Chapter 7

Comparison of Fundamental Plane and Tully–Fisher distance estimates

7.1 Introduction

The Fundamental Plane and the Tully-Fisher relation are useful tools for observational cosmology insofar as they are universal relations, as already discussed in section 1.3 and 1.5. The template relations that are used at low redshift to measure peculiar velocities, and at high redshift to measure changes in the mass-to-light ratio in galaxies, must provide an adequate description of the properties of early- and late-type galaxies, independent of the galaxy location, in order for those measurements to be of any practical value. However there are many reasons to believe that environmental effects, linked to the varying density of matter between the field and the richest clusters of galaxies, might alter systematically some important galaxy physical properties, and thus some of the galaxy observable properties, and result in a lack of universality for the TF and FP relations (see, once again, the discussion in section 1.3). In the end, because of the empirical nature of the TF and FP relations, their universality (or lack thereof) must be observationally verified. However this verification is complicated by the presence of statistical biases, that affect the derivation of TF and FP templates, and thus of redshift-independent distance estimates, and by the non-negligible uncertainties with which, even without biases, those distance estimates are obtained. The most careful treatment of statistical biases, and the use of the largest available samples (to reduce statistical uncertainties) are required if one is to deal with the question of universality in a meaningful way. Unfortunately both these requirements were seldom satisfied in previous studies on the subject.

A first assessment of the degree of universality of both the FP and the TF can be obtained comparing the templates (or the peculiar velocity estimates) that one would obtain using only galaxies in high or in low density environments, like for example separating galaxies found in cluster's cores from galaxies found at the cluster's peripheries (but here projection effects can complicate the comparison), or separating galaxies found in rich, dense clusters from galaxies found in poor, low density ones. Using this approach Djorgovski, de Carvalho & Han (1988) found strong indications of non-universality for both the TF and the FP relations. However their cluster samples were rather small (on average each cluster sample was composed of 15 objects), and they were not corrected for the cluster population incompleteness bias. This evidence has now been proven to be entirely spurious, and no indication of environmental effects in the FP and TF relations is given by these low density / high density tests, as discussed in section 5.5 and in Jørgensen *et al.* (1996) for the FP, and in G97b for the TF.

Another direct test of the universality of FP and TF is provided by the comparison of the distance scales (or, equivalently, of the peculiar velocity estimates) obtained using the two relations separately. Because of the uncertainties with which distance estimates are obtained, and because the two relations apply to galaxies of different morphological type, it is not possible to obtain a comparison on a galaxy-by-galaxy base, but only averages obtained over a rather large number of galaxies can be effectively compared, and clusters of galaxies are the preferred objects for this exercise. A cluster of galaxies provides samples of early- and late-type galaxies that are at the same distance from the observer, assuming the samples are selected using reliable cluster membership criteria. Its distance estimates obtained using the FP and the TF are thus expected to coincide. Therefore any difference between the two estimates, once the relevant statistical biases that affect those estimates have been properly accounted for, is a measure of the lack of universality of the two relations.

Comparisons of clusters distance estimates have been made a number of times in the past. To summarize the situation as it was before the beginning of the work described here, it is convenient to use a compilation of peculiar velocity estimates for nearby clusters and groups presented by Mould *et al.* (1991, see their Table 7). Figure 7.1 shows the peculiar velocity estimates obtained using early- and late-type galaxy samples in 17 clusters and groups. The empty square shows the estimates obtained for A2634 by Lucey *et al.* (1991a) and by Aaronson *et al.* (1986), which were not included in the Mould *et al.* compilation. The solid line in the figure indicates the expected one-to-one correspondence between the pairs of peculiar velocity estimates. The immediate conclusion that one would derive from this comparison, given the large scatter it shows, is that the two relations are not universal, or that the velocities are derived from inadequate template relations. Indeed Mould *et al.* (1991) conclude that, assuming that early- and late-type galaxies are indeed at the same distances, uncertainties in the distance estimates of those clusters and groups must be significantly larger than quoted. The simplest interpretation of this result would be that the extra uncertainty is contributed by environmental effects, and from the amount of extra uncertainty required to reproduce the observed scatter one could derive an estimate of the degree of universality of TF and FP. From the analysis of the most deviant pair of distance estimates, those of A2634, Lucey *et al.* (1991a) conclude that environmental effects might introduce uncertainties of up to 20% in distance estimates obtained with the FP relation.

The main limitations of the data-set collected by Mould *et al.* (1991) are in its rather heterogeneous nature, and in the often inadequate cluster membership assignments. Peculiar velocity estimates for different clusters were obtained using different templates, or data of significantly different quality. Even more important is the absence of corrections for the cluster population incompleteness bias in deriving those estimates. Finally, this data set lacks high accuracy velocity estimates. Because the sample used for each cluster were rather small, the uncertainties in the peculiar velocity estimates are all rather large, with a mean value of $\sim$400 km s^{-1}. Therefore it is not possible to say with any degree of confidence that the observed discrepancies are truly due to environmental effects, and even if this were to be the case, the quantitative limit on the TF and FP degree of universality that one could derive would not be very significant, because of the large

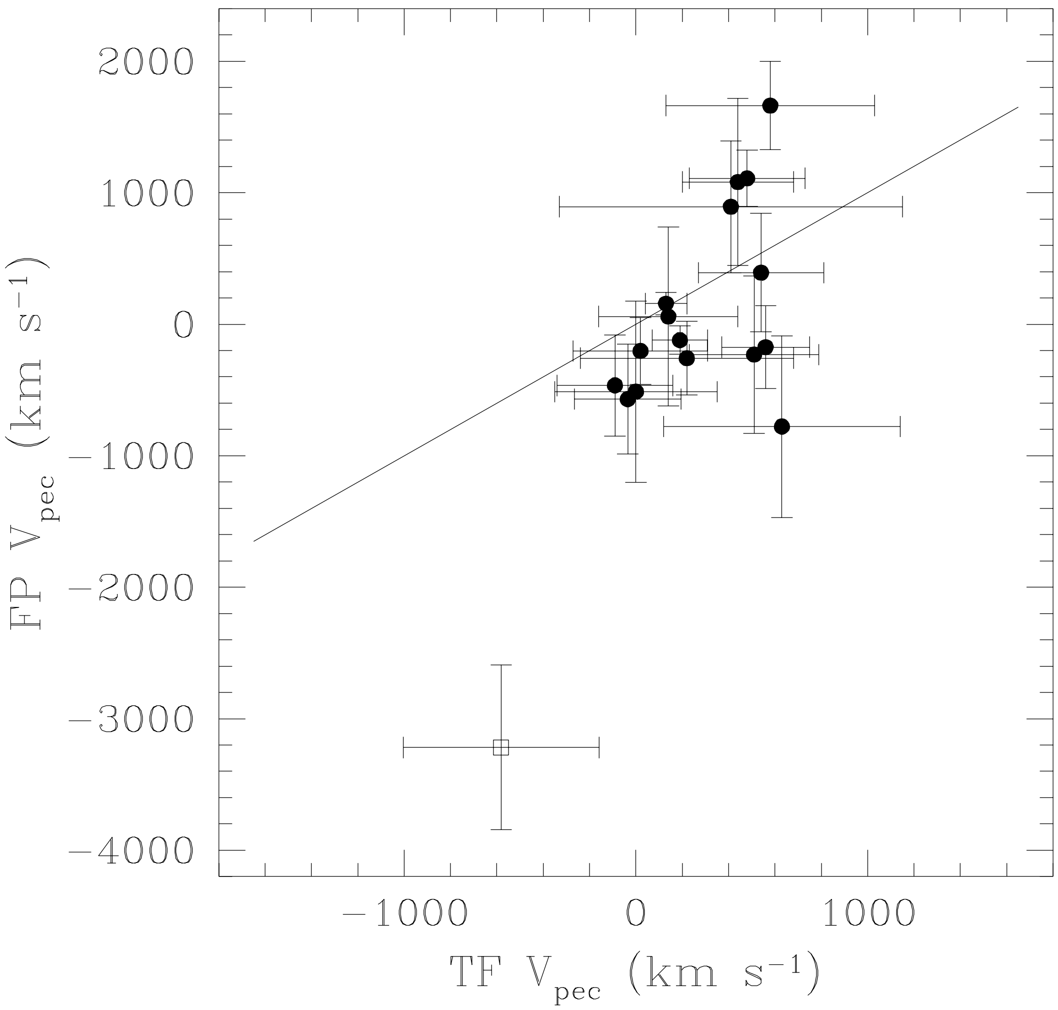

Figure 7.1 Comparison of peculiar velocity estimates obtained using the TF and the FP/$D_n - \sigma$relations, in 17 nearby clusters and groups of galaxies. This is a collection of data published prior to 1991, taken from Mould *et al.* (1991). The open square indicates the data for A2634, from Lucey *et al.* (1991a) and Aaronson *et al.* (1986), not included in Mould *et al.* compilation. The solid line is the one-to-one expected correlation between pairs of estimates.

Table 7.1 Comparison of peculiar velocity estimates

Cluster	V_{CMB} (km s^{-1})	N$_{FP}$	FP V_{pec} (km s^{-1})	N$_{TF}$	TF V_{pec} (km s^{-1})
N383 gr.	4865	20	429±290	20	60±288
N507 gr.	4808	28	234±253	13	223±270
A262	4642	35	-105±232	31	-32±203
Cancer	4939	8	210±434	26	250±213
A1367	6735	33	245±471	33	43±211
Coma	7185	109	-51±265	40	176±229
Pegasus	3519	13	64±250	18	-49±186
A2634	8895	48	-330±396	23	-279±385

uncertainties in the individual peculiar velocity estimates.

7.2 FP and TF comparison

Using the data-set presented in chapter 5 for the FP relation, and part of the data-set presented by G97a,b for the TF relation, it is possible to perform a comparison of peculiar velocity estimates similar to the one presented in Figure 7.1, for a sample of eight clusters. The key ingredients in this new comparison are: (a) larger data-sets than previously available for the estimate of peculiar velocities, that results into statistically more accurate estimates, (b) a careful cluster membership assignment process, and (c) the use of reliable corrections for the cluster population incompleteness bias in deriving those peculiar velocity estimates. Another important ingredient is the high degree of homogeneity in the two data-sets being compared. All TF-based and all FP-based peculiar velocities were derived using a single TF and FP template. The method employed to derive the templates is essentially the same, even though the samples used in the derivation are very different (just 6 clusters for the FP template, and 14 for the TF one). All bias corrections were applied using the same methodology, even if the details of how the bias correction is computed are somewhat different (see section 5.3 and G97b for details on the bias calculations). All photometric data have been reduced following one common procedure, and they are of uniformly high quality. It should be remarked, however, that the number of cluster peculiar velocities being compared in this study is only half as large as that in the Mould *et al.* (1991) comparison.

Figure 7.2 shows the comparison of peculiar velocity estimates for the 8 clusters in our sample. The solid line indicates the expected one-to-one correspondence between the pairs of peculiar velocity estimates. Table 7.1 summarizes the FP and TF data-sets. It is immediately clear there is a significant difference between this new comparison and the comparison presented in Figure 7.1. The pairs of velocity estimates are in very

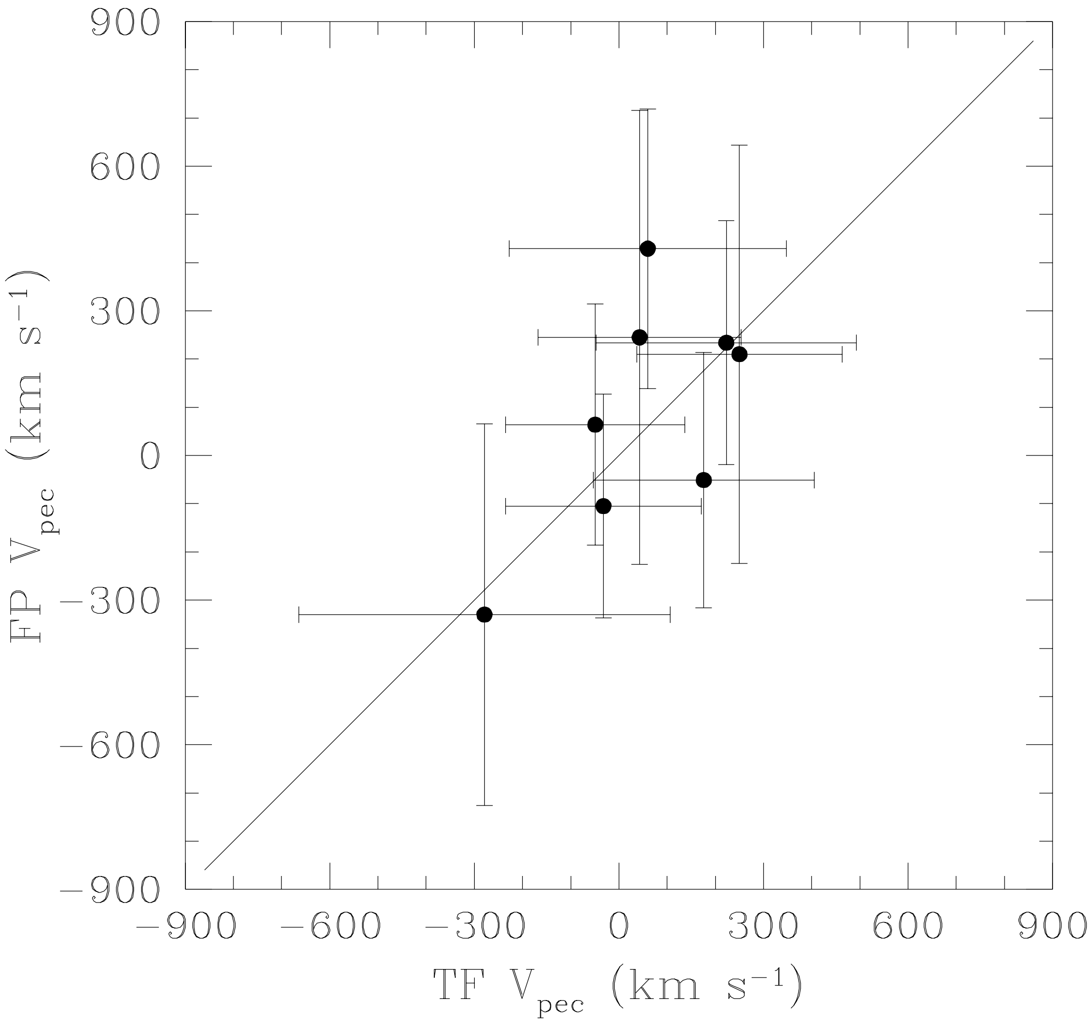

Figure 7.2 Comparison of peculiar velocity estimates obtained using the TF and the FP relations. The FP estimates are those presented in section 5.5, while the TF ones are based on the data-set presented by G97a,b. The solid line is the one-to-one expected correlation between pairs of estimates. Notice the different scale with respect to Figure 7.1.

good agreement, both individually and on average for the entire sample. The mean difference between TF and FP velocity estimates is -38±185 km s^{-1} (it was 252±875 km s^{-1} in Mould *et al.* sample), and the mean absolute difference is 136±122 km s^{-1} (it was 650±620 km s^{-1} in Mould *et al.* sample). The chi-squared per degree of freedom about the $y = x$ line is 0.20 (it was 1.49 in Mould *et al.* sample, and 2.12 if we include the most discrepant pair of measurements, those relative to A2634). Another important difference between our sample and the Mould *et al.* one is the lack of very large peculiar velocities in our sample. In the Mould *et al.* sample 6 clusters had TF and 8 clusters had FP peculiar velocities larger than 500 km s^{-1}, and 4 clusters had FP peculiar velocity larger than 1000 km s^{-1}, while in our sample no cluster has a peculiar velocity estimate larger than 430 km s^{-1}. Even in the larger sample of G97a,b only two clusters out of 24 have peculiar velocities larger than 500 km s^{-1}.

The large discrepancies observed in Figure 7.1 appear therefore to be spurious results, most likely due to the combined effect of a poor template relation and the lack of proper bias corrections. The good agreement between the TF and FP peculiar velocity estimates presented here argues strongly in favor of the universality of the two relations. Note here that the low chi-squared value of 0.20 that we obtain for the comparison of the two sets of estimates indicates that we have been, most likely, too conservative with the error estimates, and therefore that the peculiar velocity estimates listed in Table 7.1 are likely to be more accurate than we estimated. If we consider the differences between the TF and FP peculiar velocity estimates for any given cluster, ΔV_{pec}, and the ratios between this difference and the cluster systemic velocity V_{CMB}, we find that the mean absolute value of the ratios $\Delta V_{pec}/V_{CMB}$ is 0.025, that would argue for a limit to any environmentally induced spurious peculiar motion of ~2.5% of the cluster distance. These limit of course applies to environmental effects that would affect differently early- and late-type galaxies. If an effect were to exist that could alter some properties of the two galaxy populations in a way that would produce exactly the same effects on the observable parameters of those galaxies, when viewed through the TF and FP relations, it would not be bound by the limits above. However the existence of such an effect seems unlikely, given that observable parameters like the galaxy luminosity, size, internal velocity, mass-to-light ratio, enter the TF and FP relations with significantly different roles (i.e. the power-law coefficients with which these parameters enter the two relations are significantly different).

Chapter 8

Conclusions

8.1 On the FP properties

Regarding the general properties of the Fundamental Plane relation, this work has fully confirmed the recent results obtained by Guzmán *et al.* (1993) and by Jørgensen *et al.* (1996).
1) The overall linearity of the relation is confirmed.
2) Also confirmed are marginal indications that some non linearity might be present in the FP, especially at the lowermost values of $\log R_e$, where the transition between giant E and S0 galaxies and their dwarf counterparts is taking place.
This is not entirely surprising, since it has been shown that dwarf ellipticals do not follow the same FP relation delineated by the giant ones (Binggeli 1997, Held 1997). However it is also possible that some problem with the data might be present, particularly with the velocity dispersion measurements. Galaxies with $\log R_e < 0.2$ typically have a velocity dispersion ≤ 100 km s^{-1}, and the measurement of such a small velocity dispersion is rather difficult with spectra characterized by a resolution of $\sim$130 km s^{-1}. The analysis of repeated measurements (see section 4.5) has shown that the uncertainty in the velocity dispersion measurements is considerably larger for $\sigma < 90$ km s^{-1} than it is for σ larger than this value.
3) There are no significant correlations between residuals from the template FP relation and the main photometric properties of early-type galaxies, including surface brightness, apparent magnitude, luminosity, and ellipticity. A correlation is present with the galaxy velocity dispersion. This could be considered as further indication of non linearity in the FP. However, the uneven distribution of measurement uncertainties for $\log \sigma$ could play a significant role here. If an unweighted fit is used to derive the template relation, no correlation between residuals from the FP template so derived and the velocity dispersion is found.
4) The scatter shown by the FP relation is responsible for an uncertainty in the distance determination of a single galaxy of $\sim$20%, which corresponds to an uncertainty of $\sim$0.48 mag in the determination of its distance modulus. Measurement uncertainties are responsible for an uncertainty of $\sim$14%, and therefore the intrinsic scatter of the FP relation should be $\sim$16%. The precise value for the global and the intrinsic scatter depend on the coefficients of the FP template, and thus on the fitting procedure used to derive the template.
5) In agreement with Jørgensen *et al.* (1996), we confirm the absence of significant dif-

ferences between the FP relations that describe E and S0 galaxies. Small differences could be present, but the significance of this effect is dependent on the values of the FP template coefficients, and thus on the fitting procedure used to define it. Since a definitive answer on the correct method that should be used to fit the FP data is still lacking, the question of whether E and S0 galaxies obey exactly the same FP relation or not must be left unanswered. Also the problem of a correct morphological classification of relatively distant and therefore small galaxies comes into play here. Face-on S0 galaxies could easily be preferentially misclassified as ellipticals, and thus bias somehow the results about the E / S0 difference.
6) The details of the fitting procedure introduce uncertainties in the determination of the FP coefficients that are larger than the statistical uncertainties with which these coefficients are derived.
This fundamental uncertainty has important consequences. Two have been discussed above (points 4 and 5 of this section); other involve the analysis of the dynamical structure and of the processes of formation and evolution of early-type galaxies. For example, the deviation of the FP template (equation 5.9 in section 5.4) from the canonical virial expectation (equation 1.3 in section 1.3) is generally interpreted as the signature of a dependence of the mass-to-light ratio of early-type galaxies on the galaxy luminosity (see for example Faber *et al.* 1987). How strong this dependence is depends on the precise value of the FP template coefficients, most importantly on how different is the $\log \sigma$ coefficient from the virial value of 2. As another example, the intrinsic scatter in the FP relation can be used to put upper limits to the age spread, or to differences in star formation history, among early-type galaxies. The general principle is that the smaller the FP intrinsic scatter is, the more homogeneous early-type galaxies as a class must be. However the persistent uncertainty on the precise value of this intrinsic scatter, coupled with the still poor understanding of the processes of galaxy formation and evolution, prevents any quantitative use of the FP scatter as a constraint on the homogeneity of early-type galaxies.

Another important result of this work is in the demonstration that a modified version of the Fundamental Plane relation can be obtained substituting the velocity dispersion parameter with magnitude differences, computed from each galaxy observed magnitude, and a characteristic magnitude for the global cluster sample. This characteristic magnitude can be derived using the Gaussian luminosity function of giant E and S0 galaxies in the cluster, or perhaps also using the magnitude of the n^{th} brightest cluster member. This Photometric Fundamental Plane could be as effective as the regular Fundamental Plane in deriving cluster distances, provided the characteristic magnitude can be derived with an uncertainty of less than 0.25 – 0.30 mag, and it would be a lot more economical to employ, in terms of telescope time requirements.

8.2 On the universality of the FP

Regarding the universality of the FP relation, no indication to the contrary is found within our data-set (see also Jørgensen *et al.* 1996).
1) We find no correlation between the form of the FP relation (i.e. the coefficients of the $\log R_e$, $\log \sigma$ and μ_e parameters) and the principal cluster properties that measure the degree of dynamical evolution and the richness of a cluster of galaxies, like the cluster

velocity dispersion, X-ray luminosity, and X-ray temperature.
2) At the same time no correlation is found between the residuals from the FP template and the galaxy projected distances from the cluster center. While it is true that projection effects do not allow a simple conversion from projected distance to true distance for the galaxies projected near the cluster center, the existence of the morphology-density relation leads us to believe that early-type galaxies that appear projected close to a cluster center must truly be close to it. Therefore we can consider projected distance as a first approximation of true distance (once again, only for early-type galaxies), and conclude that there is no correlation between FP residuals and the galaxy distance from the cluster center.
The study of possible correlations between the FP parameters and the cluster properties, and between the FP residuals and the distance from the cluster center are two simple tests for the presence of environmental effects on the FP relation (Silk 1989, Djorgovski *et al.* 1988). The lack of any correlation, albeit in a rather small sample of 8 clusters, already shows that no strong environmental effect could be affecting the FP relation, contrary to the earlier claims by Djorgovski *et al.* (1988).

Further and more convincing proof of the universality of the FP relation is obtained applying the FP and TF relations to derive independent distance estimates to a common sample of clusters of galaxies. Significant improvements with respect to previous comparisons of this kind include the use of larger samples of TF and FP measurements than previously available, and therefore statistically more accurate distance estimates; the particular care in the derivation of a high quality FP and TF template (see chapter 5 and G97b); the accurate correction of the statistical biases that affect the samples used for the comparison. The result is that a very good agreement between the two distance scales is found.
1) Differences in individual clusters peculiar velocity estimates are generally smaller than the statistical uncertainties with which such velocities are measured.
This result, coupled also with the lack of differences in the FP parameters as a function of cluster richness (and also lack of differences in the TF parameters; see G97b) argues for the absence of any significant environmental effect on the TF and FP relations.
2) A rather strong 2-σ upper limit of 5% on environmentally induced distance errors is derived.
This conclusion relies on the fact that environmental effects are most likely to affect differently the TF and the FP relation. First, the two relations are applied to different types of galaxies, and these exhibit strong spatial segregation, with early-type galaxies found preferentially in the clusters dense cores, and late-type ones found preferentially in the clusters peripheries. Thus environmental effects like galaxy mergers, or gas stripping by the intracluster medium ram pressure, or by the cluster tidal field, or accretion of new gas through the action of a cooling-flow, are most likely to affect differently galaxies of different type. Second, parameters like the galaxy internal velocity, the mass-to-light ratio, the luminosity or the size, that could be affected by environmental effects, enter the TF and FP relation with different weights (i.e. they have different coefficients in the two relations). As a result, the same change, for example in the mass-to-light ratio, would result in a different shift away from the TF template, than it would from the FP template. Unfortunately it is still impossible, given our rather limited understanding of the physical basis of most environmental effects, to rule out completely the existence of

one such mechanism whose effects would exactly produce equivalent results on the TF and on the FP relation, and therefore escape detection in a comparison test like the one used here.

It is also important to note that the very good agreement in the peculiar velocity estimates obtained using the TF and the FP relation further confirms that most clusters peculiar velocities are rather small, as already pointed out by G97b. Among the 8 clusters studied here, no peculiar velocity larger than 430 km s^{-1} has been measured, and all measurements are consistent with the clusters being at rest in the CMB reference frame (except perhaps in the case of the N507 - N383 groups). This is a significant change from earlier results, where often peculiar velocities larger than 1000 km s^{-1} were claimed for a fraction of the clusters under study. It appears as if both the poor quality of the TF or FP template, and the lack of proper cluster population incompleteness bias corrections, were responsible for those large peculiar velocity claims.

8.3 Future work

The good agreement between independent studies on the properties of the FP makes it clear that any further improvement of our understanding in this field is mostly related to the development of a solid fitting algorithm to be used in deriving the FP template, and only marginally related to an increase in the size of the sample used to derive the template. The three-dimensional equivalent of the two-dimensional algorithm recently proposed by Akritas & Bershady (1996), that can take into consideration the covariance between variables, and the possible presence of an intrinsic scatter in the relation, would be an extremely valuable tool for FP studies. The extension of the sample to cover a larger number of clusters would be most useful for the study of environmental effects, provided that clusters even denser and with higher X-ray luminosity than Coma can be included in the sample. At the low density end of the clusters regime it would be very difficult to extend the sample significantly, because groups and poor clusters offer small samples to begin with, and often they are not very rich in early-type galaxies. It would certainly be more interesting to obtain a high quality sample of more isolated early-type galaxies, and compare those with their cluster counterparts, to check whether any significant difference, possibly related to different formation mechanisms, or different evolutionary paths, could be detected.

To further study the universality issue, the extension of the sample of clusters with high accuracy TF and FP distance estimates would be extremely valuable. Because it is impractical to extend the currently available samples to decrease the statistical uncertainty on the available peculiar velocity estimates, the only alternative way to improve on the upper limits that were set here on possible environmental effects, is to extend the sample to a larger number of clusters. Once again, this extension should focus on including denser, more X-ray luminous clusters, in order to extend as much as possible the range of probed cluster properties. This could be achieved only by studying clusters at significantly higher redshift (z $\sim$0.1–0.2) than that of the clusters in the present sample, because these very dense clusters are quite rare, and can be found in significant number only by probing large volumes of the Universe.

Of paramount importance for the development of the PFP technique will be the study of the reliability and accuracy of the determination of cluster samples characteristic magnitudes. Most studies on the use of the n^{th} brightest cluster member as a standard candle are quite old and outdated, and the question of the universality of the Luminosity Function has never been properly answered. The encouraging element here is the fact that the same data to be used to derive the PFP relation can be used to derive the characteristic magnitude, and check its reliability. On the down side, is the necessity to study a large sample of clusters, because each cluster provides just one data-point for this study. Furthermore, also in the PFP case the development of a solid fitting algorithm would be beneficial, because the problems in fitting the PFP template are equivalent to those encountered in fitting the FP template.