A physical distance indicator for spiral galaxies

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In this paper we derive a Tully Fisher relation from measured I band photometry and Hα rotation curves of a large survey of southern sky spiral galaxies, obtained in Persic & Salucci (1995) by deprojecting and folding the raw Hα data of Mathewson, Ford & Buchhorn (1992). We calibrate the relation by combining several of the largest clusters in the survey, using an iterative maximum likelihood procedure to account for observational selection effects and Malmquist bias. We also incorporate a simple model for the line of sight depth of each cluster. Our results indicate a Tully Fisher relation of intrinsic dispersion ~ 0.3 mag, corresponding to a distance error dispersion of 13%. Application of this relation to mapping the large scale velocity field is underway.

1. INTRODUCTION

In recent years substantial progress has been made by Persic, Salucci and collaborators in improving the physical basis of the Tully Fisher (TF) relation. Their 'mass decomposition' procedure – when applied to a sample of spirals with good quality rotation curves and B and V band magnitudes – yielded a TF relation which was more linear and displayed less scatter than its uncorrected counterpart (Salucci, Frenk & Persic, 1993). In this work a similar attempt is made to improve the calibration of the TF relation based on the I band CCD photometry and Hα rotation curves of a sample of cluster spirals from the southern sky redfshift survey of Mathewson, Ford & Buchhorn (1992; hereafter MFB). This provides a larger and more accurate database than that considered in Salucci, Frenk & Persic (1993), and avoids the use of redshift as a direct measure of distance. In addition, we also carefully address here the issues of selection bias and undersampling, which it has been suggested (c.f. Sandage, Tammann & Federspiel, 1995; hereafter STF) have been inadequately dealt with in the cluster calibration of MFB.

2. THE TULLY FISHER CALIBRATION DATA

The re-folding and smoothing of the raw MFB data is described fully in Persic & Salucci (1995). For each galaxy an optical radius, $R_{\rm opt}$, encompassing 83% of the integrated light, was then computed and a smoothed rotation velocity obtained at a series of standard radii – each corresponding to a fixed fraction of $R_{\rm opt}$. The calibrating sample was then selected from the subset of 161 galaxies identified in MFB as belonging to clusters or groups.

We used the smoothed rotation velocity at a radius of $0.6R_{\rm opt}$ (denoted by V_6) in the calibration: at this radius the contribution to the rotation velocity from the luminous disk is a maximum in the disk model of Salucci, Frenk & Persic (1993) and earlier papers – thus leading to a TF relation with a stronger physical basis than that obtained in MFB, where the maximum measured rotation velocity was used. These velocities were then combined with I band magnitudes, integrated to a radius of $0.6R_{\rm opt}$ (c.f. Stel, 1994; denoted here by I_6), and estimates of Δ, the ratio of semimajor and semiminor axis, to derive a linear TF relation.

3. MAXIMUM LIKELIHOOD METHOD

The MFB TF calibration used a sample of 14 galaxies in the Fornax cluster, for which a very strong correlation was obtained. This calibration has been criticised for failing to include the effects of selection bias and misrepresenting the *true* slope and dispersion of the relation due to the small sample size (Hendry & Simmons, 1994, hereafter HS; STF). In HS it was shown that for a calibrating sample of $\sim$ 30 galaxies or less, the sampling distribution of the TF slope typically has a *larger* dispersion than the bias due to selection effects, so that sampling error – not selection bias – is the dominant systematic uncertainty. In this work we address *both* problems, however. We take account of luminosity selection following the statistical formalism of Hendry & Simmons (1990) and HS. We also considerably increase the calibrating sample size by combining data from several MFB clusters.

The full details of our analysis will be described in Hendry et al (1995), and we merely summarise the main points here. We assume that the *intrinsic* conditional distribution of absolute magnitude, M_I, given $\log V_6$ and $\log \Delta$, is a normal distribution with dispersion σ and mean value a linear function of $\log V_6$ and $\log \Delta$, i.e.

$$E(M_I \,|\, \log V_6, \log \Delta) \quad = \quad \alpha \log V_6 + \beta \log \Delta + \gamma$$

We *impose* a sharp selection limit at apparent magnitude, $I_{\rm L}$ (c.f. STF), and thus derive the conditional distribution of M_I given $\log V_6$ and $\log \Delta$ for an *observable* galaxy at true distance, r.

Suppose the calibrating sample consists of n different clusters, assumed (for now) all to lie at the same distance. For the j^{th} galaxy:-

$$M_I^j \quad = \quad I_6^j - \sum_{k=1}^{n} z_{jk} 5 \log r_k - 25$$

where r_k is the distance (in Mpc) of the k^{th} cluster and $z_{jk} = 1$ if the j^{th} galaxy belongs to the k^{th} cluster and $z_{jk} = 0$ otherwise. We substitute this expression into the likelihood function and thus obtain maximum likelihood (ML) estimates for α, β, γ, the r_k and σ. Although no closed analytic form exists for the ML solution, the equations are easily solved iteratively. Following MFB, we assume a redshift distance of $1340{\rm kms}^{-1}$ for Fornax and take $H_0 = 50$, although these choices have no bearing on the ML estimate of σ.

4. RESULTS

We selected first the subsample of 68 spirals with $I_6 \leq 15$, from the six largest MFB clusters: Antlia, Eridanus, Fornax, Hydra, Pegasus and Sculptor. Applying the ML method yielded an estimate of $\hat{\sigma} = 0.41 \pm 0.04$. (Standard errors were calculated from Monte Carlo simulations). We then investigated the effect of selecting only a subset of the clusters. Clearly the optimal solution is one for which the decrease in sample size by eliminating one or more clusters is balanced by the decrease in the number of free parameters (c.f. Hendry et al, 1995). Selecting the 50 galaxies in Fornax, Hydra, Antlia and Pegasus yielded $\hat{\sigma} = 0.33 \pm 0.04$ – a significantly smaller dispersion. Adding Sculptor to these four clusters gave a sample size of 59 and $\hat{\sigma} = 0.35 \pm 0.03$. Including Eridanus instead of Sculptor, on the other hand, gave $\hat{\sigma} = 0.41 \pm 0.04$, with similar ML estimates of α, β and γ to those of the six-cluster fit. That a problem existed with Eridanus was apparent from the value of $\hat{\sigma} = 0.70 \pm 0.08$ obtained when fitting the TF relation to Eridanus alone – almost twice as large as the next largest estimate for an individual cluster. The most likely reason for this large dispersion was that the galaxies did not all lie at the same true distance – a conclusion strongly supported when discarding only 3 galaxies from Eridanus reduced $\hat{\sigma}$ to 0.33 ± 0.06.

The 'canonical' ML fit obtained from Antlia, Fornax, Hydra and Pegasus was robust when restricted to various subsets of these clusters – although further reduction in the sample size increased the formal errors on the fitted parameters. We therefore adopted this solution as our optimal TF relation, viz.

$$M_I = (-6.04 \pm 0.31) \log V_6 + (0.66 \pm 0.25) \log \Delta + (-8.19 \pm 0.66)$$

The discovery of significant line of sight depth in Eridanus led us to consider next to what extent our ML value of $\hat{\sigma} = 0.33 \pm 0.04$ might be slightly overestimated due to line of sight depth.

5. THE EFFECT OF LINE OF SIGHT DEPTH ON σ

We modelled the effect of line of sight depth in each cluster by assuming the galaxies' distance modulus to be normally distributed about some mean value, μ_{clus}, with dispersion, σ_{clus} – an assumption borne out of mathematical expediency, but one which numerical simulations show to have negligible bearing on our final results (c.f. Hendry et al, 1995). In this case the dispersion in distance modulus adds quadratically to the intrinsic scatter of the TF relation. Thus, one may determine a corrected estimate of σ according to:-

$$\hat{\sigma}^2_{\text{corr}} = \hat{\sigma}^2_{\text{obs}} - \sigma^2_{\text{clus}}$$

We estimated σ_{clus} from the projected angular dispersion, assuming galaxies to be isotropically distributed about the cluster centre. This assumption is likely to be unreasonable for an individual cluster but one might expect it to hold statistically when we merge together several clusters. From our 'canonical' sample we thus obtained $\sigma_{\text{clus}} = 0.15$, and hence derived a corrected estimate for the intrinsic dispersion of the TF relation of

$$\hat{\sigma}_{\text{corr}} = 0.30 \pm 0.04$$

6. SUMMARY

In this work we have derived an optimal TF relation using a calibrating sample of spiral galaxies from the southern sky redshift survey originally published in MFB. We have improved the physical basis of the relation by deriving I band apparent magnitudes and rotation velocities at a fixed fraction of the optical radius for each galaxy – specifically at the radius for which the contribution to the rotation velocity from the luminous matter is maximised for a Freeman disk model.

We have accounted for the effects of luminosity selection by applying a maximum likelihood analysis to a composite sample of four clusters, determing optimal estimates for the TF coefficients and the relative cluster distances in a self-consistent manner. We derive a TF dispersion of $\hat{\sigma} = 0.33 \pm 0.04$, which we strongly believe does not underestimate the *true* TF scatter since our calibrating sample is sufficiently large to overcome criticisms of undersampling.

We have identified a likely source of significant line of sight depth in the Eridanus cluster – a group of three galaxies whose removal reduces the TF dispersion in Eridanus to a value which is completely consistent with the remaining clusters and with our composite relation.

Finally, we have modelled the contribution to the observed TF scatter from residual line of sight depth using the projected distribution of galaxy positions, assuming that our composite cluster sample should be statistically isotropic – an assumption which would be considerably less justifiable for an individual cluster. This hypothesis leads to a corrected TF dispersion of $\hat{\sigma} = 0.30 \pm 0.04$, which we adopt as our estimate of the true dispersion of our best-fit TF relation. This corresponds to a distance error dispersion of 13%.

We are currently applying this relation to derive TF distance estimates to the remaining clusters and field galaxies of Persic & Salucci (1995), and are using these as input to various methods for reconstructing the large scale velocity and density fields.

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