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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 $V_{\max}$ could be determined for 73 objects.

The Tully-Fisher relation of this sample at a mean look-back time of ~ 5 Gyr shows a luminosity evolution which amounts to ~ 2 mag in rest-frame B for low-mass spirals ($V_{\max} \approx 100$ km/s) but is negligible for high-mass spirals ($V_{\max} \approx 300$ 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 $V_{\max}$, 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 ΛCDM 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 $V_{\rm max}$ (the rotation velocity in the flat outer parts of the rotation curves of spiral galaxies) as well as the velocity–size relation between $V_{\rm max}$ and disk scale length $r_{\rm d}$ we will quantify the evolution of late–type galaxies over the past 8 Gyr.

Throughout this article, the concordance cosmology with $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70\,{\rm km\,s^{-1}\,Mpc^{-1}}$ 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, an apparent R-band magnitude $R \leq 23$ mag and inclination $i \geq 40°$. In total, we took spectra of 129 galaxies with the FORS1 & 2 instruments of the VLT. For an accurate derivation of the structural parameters, we also obtained Hubble Space Telescope images of the FDF using the Advanced Camera for Surveys (F814W filter). Disk inclinations, scale lengths, B/T ratios etc. were determined via two–dimensional surface brightness profile fits with the GALFIT package of Peng et al. (2002).

The galaxies' absolute magnitudes were computed on the basis of the filter which best matched the rest–frame B-band. For objects at $z \leq 0.25$, $0.25 < z \leq 0.55$, $0.55 < z \leq 0.85$ and $z > 0.85$, we utilised the B, g, R and I magnitudes, respectively. Thanks to this strategy, the k-correction uncertainties — usually a substantial source of error to the luminosities of distant galaxies — are smaller than 0.1 mag for all types and redshifts in our sample. For the correction of the inclination-dependent intrinsic dust absorption, we followed the approach of Tully & Fouqué (1985) assuming a face–on ($i = 0°$) extinction of $A_B = 0.27$ mag. The absolute magnitudes of the FDF galaxies computed this way span the range $-18.0\,{\rm mag} \geq M_B \geq -22.7{\rm mag}$.

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 (1.0 arcsec width) covered substantial fractions of the disks. This resulted in "optical beam smearing", the equivalent of a well-known effect in radio obervations. In combination with the strong influence of seeing, this resulted in a heavy blurring of the observed rotation curves and did not allow to determine the maximum rotation velocity straightforward from the data. To overcome these problems, we generated synthetic rotation curves that introduced the

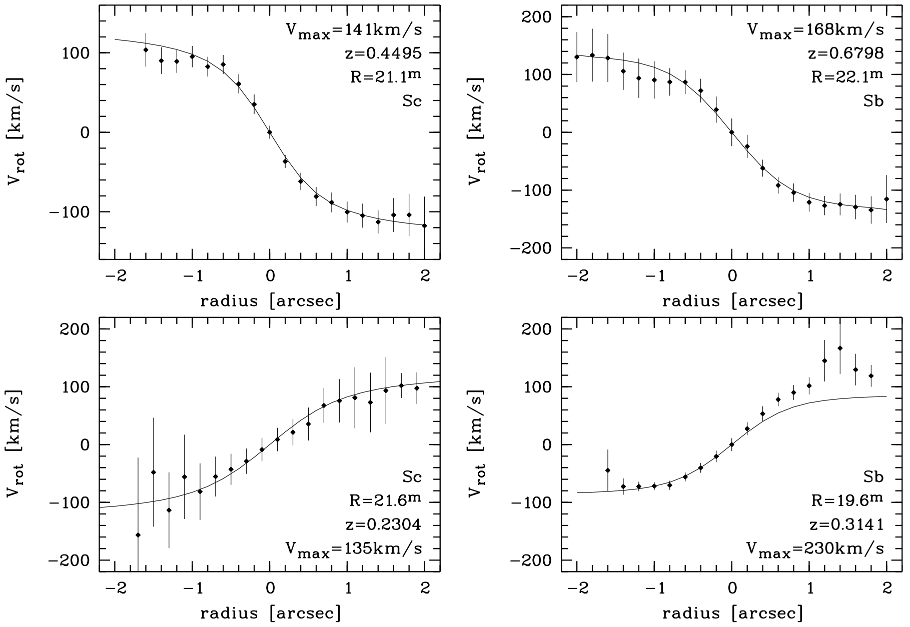

Figure 1: Examples of rotation curves from our data set. The solid symbols depict the observed rotation curves, the solid lines give the best–fitting synthetic rotation curves used to derive the intrinsic maximum rotation velocity. For each object, the spectrophotometric type, total apparent R magnitude, redshift and $V_{\rm max}$ are given. The two upper curves were classified as high quality data, the two lower ones as low quality data due to the large measurement errors (lower left) or an asymmetric shape (lower right).

same geometrical and blurring effects as the data. By fitting these synthetic rotation curves to the observed ones, the *intrinsic* maximum rotation velocity $V_{\rm max}$ 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. 39 curves showed mild asymmetries and a relatively small spatial extent, these are considered low quality data. Two examples of both classes along with the best-fitting synthetic rotation curves are presented in Fig. 1. The kinematic sample with 73 objects spans a redshift range $0.09 \leq z \leq 0.97$ with a median $\langle z \rangle = 0.45$, corresponding to look-back times $1.2\,{\rm Gyr} \leq t_{\rm l} \leq 7.6\,{\rm Gyr}$ and a median $\langle t_{\rm l} \rangle = 4.7\,{\rm Gyr}$.

3. Discussion & Conclusions

In Fig. 2, we compare the distant FDF spirals to the TFR of local spirals as given by Pierce & Tully (1992). At fixed $V_{\rm max}$ — which corresponds to a fixed total mass —, most of the distant galaxies are more luminous than their $z \approx 0$ counterparts. Computing the individual offsets from the local TFR for the total sample and the high quality data, we find median values of $\langle M_B \rangle = -0.98$ mag and $\langle M_B \rangle = -0.81$ mag, respectively. These overluminosities may indicate that the M/L ratios of the FDF galaxies are decreased with respect to present–day spirals. One possible explanation could be younger stellar populations in the distant galaxies. Interestingly, we find evidence for a differential evolution: while the *massive* distant spirals scatter around the local TFR, the *low–mass* distant galaxies are more overluminous towards lower values of $V_{\rm max}$. Using a

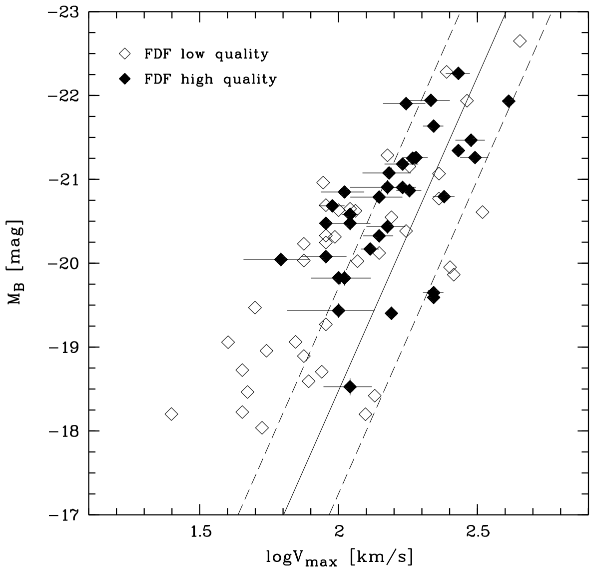

Figure 2: FORS Deep Field sample of spirals in the range $0.1 \leq z \leq 1.0$ in comparison to the local Tully–Fisher relation by Pierce & Tully (1992, solid line; dashed lines give $3\,\sigma$ limits). The distant sample is subdivided into high quality rotation curves (solid symbols) and low quality rotation curves (open symbols). At a given maximum rotation velocity, corresponding to a given total mass, the distant galaxies show a trend towards overluminosities that are larger for lower masses. Error bars are shown for the high quality data only.

parameterisation $M_B = a \log V_{\rm max} + b$ 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 measurement of the structural parameters and, in particular, the derivation of the maximum rotation velocities presented here are based on the ACS imaging (with a Point Spread Function of 0.12 arcsec), the shallow distant TFR slope confirms our results shown in Böhm et al. (2004), which were limited to ground–based VLT imaging (PSF of ~ 0.5 arcsec). Our data may thus indicate a mass–dependent luminosity evolution over the past ~ 5 Gyr which is negligible for high–mass spirals and amounts to more than 2 mag in rest–frame B for the least massive spirals.

A differential evolution would offer a straightforward explanation for the discrepant results of previous distant TFR studies which were limited to samples with 10 - 20 objects and thus could not robustly test an evolution of the TFR slope with look-back time. Since some of these samples preferentially contained very late–type galaxies — e.g., due to the target selection upon strong emission lines (Simard & Pritchet 1998) — which on the average have smaller masses than early–type spirals, a shallow distant TFR slope would explain why such studies found large mean TF offsets. Samples selected upon large disks, on the other hand, which hence mainly comprised early–type spirals (e.g., Vogt et al. 1996), yielded only a mild evolution in luminosity. In other words, the discrepancies between previous obervational TFR studies could be attributed to a combination of selection effects and small number statistics.

However, the observed mass–dependent trend is at variance with the results of simulations. E.g., Steinmetz & Navarro (1999) found a redshift–independent TFR slope with their Smoothed Particle Hydrodynamics code, while Boissier & Prantzos (2001) even predicted a *steepening* of

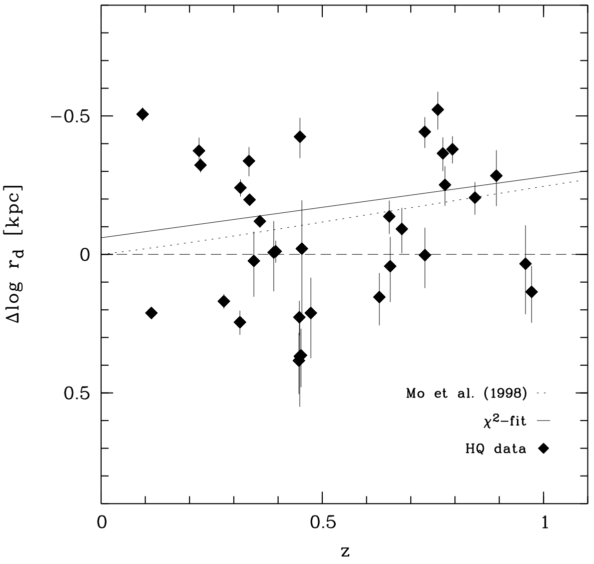

Figure 3: Offsets $\Delta \log r_{\rm d}$ of the distant FORS Deep Field galaxies with high quality rotation curves from the local $V_{\rm max}$–$r_{\rm d}$ relation (reference: Haynes et al. 1999) as a function of redshift. Objects with $\Delta \log r_{\rm d} > 0$ have *larger* disks than local spirals at a given $V_{\rm max}$, whereas values $\Delta \log r_{\rm d} < 0$ 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).

the TFR towards longer look-back times. We performed numerous tests which confirmed that our result is robust against the choice of the intrinsic absorption correction or the assumed shape of the intrinsic rotation curve. Moreover, we found that the shallow slope is very unlikely to arise from sample incompleteness towards low luminosities or tidally induced star formation in close galaxy pairs. For a detailed description of these and other tests, see Böhm et al. (2004) and Böhm & Ziegler (2004). In terms of the TF analysis, we hence find a discrepancy between simulations and observations. To gain further insight, we computed the offsets of the FDF galaxies from the velocity–size relation (correlating $V_{\rm max}$ and $r_{\rm d}$) of the local sample by Haynes et al. (1999) — note that the TFR of this sample is in very good agreement with the data of Pierce & Tully (1992). As is shown in Fig. 3, the distant galaxies' offsets $\Delta \log r_{\rm d}$ tend to increase towards higher redshifts, i.e. at given $V_{\rm max}$, the distant disks were smaller at earlier cosmic epochs. Since this *size* evolution is to be expected in a cosmology with hierarchical structure growth (e.g., Mo et al. 1998) the luminosity evolution of spiral galaxies we observe would be at variance with theoretical predictions only in terms of the *stellar population properties*.

To learn more about the driving processes behind a flat distant TFR tilt, we used single–zone models of chemical enrichment to estimate the star formation histories of the FDF galaxies on the basis of their broad-band colors (see Ferreras et al. 2004). The best-fitting models indicated that the low–mass spirals began to turn their gas into stars at later cosmic epochs and on longer timescales than the high–mass spirals. When evolved to zero redshift, the model stellar populations of low–mass galaxies had 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, this result may point towards an *anti–hierarchical evolution* of the baryonic component in late–type galaxies, a phenomenon which recently has also been referred to as “down–sizing” (e.g. Kodama et al. 2004).

References

[1] Bell, E. F., Baugh, C. M., Cole, S., et al., *The properties of spiral galaxies: confronting hierarchical galaxy formation models with observations*, 2003, MNRAS, 343, 367 [`astro-ph/0303531`]

[2] Boissier, S., & Prantzos, N., *Chemo–spectrophotometric evolution of spiral galaxies: V. Properties of galactic discs at high redshift*, 2001, MNRAS, 325, 321 [`astro-ph/0102425`]

[3] Böhm, A., & Ziegler, B. L., *The Evolution of Field Spiral Galaxies over the Past 8 Gyr*, 2004, RvMA, 18, in press, `astro-ph/0412256`

[4] Böhm, A., Ziegler, B. L., Saglia, R. P., et al., *The Tully–Fisher relation at intermediate redshift*, 2004, A&A, 420, 97 [`astro-ph/0309263`]

[5] Ferreras, I., & Silk, J., Böhm, A., & Ziegler, B. L., *The star formation history of intermediate redshift late–type galaxies*, 2004, MNRAS, 355, 64 [`astro-ph/0403536`]

[6] Haynes, M. P., Giovanelli, R., Chamaraux, P., et al., *The I-band Tully–Fisher relation for Sc galaxies: 21 cm HI line data*, 1999, AJ, 117, 2039

[7] Heidt, J., Appenzeller, I., Gabasch, A., et al., *The FORS Deep Field: field selection, photometric observations and photometric catalog*, 2003, A&A, 398, 49 [`astro-ph/0211044`]

[8] Kodama, T., Yamada, T., Akiyama, M., et al., *Down-sizing in galaxy formation at* $z \approx 1$ *in the Subaru/XMM-Newton Deep Survey (SXDS)*, 2004, MNRAS, 350, 1005 [`astro-ph/0402276`]

[9] Mo, H. J., Mao, S., & White, S. D. M., *The formation of galactic disks*, 1998, MNRAS, 295, 319 [`astro-ph/9707093`]

[10] Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W., *Detailed Structural Decomposition of Galaxy Images*, 2002, AJ, 124, 266 [`astro-ph/0204182`]

[11] Pierce, M. J., & Tully, R. B., *Luminosity–line width relations and the extragalactic distance scale I. Absolute calibration*, 1992, ApJ, 387, 47

[12] Simard, L., & Pritchet, C. J., *Internal Kinematics of Field Galaxies at Intermediate Redshifts*, 1998, ApJ, 505, 96 [`astro-ph/9606006`]

[13] Steinmetz, M., & Navarro, J. F., *The cosmological origin of the Tully–Fisher relation*, 1999, ApJ, 513, 555 [`astro-ph/9808076`]

[14] Tully, R. B., & Fouqué, P., *The extragalactic distance scale. I - Corrections to fundamental observables*, 1985, ApJS, 58, 67

[15] Vogt, N. P., Forbes, D. A., Phillips, A. C. et al., *Optical Rotation Curves of Distant Field Galaxies I: Keck Results at Redshifts to* $z \approx 1$, 1996, ApJ, 465, L15 [`astro-ph/9604096`]