Disk galaxy evolution up to redshift z=1

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We have performed intermediate-resolution VLT/FORS spectroscopy and HST/ACS imaging of 129 field spiral galaxies within the FORS Deep Field. The galaxies cover the redshift range $0.1 \leq z \leq 1.0$ and comprise all types from Sa to Sdm/Im. Spatially resolved rotation curves were extracted and fitted with synthetic velocity fields that take into account all geometric (e.g., inclination and misalignment) and observational effects (in particular, blurring due to optical beam smearing and seeing). Using these fits, the maximum rotation velocity $V_{\text{max}}$ could be determined for 73 objects.

The Tully-Fisher relation of this sample at a mean look-back time of $\sim 5 \text{ Gyr}$ shows a luminosity evolution which amounts to $\sim 2 \text{ mag}$ in rest-frame $B$ for low-mass spirals ($V_{\text{max}} \approx 100 \text{ km/s}$) but is negligible for high-mass spirals ($V_{\text{max}} \approx 300 \text{ km/s}$). This confirms our previous analysis which was limited to ground-based imaging. The observed overluminosity of low-mass galaxies is at variance with predictions from simulations. On the other hand, at given $V_{\text{max}}$, we find slightly smaller disk sizes towards higher redshifts, in compliance with the CDM hierarchical model. The observed mass-dependent luminosity evolution might therefore point towards the need for a more realistic modelling of the stellar (i.e. baryonic) component in $N$-body codes.

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1. Introduction

The Cold Dark Matter hierarchical scenario has become one of the paradigms in astrophysics and cosmology. On scales of clusters of galaxies and beyond, the observed structures are very well reproduced by simulations that assume a flat $\Lambda$CDM cosmology. However, the observed properties of individual galaxies remain challenging to the models. For example, semi-analytic recipes fail to reproduce the blue colors of low–mass spirals and the red colors of high–mass spirals in the local universe (Bell et al. 2003). To gain further insight into this issue, we performed an observational study of distant field galaxies with a data set that probes more than half the age of the universe.

Utilising the Tully–Fisher Relation (TFR) between luminosity and maximum rotation velocity $V_{\text{max}}$ as well as the velocity–size relation between $V_{\text{max}}$ and disk scale length $r_d$ we will quantify the evolution of late–type galaxies over the past 8 Gyr.

Throughout this article, the concordance cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ has been assumed.

2. The Sample

Our data set has been selected within the FORS Deep Field (FDF, see Heidt et al. 2003), a multi–band photometric survey performed with the Very Large Telescope and the New Technology Telescope operated by ESO. Based on a catalogue with spectrophotometric types and photometric redshift estimates, we chose objects for follow–up spectroscopy basically upon a late–type Spectral Energy Distribution and apparent $R$–band magnitude $R \leq 23$ mag. In total, we took spectra of 129 galaxies with the FORS1 & 2 instruments of the VLT. For an accurate derivation of the galaxies’ disk inclinations, scale lengths etc. we also obtained Hubble Space Telescope images of the FDF using the Advanced Camera for Surveys (F814W filter).

We extracted spatially resolved rotation curves by fitting Gaussians to the usable emission lines stepwise along the spatial axes of the spectra. Due to the small apparent sizes of the galaxies, the slits used for spectroscopy covered substantial fractions of the disks. This “optical beam smearing” and the seeing resulted in a heavy blurring of the observed rotation curves. To overcome these effects, we generated synthetic velocity fields that introduced the same observational effects as the data and used these to model the observed rotation curves. With this strategy, the intrinsic maximum rotation velocity $V_{\text{max}}$ was derived for 73 galaxies within the field–of–view of the ACS images. Out of these, 34 rotation curves robustly probed the region of constant rotation velocity and had a high degree of symmetry; these will be referred to as high quality data in the following. The kinematic sample with 73 objects spans a redshift range $0.09 \leq z \leq 0.97$ corresponding to look-back times $1.2 \text{ Gyr} \leq t_1 \leq 7.6 \text{ Gyr}$ with a median $\langle t_1 \rangle = 4.7 \text{ Gyr}$.

3. Discussion & Conclusions

In Fig. 1 we compare the FDF spirals at $\langle z \rangle \approx 0.5$ to the TFR of local spirals as given by Pierce & Tully (1992). At fixed $V_{\text{max}}$ — which corresponds to a fixed total mass —, the distant galaxies are more luminous than their $z \approx 0$ counterparts. For the total sample and the high quality data, the average offsets are $\langle M_B \rangle = -0.98 \text{ mag}$ and $\langle M_B \rangle = -0.81 \text{ mag}$, respectively. These
overluminosities may indicate decreased $M/L$ ratios due to, e.g., younger stellar populations in the distant galaxies. Furthermore, we find evidence for a differential evolution: while the massive distant spirals are in relatively well agreement with the local TFR, the low–mass distant galaxies are increasingly overluminous towards low $V_{\text{max}}$. Using a parameterisation $M_B = a \log V_{\text{max}} + b$ for the TFR, a bootstrap bisector fit with 100 iterations yields a slope $a = -4.05 \pm 0.58$ for the high quality data, significantly shallower than the local slope $a = -7.48$. Since the analysis presented here is based on the ACS imaging, this confirms the results shown in Böhm et al. (2004) which were limited to ground–based imaging. Our data may thus indicate a mass–dependent luminosity evolution that would be at variance with simulations: e.g., Steinmetz & Navarro (1999) found a constant slope with their SPH code, while Boissier & Prantzos (2001) even predict a steepening of the TFR towards longer look-back times. We performed numerous tests to rule out the possibility of an incompleteness bias or systematic error in our analysis (see Böhm et al. 2004). Since the intermediate–redshift disks are smaller than in the local universe (Fig. 2) — as is to be expected in a cosmology with hierarchical structure growth — the evolution of spiral galaxies we observe would be at variance with theoretical predictions only in terms of the stellar population properties.

An analysis of the broad–band colors of our sample galaxies with single–zone models of chemical enrichment showed that the low–mass FDF spirals began to turn their gas into stars at later cosmic epochs and on longer timescales than the high–mass spirals (see Ferreras et al. 2004). When evolved to zero redshift, the model stellar populations of low–mass galaxies have younger mean stellar ages and a broader age distribution than those of high–mass galaxies. Although these were relatively simple models without any spatial resolution, the result may point towards an anti–hierarchical evolution of the baryonic component in late–type galaxies which is also known as “down–sizing”.

Figure 1: FORS Deep Field sample of spirals in the range $0.1 \leq z \leq 1.0$ in comparison to the local Tully–Fisher relation by Pierce & Tully (1992, solid line; dashed lines give 3 $\sigma$ limits). The distant sample is subdivided into high quality rotation curves (solid symbols) and low quality rotation curves (open symbols). Error bars are shown for the high quality data only.
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Figure 2: Offsets $\Delta \log r_d$ of the distant FORS Deep Field galaxies with high quality rotation curves from the local $V_{\text{max}}-r_d$ relation (reference: Haynes et al. 1999) as a function of redshift. Objects with $\Delta \log r_d > 0$ have larger disks than local spirals at a given $V_{\text{max}}$, whereas values $\Delta \log r_d < 0$ correspond to disks which are smaller than in the local universe. As indicated by the fit to the data (solid line), we find a slight trend towards smaller disks at higher redshifts, in agreement with theoretical predictions based on the Cold Dark Matter hierarchical scenario (Mo et al. 1998, dotted line).

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