The Tully–Fisher relation of cluster spirals at $z = 0.83$

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ABSTRACT

We present the rest-frame $B$-band Tully–Fisher relation for a sample of 8 cluster spiral galaxies at $z = 0.83$ and 19 field spirals at $z = 0.15–0.90$ based on Very Large Telescope (VLT) spectroscopy and Hubble Space Telescope (HST) photometry. No strong difference is detected between the cluster and the field galaxies, but we find some evidence that the cluster spirals are $\sim$0.5–1 mag brighter than the field ones at a fixed rotation velocity. Although only a $\sim$1.5–2$\sigma$ result, if confirmed with larger samples this effect could be caused by the cluster spirals experiencing a period of enhanced star formation while falling into the cluster.

Key words: galaxies: evolution – galaxies: clusters: individual: MS1054.4–0321 – galaxies: spiral.

1 INTRODUCTION

Ground-based and Hubble Space Telescope (HST) observations indicate that the disc galaxy population in rich galaxy clusters has experienced remarkable evolution since $z = 1$. It has been argued that the increase with time of the S0 fraction and the simultaneous decrease in the spiral fraction suggest that star-forming spirals fall into distant clusters at a much higher rate than in the local Universe, and that these spirals ultimately become S0s when star formation is extinguished by the cluster environment (e.g. Dressler et al. 1997; Poggianti et al. 1999; but see also Andreon 1998). Recent hydrodynamical simulations of the interaction of the gaseous components of disc galaxies with the intracluster medium support these ideas (Quilis, Moore & Bower 2000). They also indicate that while the gas is being removed from the disc a brief period of enhanced star formation could be expected. The strong evolution of the cluster spiral population contrasts with the mild evolution observed in the field spirals to $z \sim 1$ (Vogt 1999, 2001, and references therein).

To quantify the evolution of the cluster spirals, we are conducting a programme measuring the stellar and dynamical masses and $M/L$ ratios for a sizeable sample of morphologically-classified disc galaxies in rich galaxy clusters at $0.2 < z < 0.9$. We here present the first results on the Tully–Fisher relation (Tully & Fisher 1977) of cluster galaxies at $z = 0.83$.

We assume $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.05$ in order to compare our results easily with those of Vogt and collaborators.

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2 THE DATA

2.1 Sample selection

We targeted the galaxy cluster MS1054–03 at $z = 0.83$ since it is a rich X-ray selected cluster at high redshift and has extensive HST imaging and 8-m spectroscopy available. We based our galaxy selection on the spectroscopic and photometric catalogues of known cluster members of van Dokkum (1999) (see also van Dokkum et al. 2000). The spectroscopic catalogue was based on an $I$-band selected sample with $20.0 < I < 22.7$ (corresponding to $-22.3 < M_B < -19.6$ at this redshift). The catalogue gives Keck-based $H_0$ and [O II] equivalent widths (EWs) and spectral types (emission, absorption or E + A). The photometric catalogue gives $HST$-based magnitudes, colours and morphologies. The combined catalogue contains 87 galaxies, for which 74 have both photometric and spectroscopic information. From this sample, we selected spiral galaxies as follows.

(i) Galaxies having spiral morphology and emission spectral type (EW([O II]) $\geq 5$ Å). We included galaxy 2011, which has spiral morphology, although it was originally classified as merger/peculiar (M/P). Two galaxies were removed owing to geometric constraints (1733 and 1888X). This gave six galaxies, of which five yielded rotation velocities.

(ii) Galaxies having spiral morphology and a less secure emission spectral type (EW([O II]) $\geq 5$ Å, but with larger errors). This gave four galaxies, but only two rotation velocities.

(iii) Galaxies having spiral morphology and no listed spectral type. After removing one galaxy (1354) owing to geometry, this
L2  B. Milvang-Jensen et al.

gave two Sa galaxies. However, we were unable to measure rotation velocities for them.

12 spiral galaxies in the catalogue (50 per cent) did not have emission spectral type, and these were not selected. All galaxies were required to have an inclination of $i > 30^\circ$ (with 0° being face-on). Finally, we included an M/P cluster galaxy with strong [O II] emission (1801) out of curiosity, since it did not conflict with any of the high priority targets. Thus, we started with a sample of 13 known cluster galaxies. To fill the remaining space in our two spectroscopic masks, additional galaxies were selected. We morphologically classified the galaxies in the WFPC2 mosaic which were not in the cluster catalogue of van Dokkum (1999) and then selected galaxies with spiral/disc morphology and $i > 30^\circ$. We imposed magnitude and colour limits corresponding to those spanned by the selected cluster galaxies, i.e. $F814W = 20.1–22.7$ and $(F606W–F814W) = 0.8–2.2$. When there was a geometrical conflict, the brightest galaxy was chosen. In order to fill all gaps in the mask we sometimes relaxed the magnitude and colour limits. There were relatively few galaxies in the red end of our search window. This supplementary sample of 34 spirals yielded one additional cluster galaxy (C01, $F814W = 22.25$) for which the rotation velocity was measured, and 19 $z = 0.15–0.90$ field galaxies with rotation velocities. The magnitude range for these was $F814W = 19.1–23.2$. The field galaxies observed provided an ideal comparison sample since it was observed under the same conditions as our cluster sample. A montage of WFPC2 images of the galaxies with detected emission is shown in Fig. 1.

2.2 Spectroscopy

Observations were carried out with the FORS2 instrument at the VLT (UT2) on 2001 Feb 23. Two spectroscopic masks were designed with position angles (PAs) at right angles to each other, in order to be able to cover all galaxy PAs. The slits were aligned with the major axes of the galaxies, tilting the slits with respect to the PA of the mask by an angle $\theta_{\text{slit}}$ (cf. Fig. 1). The slits were 1 arcsec wide in the dispersion direction. Typical slit lengths were 11 arcsec. The spectral resolution was FWHM = 4.2 Å, and the pixel size 1.075 Å × 0.201 arcsec. The median wavelength range was 5400–7600 Å. Each mask was observed for $7 \times 30$ min. The seeing in the combined frames was 1.04 arcsec for mask 1, and 0.94 arcsec for mask 2.

Details of the spectroscopic data reduction will be given in Milvang-Jensen (PhD thesis, in preparation). Briefly, after bias subtraction, cosmic rays were removed using the 7 frames taken for each mask. The geometric distortion was mapped and removed using the edges of the spectra in the ‘dome’ flats. Dome and sky flats were used to correct for pixel-to-pixel variations and slit profiles respectively. The science frames were then cut up into individual slit spectra, wavelength-calibrated, and sky-subtracted.

Figure 1. HST + WFPC2 F814W images of the galaxies with detected emission. Below each image is given galaxy ID, redshift and slit angle ($\theta_{\text{slit}}$, measured counter-clockwise from vertical). The IDs follow van Dokkum (1999) for the cluster galaxies, with the exception of C01 (a cluster galaxy found by us). The VLT slits were aligned with the major axes of the galaxies. The images shown have been rotated to the mask position angle and are 4 arcsec on a side. The intensity scaling is linear, and the intensity cuts are the same for all the galaxies.
Depending on redshift, different emission lines were visually identified in the 2D spectra ([O II]λ3726.1, 3728.8, Hγ, Hβ, [O III]λ4959, [O III]λ5007 and Hα).

2.3 Rotation velocities

Projected rotation velocities were determined from the 2D emission-line spectra using the synthetic rotation curve method of Simard & Pritchet (1998, 1999). A simple parametrized intrinsic rotation curve and an exponential emission intensity profile are assumed. Synthetic 2D emission-line spectra are then produced taking into account known observational parameters such as seeing, spectral resolution and slit width. The model parameters are projected rotation velocity $V_{rot}$, residual background level $b$ and [O II] doublet intensity ratio $R$. The main inputs are a continuum-subtracted postage-stamp spectral image of the emission line, an estimate of the background noise, and the inclination $i$ (cf. Section 2.4). The Metropolis algorithm (Metropolis et al. 1953) is used to search the parameter space to get ‘best-fitting’ values and 68 per cent confidence intervals.

The fitting was done for all well-detected emission lines. Examples of emission lines, model spectra and residual images are shown in Fig. 2. Out of the 31 galaxies with well-detected emission lines, 3 field galaxies did not yield acceptable fits. One (F04) had a strange line morphology: the line showed a tilt only on one side of the nucleus, whereas on the other the line was flat. Two (F02 and F06) had an intensity profile that looked more extended than exponential. F06 is shown in Fig. 2. The galaxies with rejected fits have been excluded from our analyses. The M/P cluster galaxy (1801) was surprisingly well matched to the model. However, the emission was asymmetric, being strongest in the two bright knots (cf. Fig. 1). We show this galaxy in Fig. 3, but we do not include it in the analyses.

Two different intrinsic rotation curves were tried: a step-wise flat rotation curve and the ‘Universal’ rotation curve of Persic & Salucci (1991). The latter is a function of the luminosity of the galaxy. The differences in the model images are small, owing to the effect of the seeing and the relatively coarse sampling. For the low-luminosity galaxies the Universal rotation curve gives marginally higher rotation velocities that the flat one. For the high-luminosity galaxies (i.e. the cluster galaxies and some of the field galaxies) there is little difference between the results from two rotation curves. In

Figure 2. Illustration of the emission-line fitting. The first column shows HST + WFPC2 F814W images of the six example galaxies, rotated to have the slit along the y-axis. The following columns show 2D spectral images: observed, best-fitting model and residual, with wavelength along the x-axis. The intensity cuts have been adjusted from galaxy to galaxy, except for the residual images. The galaxy ID, redshift, line ID and spectral image size are given on the figure, as well as the fitted values of the projected rotation velocity ($V_{rot}$ sin $i$) and the emission-line exponential scalelength ($r_{d,spec}$). The inclination ($i$) and the F814W photometric scalelength ($r_{d,phot}$) are also given. For each galaxy the height in arcsec of all 4 images is the same. We rejected the fit of galaxy F06, cf. Section 2.3.
the analyses we will use the results from the Universal rotation curve, since this rotation curve has some physical motivation. For galaxies with more than one emission line in the observed wavelength range, the rotation velocities derived from the different lines agreed within the errors, and weighted averages were used in the analyses.

The ratio $r_{\text{spec}}/r_{\text{phot}}$ had a median value of 1.1 and a typical range of 0.7–1.7, in broad agreement with what is found locally (Ryder & Dopita 1994). This indicates that the fitting procedure is producing sensible results. The fitted $r_{\text{spec}}$ was typically in the range 0.2–1.2 arcsec, and almost always greater than zero at the 3σ level. Spectral signal is detectable and thus contributes to the fit up to typically $\gtrsim2$ scalelengths.

2.4 Photometry

Photometry was carried out on the F814W and F606W HST + WFPC2 images (van Dokkum et al. 1999). The typical exposure time for the combined $HST$ images was 3.3 ks. Photometric zeropoints were taken from the May 1997 WFPC2 SYNPHOT update. The Sextractor programme (Bertin & Arnouts 1996) was used to measure total magnitudes. Rest-frame $B$ magnitudes were derived from the observed F814W and F606W photometry. F814W matches almost exactly the rest-frame $B$-band at $z = 0.83$, and thus the $B$ magnitudes can be derived very accurately for galaxies close to this $z$. F606W matches the $B$-band at $z \approx 0.37$. Thus, $B$ magnitudes for all the galaxies in our sample can be interpolated with reasonably small uncertainties. The interpolation (and in a few cases, small extrapolation) was carried out using spectral energy distributions (SEDs) of local galaxies with different spectral/morphological types (Coleman, Wu & Weedman 1980). For each galaxy, the SED (or linear combination of SEDs) that yielded the observed (F606W–F814W) colours at the galaxy’s redshift was chosen for the interpolation. The formal uncertainty in this transformation is very small (rms $\sim 0.01$ mag), but that assumes perfect knowledge of the filter response in each band. Tests with different filters indicate that systematic uncertainties of $\sim0.1$ mag could be present, but these are negligible in our analyses. Absolute $B$ magnitudes corrected for internal extinction, $M^*_B$, were calculated following Tully & Fouqué (1985). The correction, which is a function of $i$, was in the range $0.32–0.96$ mag, with a median value of 0.61 mag.

The disc inclinations ($i$) were determined on the F814W images using the GIM2D programme (Simard et al. 2002). The uncertainties on $i$ were included in the uncertainties on $V_{\text{rot}} = (V_{\text{rot}} \sin i)/\sin i$. The inclinations were in the range $33–82^\circ$ (90° being edge-on), with a median value of $68^\circ$.

3 DISCUSSION OF THE TULLY–FISHER RELATION

The Tully–Fisher plot is shown in Fig. 3(a). Galaxies 1459 and F03 deviate strongly from the rest. Galaxy 1459 may be two galaxies (or a chain galaxy (cf. Fig. 1). Galaxy F03 has a very low surface brightness (the lowest in the sample). These two galaxies will be excluded from the analyses. In Fig. 3(a) we plot the local Tully–Fisher relation (TFR) from Pierce & Tully (1992), as adapted by Vogt (1999). Most of our field galaxies and all our cluster galaxies fall on the high luminosity/low velocity side of this relation. The absolute magnitude residuals at fixed rotation velocity ($\Delta TF$) are plotted against redshift in Fig. 3(b). For the field galaxies, $\Delta TF$ becomes more negative with $z$ (94 per cent significance from a Kendall’s tau test). Assuming that the errors in $\Delta TF$ are the individual measurement errors plus 0.6 mag added in quadrature (a guessed intrinsic scatter in the $B$-band TFR for this redshift range), a chi-square fit for the field galaxies gives $\Delta TF = (-1.6 \pm 0.3)z$ with $\chi^2 = 1.0$. If taken at face value and interpreted as luminosity evolution, the effect is $\sim 0.8$ mag at $z = 0.5$, much larger than the $\sim 0.2$ mag Vogt (1999) found at similar redshifts. This interpretation assumes a non-evolving TFR slope, which is important since our field sample has
a built-in positive correlation between luminosity and redshift. Our sample does not allow us to constrain the TFR slope, but Ziegler et al. (2002) found some evidence for a slope change at $z \sim 0.5$ for a sample of 60 field spirals. Thus, the derived luminosity evolution of the field spirals must be regarded with extreme caution. One might worry that the low $\Delta TF$ values instead reflected underestimated rotation velocities due to not detecting the emission at sufficiently large galactocentric distances. In that case low $\Delta TF$ values should be accompanied by low $R_{\alpha, spec}/R_{\alpha, phc}$ values, and Kendall’s tau tests for the cluster and the field galaxies show this not to be the case.

In order to compare the cluster and field spirals, we will use a constant TFR slope equal to the local value. We will make this comparison under two alternative (and extreme) hypotheses. First, we will assume that the zero-point of the field TFR does not evolve with $z$ and compare the residuals from the local TFR ($\Delta TF$) for the field and cluster spirals. Secondly, we will assume that the zero-point of the field TFR evolves with $z$ as shown by the dotted line in Fig. 3(b), and compare the residuals from the local TFR corrected for this evolution, $\Delta TF_{\text{corr}} = \Delta TF - (-1.6c)$. In both cases we compare the cluster sample ($N_{\text{clus}} = 7$) with the full field sample ($N_{\text{field}} = 18$) and a field subsample spanning the luminosity range of the cluster galaxies ($M_B < -19.8$; $N_{\text{field}} = 7$). Two statistical tests are carried out, a simple difference of the mean values (assuming rms/$\sqrt{N}$ uncertainties) and a Kolmogorov–Smirnov (K–S) test. For comparison purposes, the K–S probability that the field and cluster samples are drawn from two different populations has been translated into a number of sigmas for a normal distribution. The results of these comparisons are given in Table 1. The difference between cluster and field samples are larger and more significant using the first set of assumptions, but it is clear that the data suggest the cluster spirals are $\sim 0.5$–1 mag brighter than the field ones at a fixed rotation velocity. The only other published cluster TF study at intermediate $z$ is that of Metevier, Koo & Simard (2002), who found a larger TFR scatter for their 7 cluster spirals at $z = 0.39$, but no evidence for a zero-point or slope change. The larger look-back time of our study could explain the fact that we do find some luminosity evolution.

The increment in luminosity that we have found could be the result of enhanced star formation in spiral galaxies falling on to the cluster. However, these suggestive results are far from conclusive since we have studied one single cluster and our current sample is small. It is clear that a similar study of a reasonable cluster sample, spanning a broad redshift baseline, can provide strong empirical results on the evolution of the cluster spiral population.

| Variable | Sample | $(\text{cluster}) - (\text{field})$ [mag] | $p_{\text{K-S}}$ | $\text{diff }\Delta TF$ |
|----------|--------|--------------------------------------|-----------------|----------------------|
| $\Delta TF$ | All | $-1.32 \pm 0.43$ (3.1σ) | 96 per cent (2.0σ) |         |
| $\Delta TF$ | High $L$ | $-1.00 \pm 0.46$ (2.2σ) | 87 per cent (1.5σ) |         |
| $\Delta TF_{\text{corr}}$ | All | $-0.71 \pm 0.42$ (1.7σ) | 83 per cent (1.4σ) |         |
| $\Delta TF_{\text{corr}}$ | High $L$ | $-0.67 \pm 0.43$ (1.6σ) | 87 per cent (1.5σ) |         |

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