A Comparison of Tully-Fisher and Fundamental Plane Distances for Nearby Clusters

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Abstract. With the aim at obtaining a quantitative measure of the degree of universality of the Tully-Fisher and Fundamental Plane relations, we are comparing accurate redshift-independent distance estimates of nearby clusters of galaxies derived using both relations. Systematic differences in the two distance scales, once cluster membership and sample bias related issues have been resolved, would indicate a lack of universality in the relations, and seriously question their use in mapping the large-scale peculiar velocity field, and in studying the cosmological evolution of early and late-type galaxies in high redshift clusters. New accurate Fundamental Plane distance estimates for 6 nearby clusters are presented here, and compared with comparable Tully-Fisher distance estimates. The agreement between the two sets of distances provides good support to the universality of the Tully-Fisher and Fundamental Plane relations.

1 Introduction

The use of the Tully-Fisher (TF) relation (Tully & Fisher 1977), and of the Fundamental Plane (FP) relation (Djorgovski & Davis 1987; Dressler et al. 1987) as distance-indication relations relies heavily on an assumption of universality: for all galaxies in all environments the correlation between magnitude and rotation velocity, or among effective radius, effective surface brightness, and velocity dispersion is described by the same linear relation (the TF or FP template), within observational uncertainties, and a small intrinsic scatter. However little effort has been made to precisely quantify the degree of universality of the TF and FP (see Aaronson et al. 1986; Djorgovski et al. 1988; Guzmán et al. 1992; Jørgensen et al. 1996).

An invalid or biased template relation will yield spurious peculiar velocities. It has even been argued, for example, that the very evidence suggesting the existence of a Great Attractor might result from bias (Silk 1989). A comparison by Mould et al. (1990) between cluster peculiar velocities obtained using the TF and FP (or $D_n - \sigma$) techniques shows disagreements which exceed those expected from the reported uncertainties associated with the two methods. The case of A2634 is even more notorious: Aaronson et al. (1986) applied the TF relation to find the cluster roughly at rest in the Cosmic Microwave Background (CMB) reference frame, while Lucey et al. (1991) used the $D_n - \sigma$ relation to obtain a cluster peculiar velocity of -3400 km s^{-1}.

The most direct way to test the reliability of a distance-indication relation is to compare its predictions with those of another independent, and at least equally reliable, method. The TF and FP relations provide the opportunity for such a comparison. They have similar accuracy, and they are totally independent methods, because they are applied to galaxies of different morphological type. Also, these galaxies populate different environments (E and S0 in the cluster cores, spirals preferentially at the cluster peripheries), and it seems likely that, even in the case both the TF and FP might not be universal relations, they would be biased by different amounts by any environmentally-related mechanisms. Therefore a comparison between the two methods would still provide an opportunity to quantify their universality. Because of the limited accuracy of the distance estimates obtained with the TF and FP relation, a direct comparison of the two methods can be done only using clusters of galaxies, where large samples can be used to reduce the statistical uncertainty in the estimate of the cluster distances. Also, the existing correlation between cluster richness and the properties of the intra-cluster medium (see for example Edge & Stewart 1991) offers the opportunity to perform the TF–FP comparison under different environmental conditions, using clusters of different richness.

Here we present the first results of a project aimed at obtaining a comparison of very accurate TF and FP distance estimates in nearby clusters, and therefore at providing a reliable quantification of the universality of the two relations.

2 The Data

A large data-set of TF distance-estimates in 24 nearby clusters and rich groups has been recently collected by Giovanelli et al. (1997a,b). We have selected 10 of the clusters and groups in that sample to build a comparable data-set of FP distance-estimates. These are: Coma, A1367, Hercules (A2147 and A2151), A2634, Pegasus, A262, Cancer, and the NGC 383 and NGC 507 groups. Here we present results for 6 of those clusters (Coma, A1367, A2634, A262, Pegasus, and NGC 507 group).

Photometric parameters for early-type galaxies in those clusters were derived from I band CCD observations obtained with the KPNO 0.9m telescope. The core of each cluster was mapped with a mosaic of frames on a regularly spaced grid, and photometric parameters were measured for all E and S0/S0a galaxies that are to be considered cluster members (see Giovanelli et al. 1997a for membership criteria), for a total of 624 galaxies. Exposures were all 10 minutes long. A galaxy's light distribution was fitted with elliptical isophotes to derive its radial surface brightness profile. This was fitted with a de Vaucouleurs $r^{1/4}$ profile, yielding an effective radius r_e and effective surface brightness μ_e (the mean surface brightness within r_e). The fit was performed from a radius equal to twice the seeing radius, out to the outermost isophotes for E galaxies; for S0 and S0a galaxies only the central core was fitted. The median uncertainty on the determination of r_e is 5%, and 0.06 mag on that of μ_e.

Stellar velocity dispersion measurements for a subset of the photometric sample, composed of 273 galaxies, were obtained from moderate dispersion optical spectra. All spectroscopic observations were obtained with the Hale 5m telescope of the Palomar Observatory. A 1200 lines mm^{-1} grating and a $2'' \times 128''$ slit were used to obtain spectra with a dispersion of 0.86 Å per pixel, and a resolution of 2.2 Å (corresponding to a velocity resolution of 129 km s^{-1} at 5300 Å). The spectral coverage was approximately from 5000 to 5600 Å, centered on the Mg Ib lines at ~5175 Å. Exposure times ranged from 15 to 90 minutes, depending on the brightness of the target galaxy, with a median value of 30 minutes. Late G and early K type giant stars were used as velocity standards and as templates for the velocity dispersion measurements. One-dimensional galaxy spectra, to be used for the velocity dispersion determinations, were extracted using a $6''$ wide window (in the cross-dispersion dimension), centered on the peak of the galaxy continuum. All measurements of velocity and velocity dispersion were obtained using the cross-correlation technique of Tonry & Davis (1979), implemented in the IRAF task *fxcor*, by assuming that the line-of-sight velocity dispersion is Gaussian. The median uncertainty on the determination of the velocity dispersion is 5%, for $\sigma > 90$ km s^{-1}.

3 The Fundamental Plane

It has been argued that cluster samples for TF and FP work are almost bias-free, since all galaxies are roughly at the same distance. While it is certainly true that the classical Malmquist bias is avoided, a different and equally important bias affects cluster samples. This is generally referred-to as the "cluster population incompleteness bias" (Teerikorpi 1987). Sandage (1994) provided a detailed analysis of this bias and of the corrections it requires before unbiased distance estimates can be obtained with cluster TF samples. Here we have derived incompleteness bias corrections following the spirit of that treatment, but using Monte Carlo simulations to reproduce as closely as possible the completeness, measurement uncertainties, and scatter characteristic of our samples.

The FP template was obtained combining all individual bias-corrected cluster samples, under the assumption that, on average, these clusters are at rest with respect to the CMB reference frame. A chi-square fitting that minimizes the residuals in the orthogonal distance of each data-point from the plane was used. The resulting FP template is given by the relation

$$\log R_e = 1.55 \log \sigma + 0.326(\mu_e - 19.45) - 2.919 - \log h \qquad (1)$$

(or equivalently $\log R_e = 1.55 \log \sigma - 0.815 \log I_e - 9.26 - \log h$), where R_e is in kiloparsec. Each cluster sample mean deviation from the global template provides an estimate of that cluster peculiar velocity (see Tab. 1).

Figure 1 shows an edge-on view of the FP relation for the combined sample, composed of 257 galaxies. The solid line is the projection of the template relation (1). The dispersion around this relation, measured as the rms scatter of the residuals in $\log R_e$, is 0.088, equivalent to an uncertainty of 20% in the distance estimate of a single galaxy, or of 0.44 magnitudes in the estimate of its distance modulus. No correlation is present between the residuals from the FP relation and the most important galaxy parameters, like luminosity and ellipticity, or

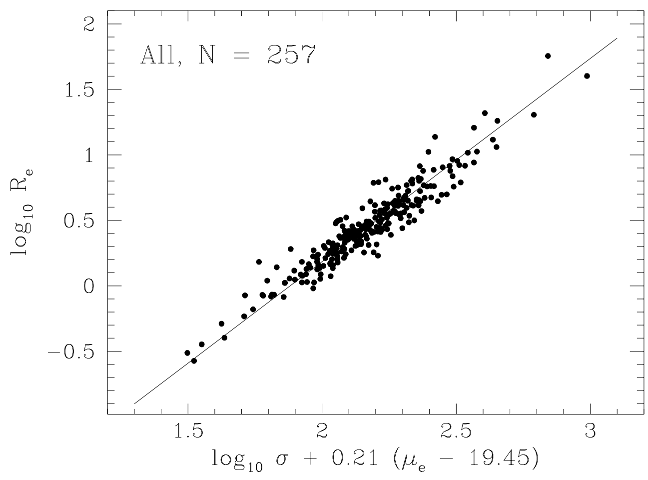

Fig. 1. Edge-on projection of the FP.

the FP parameters themselves. Also no significant difference is found in the FP template when only E or only S0 galaxies are considered.

A simple test for the presence of environmental effects can be performed analyzing the distribution of FP parameters as a function of cluster properties like the velocity dispersion, and the X-ray luminosity and temperature. All these quantities provide a measure of the richness of the cluster, and of its degree of dynamical evolution, and therefore should provide a measure of the strength of the environmental effects that might bias the FP relation. In agreement with the results of Jørgensen et al. (1996), we find no significant correlation between FP parameters and cluster properties, for a sample that spans two orders of magnitude in X-ray luminosity, and approximately a factor of three in velocity dispersion. No significant differences in the FP relation as a function of position within the cluster are found, either.

4 TF–FP Comparison

Giovanelli et al. (1997b) have obtained cluster peculiar velocities based on TF measurements, using the same approach described in the previous paragraph. The main difference between those peculiar velocities, and the ones derived here using the FP, is that their TF template was obtained using a larger, more evenly distributed in the sky, cluster sample. We list in Tab.1 their estimates of the peculiar velocity for the six clusters discussed here, together with our estimates based on the FP relation. A comparison of the six pairs of measurements is shown in Fig.2, where the solid line represents the one-to-one correspondence of the measurements. The good agreement between the two methods is evident.

Table 1. TF and FP peculiar velocities

Cluster	V_{CMB} (km s^{-1})	FP V_{pec} (km s^{-1})	TF V_{pec} (km s^{-1})
N507 gr.	4808	422±238	206±262
A262	4642	-156±203	0±187
A1367	6735	-117±352	-62±206
Coma	7185	43±196	228±214
Pegasus	3519	58±247	16±168
A2634	8895	-307±336	61±378

The new FP measurements have contributed to a solution of the A2634 discrepancy, by showing that the large peculiar velocity estimate obtained by Lucey et al. (1991) was a spurious result (Scodeggio et al. 1997). There is also much better agreement than before for the remaining 5 clusters in the sample, although no discrepancy comparable to the one in A2634 was evident within the older, less accurate, distance estimates for those clusters. The agreement between the FP and TF sets of measurements could be even better if the different cluster samples used in deriving the two relation templates are taken into consideration. Within the larger Giovanelli et al. (1997b) TF sample, the six clusters discussed here have an average peculiar velocity of 75 km s^{-1}, while the FP peculiar velocities average to zero by definition. If we were to impose for this last sample a mean peculiar velocity equal to that obtained with the TF relation, this would slightly improve the agreement between the two methods.

We conclude that the absence of any significant difference in the form of the FP and TF relation as a function of cluster environment (this work, and Giovanelli et al. 1997b), and the good agreement between the distance-scales based on the two relations (this work) give strong support to the hypothesis of universality for both the TF and the FP relation. In particular no discrepancy of statistical significance has been observed in the comparison of cluster peculiar velocities, for clusters that have very different richness and therefore represent a rather diversified environment for both the early and late-type galaxy populations. It seems at this point undesirable to try to observe fainter galaxies in the attempt to improve on the accuracy achieved here for individual cluster measurements, because of the possible breakdown of the TF and FP relations for low mass galaxies, and because of many observational complications. Any further study of the universality of the two relations would therefore require a much larger sample than the present one, to obtain reliable statistics on the distribution of the differences in the two distance-scales. However, given the results discussed here, the existence of any environmental bias that could alter the TF or FP template by more than 5% seems extremely unlikely.

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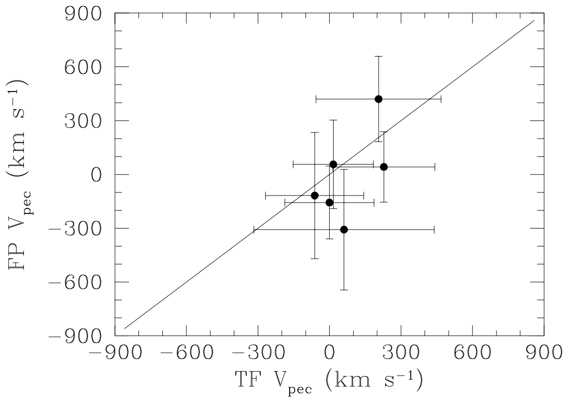

Fig. 2. Comparison of the TF and FP peculiar velocity estimates

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