GENERALIZATIONS OF THE TULLY-FISHER RELATION FOR EARLY- AND LATE-TYPE GALAXIES

SVEN DE RICKE, WERNER W. ZEILINGER, GEORGE K. T. HAU, P. PRUGNIEL, AND HERWIG DEJONGHE

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ABSTRACT

We study the locus of dwarf and giant early- and late-type galaxies on the Tully-Fisher relation (TFR), the stellar mass Tully-Fisher relation (sTFR), and the so-called baryonic or H I gas+stellar mass Tully-Fisher relation (gsTFR). We show that early-type and late-type galaxies, from dwarfs to giants, trace different yet approximately parallel TFRs. Surprisingly, early-type and late-type galaxies trace a single yet curved sTFR over a range of 3.5 orders of magnitude in stellar mass. Moreover, all galaxies trace a single, linear gsTFR, over 3.5 orders of magnitude in H I gas+stellar mass. Dwarf ellipticals, however, lie slightly below the gsTFR. This may indicate that early-type dwarfs, contrary to the late types, have lost their gas, e.g., by galactic winds or ram pressure stripping. Overall, environment only plays a secondary role in shaping these relations, making them a rather “clean” cosmological tool. ΛCDM simulations predict roughly the correct slopes for these relations.

Subject headings: galaxies; dwarf — galaxies: kinematics and dynamics — galaxies: structure

1. INTRODUCTION

The Tully-Fisher relation (TFR) relates the intrinsic luminosity to the maximum rotation velocity of the gas, vrot, a proxy for the circular velocity, of late-type galaxies (Tully & Fisher 1977). It reflects the equilibrium state of late-type galaxies, which is a three-parameter relation (Djorgovski & Davis 1987; Prugniel & Simien 1996), has only two parameters, implying additional relations between the observational characteristics. Still for gas-rich, that while the TFR undergoes strong luminosity evolution, the sTFR and gsTFR have remained constant since z ≈ 1. To test for any possible environmental influences, these authors switched off star formation in a disk galaxy by removing all its halo gas. After some fading and reddening, this galaxy ends up slightly below the B-band TFR but remains on the sTFR and gsTFR. Tassis et al. (2006) have simulated the evolution of the TFR of massive late types (vrot ≳ 100 km s⁻¹) and show that while the TFR undergoes strong luminosity evolution, the sTFR and gsTFR have remained constant since z ≈ 1. To test for any possible environmental influences, these authors switched off star formation in a disk galaxy by removing all its halo gas. After some fading and reddening, this galaxy ends up slightly below the B-band TFR but remains on the sTFR and gsTFR. Tassis et al. (2006) have simulated the evolution of the TFR of massive late types (vrot ≳ 100 km s⁻¹). Again, little evolution of these relations with redshift is found. These authors predict a steepening of the sTFR slope below a stellar mass of M_* ≳ 10^10 M⊙, while the gsTFR is expected to have a constant slope.

If instead of the observed rotation we consider the circular velocity characterizing the gravitational potential, these relations can be extended to any type of galaxies, in particular to giant and dwarf ellipticals (dEs), which are not dominated by rotation. This generalization would allow us to probe further the similarities of the dark matter distribution of early- and late-type galaxies that were already investigated by Bertola et al. (1993). The rotation curves of ellipticals cannot readily be observed, since they contain little or no H I (Conselice et al. 2003; Buyle et al. 2005). Kronawitter et al. (2000) and Magorrian & Ballantyne (2001) determined the circular velocities of bright ellipticals using dynamical models; van Zee et al. (2004) measured stellar rotation curves for a sample of 16 flattened Virgo dEs. These authors found dEs to adhere closely to the TFR of gas-rich dwarf and spiral galaxies. However, they did not correct for asymmetric drift, which, for dEs, can be as large as the velocity dispersion. In order to obtain more reliable rotation curves of dEs, we constructed dynamical models for 13 dEs from the Fornax Cluster, nearby southern groups, and the Local Group, to stellar kinematics out to 1R_e–2R_e. The Local Group dEs were observed with the OHP 1.93 m telescope (Simien & Prugniel 2002). The other dEs were observed in the course of ESO Large Program 165.N 0115 (see, e.g., De Rijcke et al. 2001). We use the observed surface brightness distribution, the mean velocity, the velocity dispersion, and, if available, the central fourth-order moment of the line-of-sight velocity distributions calculated from the kinematic parameters up to h4 (van der Marel & Franx 1993), as data. A detailed account of the modeling method can be found in Dejonghe & de Zeeuw (1988), Dejonghe et al. (1996), and De Rijcke et al. (2004, 2006). In De Rijcke et al. (2004) the model for FS 373 is discussed; in De Rijcke et al. (2006) we present the models for NGC 147, NGC 185, and NGC 205 (including a technical description of the modeling method, a presentation of the data, and a comparison of the models with the data). We can define the range of models, and hence mass distributions, that are consistent with the data and determine the best-fitting model. The strong dependence of the model mass profile, and consequently the corresponding circular velocity curve, on the velocity dispersion profiles makes estimates of v_circ based on dynamical models much less sensitive to the unknown inclination than v_circ estimates based on direct measurements of stellar rotation curves. There remains the caveat that v_circ estimates derived from dynamical models are by construction to some extent model dependent and are the result of the nontrivial conversion of stellar kinematics into a dark matter density profile.
The new data for the 13 dEs are presented in Table 1, where $v_{\text{circ}}$ is the maximum circular velocity of the best-fitting model, and $v_{\text{circ, low}}$ and $v_{\text{circ, up}}$ are the lowest and highest maximum circular velocities of models that are consistent with the data at the 90% confidence level. All velocities are expressed in kilometers per second; $M_B$ and $M_K$ are the $B$-band and 2MASS $K_s$-band absolute magnitudes, respectively. The maximum extent of the kinematic data in units of the half-light radius is indicated by $R_{\text{data}}/R_e$. The dEs with “FC” designations are taken from the Ferguson & Sandage (1991) catalog of southern groups; NGC 5898 DW1 and NGC 5898 DW2 are two dEs in the NGC 5898 group (De Rijcke et al. 2005). Throughout this paper, we use $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. THE TULLY-FISHER RELATION

The $B$-band TFRs traced by early- and late-type galaxies are plotted in the left panel of Figure 1. The spirals represent late-type galaxies taken from Tully & Pierce (2000, hereafter TP00), Coté et al. (2000, hereafter C00), McGaugh (2005, hereafter M05), and Geha et al. (2006, hereafter G06). If galaxies appear in more than one data set, we use only the TP00 data. Based on 115 galaxies, TP00 find $\log (L_B) = 3.84 \pm 2.91 \log (v_{\text{circ}})$, with $L_B$ expressed in solar $B$-band luminosities and $v_{\text{circ}}$ in kilometers per second. We fitted a straight line to the combined TP00 and M05 data sets, taking into account the errors on the luminosities $\log (L_B)$ and on the circular velocities $v_{\text{circ}}$, using the routine fitexy of Press et al. (1992). The diagonal elements of the covariance matrix are used as approximations of the variances of the regression coefficients. Going back to the original papers from which the M05 data set is compiled, the average error on $v_{\text{circ}}$ is $\sim 10$ km s$^{-1}$. We adopt a 15% error on the total luminosity, roughly accounting for the various sources of statistical and systematic errors. Limiting ourselves to the 128 galaxies brighter than $\log (L_B) = 9.5$, or $M_B = -18$ mag, we find the relation

$$\log (L_B) = (3.42 \pm 0.20) + (3.09 \pm 0.12) \log (v_{\text{circ}}).$$

At lower luminosities, the situation becomes very unclear. The M05 late types fall systematically below the TFR, whereas the G06 galaxies lie above it. This may be due to an increased scatter about the TFR at low luminosities. C00 note that at $\log (L_B) = 8$, turbulent gas motions start dominating the ordered rotation, causing the scatter about the TFR to increase dramatically. They also suggest that, at that point the notion of a thin, well-aligned gas disk might break down. On the other hand, even if low-mass galaxies are supported by turbulence rather than by rotation, one would expect some kind of TFR to persist, even though the underlying equilibrium of these fainter systems might be different.

We fitted a straight line to the data of the early-type galaxies, taking into account the errors on the luminosities $\log (L_B)$ and on the circular velocities $v_{\text{circ}}$. This data set consists of the luminosities and the circular velocities of bright ellipticals, estimated by Kronawitter et al. (2000, hereafter K00) and Magorrian & Ballantyne (2001, hereafter MB01) from spherical dynamical models, and dEs from De Rijcke et al. (2005) and De Rijcke et al. (2006, hereafter D06). In cases where galaxies appear in both the K00 and MB01 data sets, we opted to use the K00 data because these models allow for a radially varying anisotropy. We note that the K00 and MB01 $v_{\text{circ}}$ estimates of overlapping galaxies are in good agreement. For the luminosities, as for the late-type galaxies, we assume a 15% error; for the circular velocities, we use the 90% confidence level uncertainties given by the various authors. We find that the TFR of the early-type galaxies can be

![Fig. 1.—Left: B-band Tully-Fisher relation. Right: K-band Tully-Fisher relation. Late-type galaxies are indicated by spirals. Early types are indicated by circles (dEs) and pentagons (Es). The adopted mean uncertainty on the luminosities is indicated with a vertical error bar. The origin of the data is indicated in the figures (with spiral = TP00+C00+M05+G06). In the right panel, only the TP00 data set, being the only late-type data set giving $K$-band luminosities, is included.](image-url)
well represented by a single power law over three decades in luminosity:

$$\log (L_B) = (3.15 \pm 0.63) + (2.97 \pm 0.26) \log (v_{\text{circ}}).$$  \quad (2)

Within the error bars, the \(B\)-band TFRs of early- and late-type galaxies have the same slope. In the DE regime, at about \(\log (L_B) \approx 8.5\), or \(M_B = -16\) mag, late- and early-type dwarfs essentially overlap in a \(\log (L_B)\) versus \(\log (v_{\text{circ}})\) diagram. In the \(B\) band, ellipticals, in the regime defined by \(\log (L_B) \approx 8-11\), or \(M_B = -14.5\) to \(-22\) mag, are about a factor of \(-4\), or about 1.5 mag, fainter than spiral galaxies with the same \(v_{\text{circ}}\).

The \(K\)-band TFR of early- and late-type galaxies is plotted in the right panel of Figure 1, using 2MASS \(K_S\)-band magnitudes for the dwarf and giant early-type galaxies. TP00 find \(\log (L_K) = 2.87 + 3.51 \log (v_{\text{circ}})\) for the \(K\)-band TFR of late-type galaxies. Our fit to the \(K\)-band TFR of the D06, K00, and MB01 galaxies yields

$$\log (L_K) = (2.44 \pm 0.35) + (3.46 \pm 0.15) \log (v_{\text{circ}}).$$  \quad (3)

In the \(K\) band, ellipticals are roughly a factor of 3, or \(-1.2\) mag, fainter than late types with the same \(v_{\text{circ}}\).

3. THE STELLAR MASS TULLY-FISHER RELATION

Going from the well-known TFR to the stellar mass Tully-Fisher relation (sTFR) requires the conversion of luminosities, and, if available, colors, to stellar masses, \(M_\star\). Bell & de Jong (2001) have fitted a suite of spectrophotometric disk evolution models to a set of observed properties of late-type galaxies. The acceptable models produce a tight correlation between the stellar mass—\(M/L\) and color. Alternatively, one can use the stellar \(M/L\) that gives the best modified Newtonian dynamics (MOND) fit to the rotation curves or use the maximum disk \(M/L\) (Sanders & McGaugh 2002). These \(M/L\) estimates generally agree to within a factor of 2. In short, the \(M/L\) values and stellar masses of late-type galaxies can be estimated straightforwardly from their colors or rotation curves. Here, we use the \(M/L\) based on the properties of the stellar population (colors, ages, and metallicities). The uncertainty on \(M_\star\), which is the combined uncertainty on \(L_B\) and \(M/L\), can be quite substantial, and we estimate it to be of order 100%, on average.

No easy-to-use tool for estimating \(M/L\)s of early-type galaxies exists. However, the mass-metallicity relation of early-type galaxies is observationally well constrained, from the faintest dwarfs up to the brightest giants, using either luminosity (Mateo 1998; Bender et al. 1993; Grebel et al. 2003) or velocity dispersion (Proctor et al. 2004; Thomas et al. 2005) as a substitute for galaxy mass. The theoretical predictions for this relation and the observations are in reasonably good agreement (Nagashima & Yoshii 2004; De Lucia et al. 2006). We tried different methods to calculate \(M/L\). (1) We fit a fourth-order polynomial to the empirical luminosity-metallicity relation of Nagashima & Yoshii (2004) in order to estimate the metallicities of the galaxies in the K00, MB01, and D06 data sets. Plugging this metallicity, along with an average age of 10 Gyr (Rakos et al. 2001), in the single stellar population models of Vazdekis et al. (1996), or Bruzual & Charlot (2003) yields the \(B\)-band \(M/L\). (2) For the giant ellipticals, one can use the relation \(\log (M_\star) = 0.63 + 4.52 \log (\sigma)\) of Thomas et al. (2005) between stellar mass \(M_\star\), expressed in solar masses, and velocity dispersion \(\sigma\), expressed in kilometers per second; or, alternatively, (3) the empirical metallicity and age relations, \([Z/H] = -1.06 + 0.55 \log (\sigma)\) and \(\log (\sigma/\text{Gyr}) = 0.46 + 0.238 \log (\sigma)\), of Thomas et al. (2005) in combination with the Vazdekis et al. (1996) or Bruzual & Charlot (2003) models. We found all methods to be in excellent agreement. They have systematic offsets much smaller than the error bars on the data points and yield sTFR slopes that agree to within the parameter uncertainties (see below). We also converted the 2MASS \(K\)-band magnitudes into \(M_\star\) using the Bruzual & Charlot (2003) models. This gave results that were entirely consistent with the sTFR based on the \(B\)-band data. For the remainder, we adopt approach (3) for the giant ellipticals and approach (1) for the dEs.

The sTFRs of early- and late-type galaxies are plotted in the left panel of Figure 2. Both early- and late-type galaxies trace a single yet curved sTFR over 3.5 orders of magnitude in stellar mass. For all galaxies in the range \(\log (M_\star) \approx 9.0-12.0\) we find

$$\log (M_\star) = (3.08 \pm 0.20) + (3.27 \pm 0.09) \log (v_{\text{circ}}).$$  \quad (4)

Using the \(M_\star - \sigma\) relation of Thomas et al. (2005) yields a sTFR slope of \(3.31 \pm 0.09\), consistent with equation (4). This is in good agreement with theoretical predictions (Porinari & Sommer-Larsen 2007; Tassis et al. 2006). The curvature of the sTFR is at least partially responsible for Gerhard et al. (2001) concluding...
that early-type galaxies have lower stellar masses than late-type galaxies at the same $v_{\text{circ}}$ if the sTFR of the late types is extrapolated.

4. **THE H I GAS+ STELLAR MASS TULLY-FISHER RELATION**

The mass of the gaseous component in late-type galaxies follows from 21 cm observations. We denote the sum of the stellar and H I gas mass by $M_{\text{gsTFR}}$. Since early-type galaxies do not contain a significant interstellar medium (see Gerhard et al. 2001 and references therein; Buyle et al. 2005; Conselice et al. 2003), the H I gas+stellar mass Tully-Fisher relation (gsTFR) of early types to a good approximation equals their sTFR. For the late types, we use the data of M05.

The gsTFR of the early- and late-type galaxies, presented in the right panel of Figure 2, is less curved than the sTFR, and, for the whole range $\log(M_{\text{gsTFR}}) \approx 8.0-12.0$, can be fitted by the linear relation

$$\log(M_{\text{gsTFR}}) = (3.25 \pm 0.14) + (3.15 \pm 0.07) \log(v_{\text{circ}}).$$

This can be compared with the gsTFR for giant and dwarf late-type galaxies constructed by G06, who find a slope $3.70 \pm 0.15$. Our result agrees much better with the slope of 3, which one would expect from the virial theorem, assuming a constant virial overdensity and a constant baryon–to–total mass ratio (Tassis et al. 2006). Late types show a vertical scatter of 0.2 dex in $M_{\text{gsTFR}}$ about the gsTFR. Giant early types have a slightly larger scatter of 0.3 dex; dEs are offset downwards by 0.4 dex, probably due to them having lost part of their baryons by galactic winds (Mac Low & Ferrara 1999; De Rijcke et al. 2005) or ram pressure stripping (Mori & Burkert 2000).

5. **CONCLUSIONS**

Early-type and late-type galaxies trace different yet approximately parallel TFRs, with early types being roughly 1.5 mag fainter in the B band than late types for the same $v_{\text{circ}}$. Surprisingly, all galaxies trace the same sTFR and gsTFR over a range of 3.5 decades in stellar or H I gas+stellar mass; dEs lie slightly below the general gsTFR. This seems to indicate that early-type dwarfs, which, contrary to the late types, reside in high-density environments, have lost their gas due to environmental influences, e.g., by galactic winds or ram pressure stripping. This also shows that the environment only plays a secondary role in shaping these relations, making them a “clean” cosmological tool. CDM simulations are able to account for the observed slopes of these relations.

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