spectral features suitable for our analysis are situated in the rest-frame optical, and we target galaxies up to $z = 1.24$, we needed to measure the spectra as far toward the red as possible, at wavelengths of about 850 nm, where FORS2 is very sensitive.

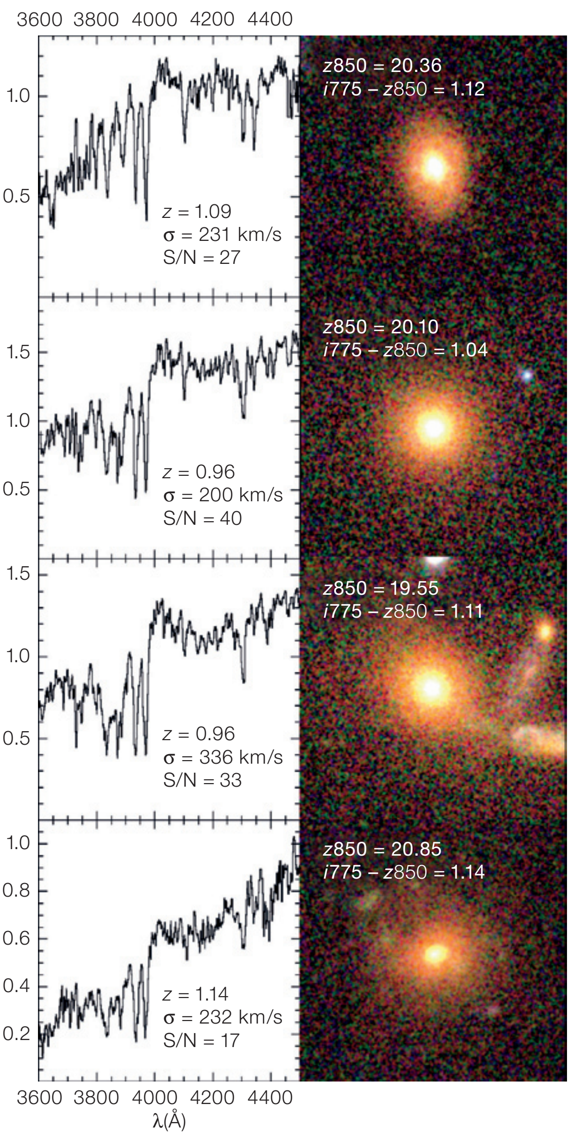

Figure 2: VLT/FORS2 spectra and HST/ACS colour images of four field early-type galaxies at $z \sim 1$. The images, which are 5.4″ (43 kpc at $z = 1$) on a side, are a combination of F606W, F775W, and F850LP ACS images.

The obtained spectra are of outstanding quality. In particular, the S/N of the spectra of the CL1252 cluster members is unprecedented after 24 hours of integration with a typical seeing of 0.65″. The integration times for the galaxies in the CDF-S are typically 10 hours, with a typical seeing of 0.9″. In Figure 2 we show four examples of VLT spectra and HST images of $z \sim 1$ field early-type galaxies. The spectra clearly show that the stellar populations of these galaxies are several billion years old, although there are age differences among these galaxies: the $z = 1.09$ galaxy is the youngest, which can be seen from the strong high-order Balmer lines. For the other three galaxies, there is a clearer 4000 Å break, indicative of evolved stellar populations without significant star formation for at least a billion years before the epoch of observation. The smooth, concentrated morphologies of the images indicate that these are genuine early-type galaxies. A de Vaucouleur model fits best to the surface-brightness profiles. These deep spectra are used to compare the widths of absorption features with those in stellar spectra in order to obtain velocity dispersions of the stars in the galaxies, measuring the third FP parameter. We measured 42 velocity dispersions of galaxies in the redshift range $0.62 < z < 1.25$. Four of these are cluster early-type galaxies at $z = 1.24$, (Holden et al. 2005) and 20 are field early-type galaxies at $0.95 < z < 1.15$ (van der Wel et al. 2004, 2005).

Our field sample is of similar size and quality as the cluster samples, such that we can properly compare the evolution of field and cluster early-types. The offset of $z \sim 1$ field early-type galaxies from the local Fundamental Plane is shown in Figure 1. We find that this offset of the $z \sim 1$ field early-types corresponds to a luminosity evolution of almost 2 magnitudes in the B-band. This is significantly larger than for cluster early-types, which are about 1.4 magnitudes brighter at $z = 1$ than at $z = 0$. This apparently agrees with

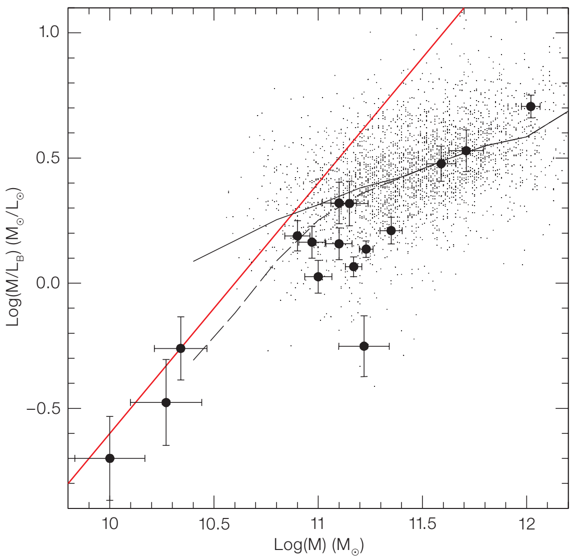

Figure 3: M versus M/L for the $z \sim 1$ field galaxies (large circles) and local galaxies from SDSS corrected for luminosity-evolution to $z = 1$ (small dots). The red line indicates the luminosity limit of our survey. The solid black line shows the relation between M and M/L_B for the SDSS galaxies. The dashed black line indicates the same relation for the SDSS galaxies, but only including those that are brighter than the $z = 1$ luminosity limit.

the model prediction that field early-types are younger than cluster early-types. However, the galaxies in the field sample are on average less massive than those in the cluster samples. If only massive galaxies (with $M > 2 \times 10^{12}\ M_\odot$) are selected, there is no difference between the field and cluster samples: the luminosity evolution amounts to about 1.3 magnitudes, implying high formation redshifts ($z > 2$) for massive early-type galaxies in either environment, falsifying the prediction by some models that there is a large age difference between field and cluster galaxies.

As was suggested above, there is a difference in luminosity evolution between high- and low-mass early-types. Indeed, galaxies with masses $M < 2 \times 10^{12}\ M_\odot$ are 2.1 magnitudes brighter at $z = 1$ than at $z = 0$, which is much more than the 1.3 magnitudes brightening inferred for massive galaxies. This is illustrated in Figure 3, where we show that high-mass galaxies have higher M/L than low-mass galaxies, and that the observed relation between M and M/L for the $z \sim 1$ field galaxies clearly differs from the equivalent relation at $z = 0$. Other workers in this field have, independently, also found such a strong relation (Treu et al. 2005; Di Serego Alighieri et al. 2005). This change in slope might indicate that the mass of an individual galaxy determines its formation redshift. The idea that massive galaxies form earlier than low-mass galaxies is referred to as down-sizing and is supported by other observational evidence besides the FP results described here, and can be reproduced by recent theoretical models.

However, selection effects severely hamper data sets such as these. Our magnitude-limited sample, at a given galaxy mass, is biased towards galaxies with low M/L, i.e., young stellar populations. Obviously, this effect is strongest for low-mass/faint galaxies. We show the luminosity limit of our survey in Figure 3 by the red line. It is clear that the galaxies with the lowest M/L are likely not representative of all early-type galaxies with such masses. Considering the distribution of luminosities and M/L of the galaxies in our sample and the magnitude limit of the survey, we conclude that the described bias is the main cause of the observed differential evolution of galaxies with different masses. But even if this selection effect is taken into account, we still find a mass-dependent evolution in M/L, although it is reduced to a very subtle effect (see also Figure 3).

Di Serego Alighieri et al. (2005) use a *K*-band selected sample, and also find a steep relation between M and M/L. This shows that selecting galaxies by their *K*-band luminosity is very different from selecting by stellar mass (see also the next section). We note that Treu et al. (2005) claim that selection effects cannot account for the steep observed slope and $z = 1$, and that the strongly mass-dependent evolution of M/L is largely intrinsic. Remarkably, they find an equally steep slope for all redshifts $z > 0.3$, implying a sudden steepening between $z = 0.3$ and the present, and no evolution after that. We conclude that even deeper surveys, probing the early-type galaxy population to lower masses, are needed to determine, in a model-independent way, whether the FP slope has or has not evolved strongly over the past 7 Gyrs.

The evolution of the rest-frame near-IR properties of early-type galaxies

As is clear from the above, obtaining masses of high-z galaxies dynamically is observationally extremely expensive. It is therefore not feasible to obtain masses of very large samples in order to measure the evolution of quantities such as the total mass density of the galaxy population. Such measurements necessarily rely on mass estimates based on photometric properties. These estimates are derived from stellar population models that predict how colours and M/L depend on each other. To verify the robustness and accuracy of this method, the correspondence between models and observations of the evolution of colours and M/L needs to be tested. With our dynamically determined M/L we are in a position to perform such a test.

First, it is important to note that there is a strong correlation between the dynamically obtained M/L and the rest-frame optical colours of the galaxies in the $z \sim 1$ sample presented above (van der Wel et al. 2005). Furthermore, in Figure 4 we show that the evolution in the rest-frame $B-I$ colour generally agrees well with the predictions of stellar population models: assuming a single stellar population with solar metallicity and a Salpeter IMF, the evolution in M/L_B implies a certain amount of evolution in $B-I$. The expected $z = 1$ colours are indicated for three different models in Figure 4 by the coloured squares. This indicates that the methodology of converting colours into M/L is viable.

Next, it is especially interesting to include the near-infrared (NIR) in the analysis, as this is much less sensitive to extinction by dust, and probably less affected by recent and ongoing star-formation. In other words, NIR light is thought to be more representative of stellar mass than optical light. It should be noted, however, that various results in the literature have already indicated that the NIR photometric properties of galaxies are rather poor indicators of their ages and M/L, contrary to their optical colours. To investigate this matter, we use Spitzer/Infrared Array Camera (IRAC) images at 3.6 μm and 4.5 μm to determine the optical-to-NIR colours of our $z = 1$ galaxies. We compare those with the rest-frame colours of local early-types. In Figure 5 we show that the evolution in the rest-frame *B–K* colour is about 0.3 magnitudes between $z = 1$ and $z = 0$ (van der Wel et al. 2006). In Figure 5 we make a similar comparison as in Figure 4. First, it is very remarkable that the predictions differ by much from each other. Second, the most widely used model, that of Bruzual and Charlot (2003), predicts much faster evolution of *B–K* than observed. The Vazdekis (1996) and Maraston (2005) models provide better agreement.

We have tested whether our result can be reconciled with the Bruzual-Charlot model by adopting different metal contents, stellar initial mass functions and more complex star-formation histories, but it turns out that the discrepancy persists. Large quantities of dust in the high-*z* sample may affect the *B–K* colours such that slow evolution of *B–K* is mimicked. Spitzer/MIPS photometry at 24 μm will be a useful test to constrain the dust content. However, the red colours are most likely intrinsic to the stellar populations of the galaxies.

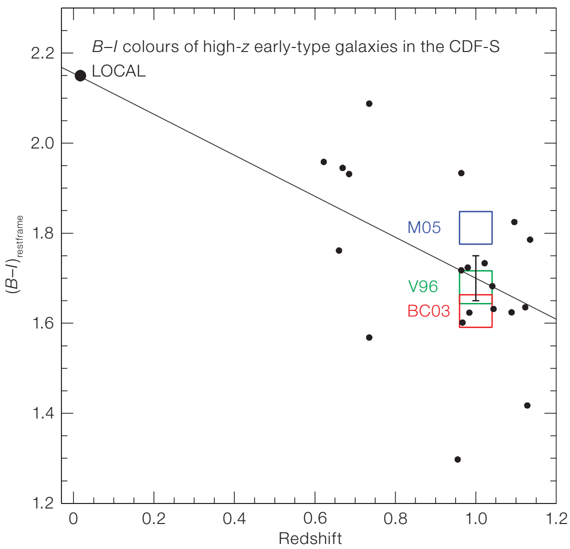

Figure 4: Evolution of the rest-frame *B–I* colour of early-type galaxies. The observed evolution is about 0.45 mag. The error-bar shows the uncertainty in the measured evolution. The coloured squares are model predictions for *B–I* at $z = 1$. The three different colours indicate different stellar population models. From top to bottom: Maraston (2005), Vazdekis (1996), and Bruzual & Charlot (2003). These models are for single stellar populations with a Salpeter IMF and solar metallicity.

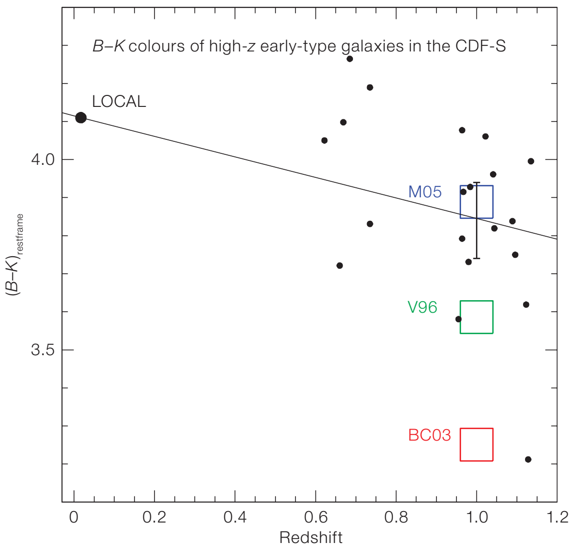

Figure 5: Evolution in the rest-frame *B–K* colour of early-type galaxies. The observed evolution is about 0.3 mag. The error-bar shows the uncertainty in the measured evolution of the sample. The coloured squares are model predictions for *B–K* at $z = 1$ (see Figure 4).

We conclude very generally that estimating galaxy masses from rest-frame NIR photometry is not very robust. First, the M/L in the NIR evolves at a comparable rate as the optical M/L, which means that the NIR magnitude of a galaxy is not a better indicator of its M/L than its optical magnitude (this is at least true for dust-poor galaxies). Second, the disagreement among the models indicates that there is a systematic uncertainty in the M/L as derived from NIR photometry of at least a factor of two for this type of galaxy. More specifically, the systematic difference between the observations and the Bruzual-Charlot model implies that M/L as derived from NIR photometry and this model are a factor of ≈ 2 too high. This is a severe problem. For example, the evolution in the mass density of early-type galaxies is about the same factor of two between $z = 1$ and the present. The agreement among the models and between the models and the observations are much better in the optical, which should therefore be preferred over the NIR to estimate M/L. Before we can take advantage of the full potential of rest-frame NIR observations, the models need to converge to similar predictions that can stand empirical tests such as described here.

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