

Chemical and mass evolution of galaxies

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Abstract. An introduction is given to projects investigating galaxy evolution quantitatively by spectroscopic observations of very distant galaxies that have weak apparent brightnesses and small sizes as it is feasible with 10m-class telescopes like SALT. Such methods encompass scaling relations like the Tully–Fisher and Fundamental Plane relations that can be utilized to determine the luminosity evolution and mass assembly of galaxies. The stellar populations can be analyzed with respect to age, metallicity, and chemical enrichment by measuring absorption line strengths. Possible effects on galaxy evolution of the environment in rich clusters of galaxies compared to the field are also addressed. For each method, recent applications are presented like the evolution of the TFR determined with 77 field spirals up to $z = 1$, a study of the internal kinematics of distant cluster spirals and a comparison of the stellar populations of ellipticals in the field and in rich clusters at $z = 0.4$.

1. Introduction

In the local Universe we see a variety of galaxy types that can be distinguished both by their morphology and their internal kinematics. The two main families are the spiral galaxies in which stars and gas rotate around the center in a disk and the elliptical galaxies that are gravitationally stabilized by the random motion of the stars within a triaxial body. Some kind of intermediate class are the lenticular or S0 galaxies with central bulges surrounded by disks. In addition, we observe irregular galaxies with many different structures.

One of the main tasks of extragalactic research is to understand why the galaxies appear in such different types. Is the structure of a galaxy already fixed at the time of its formation? Or does it change during the time of its evolution and is it subject to external influence? The vastly accepted paradigm of galaxy formation is nowadays the theory of the hierarchical growth of all structure in the Universe. Large galaxies are built up via the merging of smaller systems. In such events, the disk structure of the progenitors is transformed into a spheroidal shape. An important ingredient of the theory is the dominance of cold dark matter and the main prediction is that the total mass of galaxies is growing during the evolution.

A first step to quantify galaxy evolution is to study the luminosity of galaxies up to high redshifts with deep photometric observations. Well-known deep imaging are the Hubble Deep Fields (Williams et al. 1996; Casertano et al.

2000) but their major drawback is their very small field size. Therefore, the FORS consortium¹ made the effort to observe a comparable deep but larger field with the FORS instrument at the VLT. Consuming some 72 hours pure integration time, deep images were taken in the *UBgRIz* filters, supplemented by *J* and *K* near-infrared exposures with the NTT (Heidt et al. 2003). With the aid of photometric redshifts, number counts and luminosity functions can be constructed up to redshifts $z \approx 5$ in this FORS Deep Field (FDF; Gabasch et al. 2004).

But a more robust test of the Cold Dark Matter theory would be the measurement of the mass and size of distant galaxies, because the brightness of galaxies is subject to star formation processes. A rather quiescent luminosity evolution of the stellar population of a galaxy can get quickly wiped out by any contemporary star burst even if it involves only a small fraction in mass. From pure photometry it is very difficult to judge whether any galaxy within a sample is undergoing such an event.

With 10m-class telescopes it is nowadays possible to take spectra with sufficient spectral and spatial resolution of faint galaxies down to $\sim 23R$ mag reaching the necessary S/N within reasonable exposure times. Analyzing spectral lines, the characteristic velocity of the stars and gas within a galaxy can be determined which is a measure for its total mass. For elliptical galaxies, the width of absorption lines reflects the internal velocity dispersion, while for spiral galaxies, the Doppler shifts of emission lines trace the rotational speed. The characteristic size of distant galaxies can be determined in spatially highly resolved images as they can be obtained either with the HST or groundbased telescopes equipped with adaptive optics. Important tools for the quantitative investigation of galaxy evolution are scaling relations because entire samples of galaxies can be compared with each other rather than just individual galaxies. Such scaling relations are, for example, the Fundamental Plane of ellipticals (e.g. Bender, Burstein, & Faber 1992) or the Tully–Fisher relation (TFR) of spirals (e.g. Pierce & Tully 1992 [PT92]).

2. Evolution of the Tully–Fisher relation

As one example, the TFR of galaxies up to $z \approx 1$ corresponding to a lookback time of ~ 8 Gyr or half the age of the Universe² is shown in Figure 1. Only emission–line galaxies that exhibit a rotation curve (RC) which turns into a flat regime with constant velocity are suitable for display in such a TF diagram. The maximum rotational speed (v_{\max}) in such a case is then a measure for the total mass of the galaxy including its Dark Matter. Distant galaxies impose difficulties on the analysis of RCs not only due to their faintness but because their small sizes limit strongly the spatial extent of any emission line. From a sample of 113 spirals in the FDF, we were able to determine v_{\max} for 77 galaxies with $0.1 \leq z \leq 1$.

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²The “concordance” cosmology is used with $\Omega_{\text{matter}} = 0.3$, $\Omega_{\lambda} = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

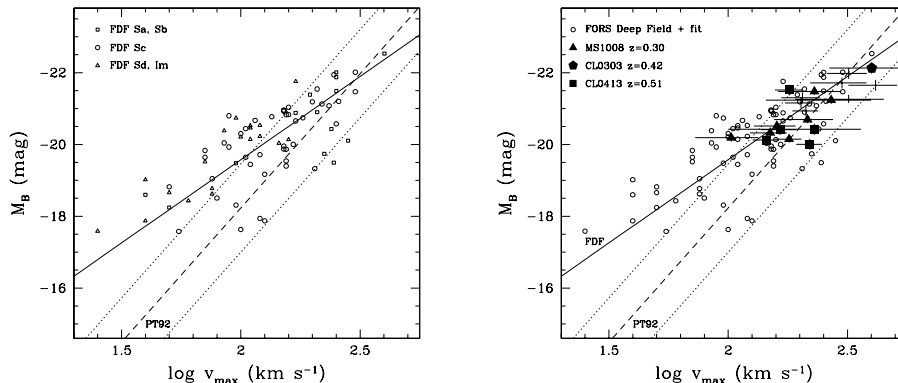


Figure 1. Panel a) The TFR of 77 distant FDF field spirals compared to the local relation ($\pm 3\sigma$) from [PT92]. The distant sample is subdivided into types Sa & Sb, Sc, and Sd & Im. Panel b) 13 galaxy members of distant clusters overplotted on the FDF field sample.

Comparing the restframe B magnitudes for fixed v_{\max} between the distant FDF sample and a local sample by PT92, we find a substantial increase in the luminosity for small galaxies but very similar brightnesses for large ones (Ziegler et al. 2002; Böhm et al. 2004). Such a mass-dependent evolution is not easily explained by CDM theory since it involves the modeling of stellar populations. First simulations indicate that the efficiency, strength and duration of star formation in a galaxy may depend on its total mass. For a better understanding, spectroscopic observations of many more distant galaxies are needed, too, as it will be possible with SALT. This becomes even more obvious when we try to subdivide the emission-line galaxies into different types as in Figure 1a. Looking into such subsamples will allow to investigate the impact of varying global parameters like star formation rates or mass-to-light ratios.

3. Environmental dependence of galaxy evolution

Looking at the distribution of different galaxy types, it becomes obvious that the average mean distance between galaxies must play a role in shaping a galaxy's structure. This morphology-density relation manifests itself most clearly in the prevalence of early-type galaxies in the center of rich clusters of galaxies (Dressler 1980). At the same time, interactions between cluster galaxies and the hot X-ray emitting intracluster gas or the cluster potential indicate phenomena specific to clusters (e.g. van Gorkom 2003). We also observe evolution in the galaxy population of clusters, i.e. the mixture of the various types. Distant clusters at $z \approx 0.5$ have, for example, a greatly reduced fraction of S0 galaxies that dominate the bright population locally while the number of ellipticals stays nearly constant (Dressler et al. 1997). These findings have provoked the question whether field spirals falling into a cluster could get transformed into S0 galaxies during the time due to clusterspecific processes. Another environmental dependence is given for the global star formation as it is observed to be largely

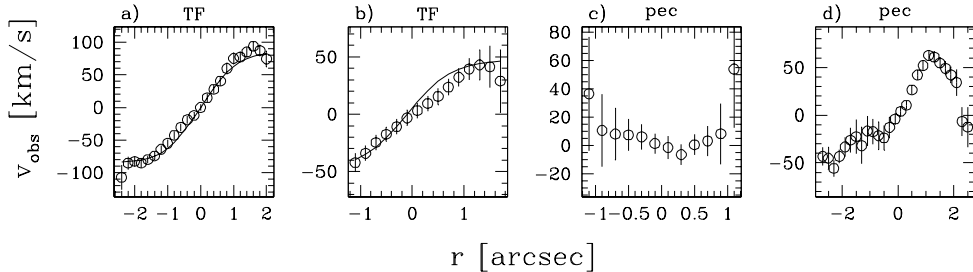


Figure 2. Examples of rotation curves of galaxies in distant clusters. Panels a) and b) represent RCs turning into a flat part where v_{max} can be measured by modeling the synthetic velocity field (solid line). Panels c) and d) display peculiar velocity curves.

suppressed in cluster members (e.g. Gómez et al. 2003). Investigating galaxies in densities intermediate between the field and cluster environments reveals that at least two different interaction processes on different timescales must be responsible for transforming galaxy structure and suppressing star formation, respectively (e.g. Balogh et al. 2002).

Interactions can also affect a galaxy’s internal kinematics creating asymmetric RCs, for example, or totally corrupted velocity fields (e.g. Rubin, Waterman, & Kenney 1999). In a Universe with hierarchically growing structure, it is predicted that the galaxy merger rate and frequency of infalling galaxies increases with redshift. Observations should therefore investigate the internal kinematics of galaxies in clusters up to $z \approx 1$ as it is now possible with the big telescopes like SALT. Indeed, spirals in clusters with $0.3 < z < 0.6$, which we studied with FORS, display peculiar RCs (Figure 2; Ziegler et al. 2003). On the other hand, several cluster members have undistorted RCs with an outer flat part. These galaxies can be compared to field galaxies in a TF diagram allowing to investigate whether they might be under- or over-luminous for their measured v_{max} . Truncation of star formation in a cluster member leads to a dimming, whereas interaction-induced star bursts results in a brightening of the galaxy. Our cluster targets are distributed very similar to the distant FDF spirals, so that their stellar populations are momentarily not suspect to any changes (Figure 1b). But it may well be that those galaxies with distorted RCs in our sample have star formation rates which got affected by the same interaction process that produced the kinematic peculiarity. Much larger samples of distant cluster galaxies are needed to robustly investigate these issues.

4. Evolution of the stellar populations

Another important tool next to scaling relations for the quantitative measurement of galaxy evolution are diagnostic diagrams where absorption line strengths are plotted versus each other and compared to a model grid. A widely used application is the Lick/IDS system, in which Balmer lines (in particular $H\beta$) are taken as age sensitive indicators whereas the metallicity ($[Z/H]$) is measured by

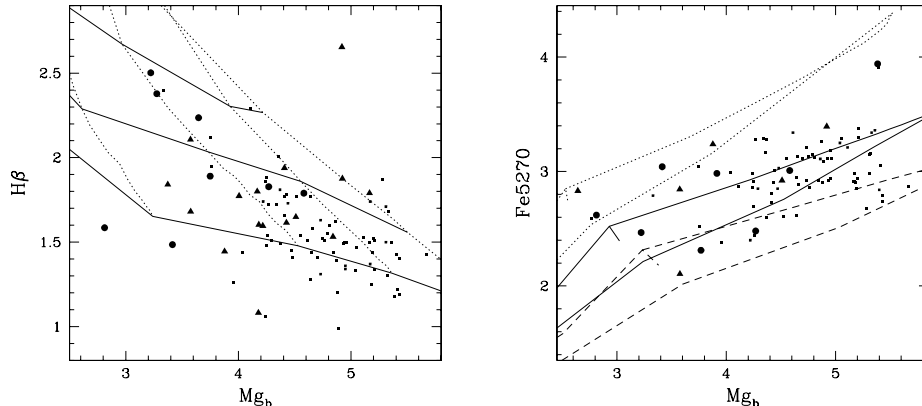


Figure 3. Panel a) Age-metallicity diagram for field (circles) and cluster (triangles) ellipticals with $\langle z \rangle \approx 0.4$ compared to a sample of Coma cluster galaxies (small squares; from [K01]). Overplotted are [TMB03]-models enhanced in Mg ($[Mg/Fe] = 0.3$) with ages 1, 5 & 15 Gyr (solid lines, top to bottom) and $[Z/H] = -0.3, 0, 0.3, 0.7$ (dotted lines, left to right). Panel b) The same samples with models separated by $[Mg/Fe] = 0, 0.3, 0.5$ (top to bottom).

combining Mg and Fe lines (e.g. Faber et al. 1985). More sophisticated stellar population models can nowadays also distinguish between different enrichment histories for various elements and are no longer fixed to the solar abundance (e.g. Thomas, Maraston, & Bender 2003 [TMB03]). This opens the possibility for another important test of CDM theory. It is predicted that large elliptical galaxies in high-density peaks corresponding to rich clusters are formed in a very short time (< 1 Gyr) with the bulk of their stars created in a vigorous star burst, whereas ellipticals in the field get assembled all the time by major mergers of spirals that already had an extended star formation history (e.g. Kauffmann 1996). The stellar populations of ellipticals in different environments should therefore have different enrichment histories for the Mg or α elements and the Fe-peak elements which can only be measured by spectroscopy. This comes about, because these element families are to first order mainly produced by supernovae of type II and type Ia, respectively, which have very different timescales. SNIIs are exploded massive stars which have a lifetime of only a few Myrs. SNIa are the endproducts of a binary stellar system with an evolutionary time of ~ 1 Gyr. If a cluster elliptical ended its star burst within a few Myrs, then it should be deficient in Fe leading to Mg/Fe ratios much larger than the solar mix or than in field ellipticals. Since an accurate measurement of the absorption line strengths needs a minimum S/N of ~ 30 , spectroscopy of distant faint galaxies is only feasible with the 10m-class telescopes like SALT.

As an example, two diagnostic diagrams are shown in Figure 3 for early-type galaxies in the Coma cluster (Kuntschner et al. 2001) together with field ellipticals from the FDF (Ziegler et al. 2004) and cluster ellipticals (Ziegler & Bender 1997) both samples having $\langle z \rangle \approx 0.4$. Since absorption lines of distant galaxies can be corrupted if they are redshifted to a region with strong terrestrial

emission or absorption, the number of galaxies is different for the two panels, and we do not use the classical combination of Fe lines but only the Fe5270 index for the assessment of Fe abundance. The bulk of the data in Panel a) can be modeled with old ages with the distant galaxies being younger by ~ 4 Gyr on average than Coma compatible with the lookback time. Three of the FDF field objects have luminosity-weighted ages of ~ 2 Gyr and solar metallicity which may indicate that these galaxies are the endproducts of a recent merger between spirals. None of the distant field ellipticals reach the peak values in metallicity of the cluster members. The majority of the $z \approx 0.4$ galaxies exhibit a super-solar Mg overabundance relative to Fe like the local reference (Panel b).

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