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An Economical Technique for the Estimate of Galaxy Distances: the Photometric Fundamental Plane

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ABSTRACT

We show that it is possible to define a purely Photometric Fundamental Plane (PFP) for early–type galaxies. This relation is similar to the standard Fundamental Plane (FP), and is obtained by replacing the velocity dispersion parameter with the difference between the magnitude of a galaxy and that of the mode of the Gaussian luminosity function of E and S0 galaxies. The use of magnitude differences as a third parameter allows a significant reduction in the dispersion of the PFP relation when compared to the Kormendy relation between effective radius and effective surface brightness, but limits the application of this method to galaxies in clusters. The dispersion of ~ 0.10 in $\log R_e$ about the mean plane in the PFP is comparable to that of the standard FP. However, the use of the mode of the luminosity function to compute the magnitude differences introduces a systematic uncertainty in the derivation of the PFP relation zero-point, so that its accuracy for distance determinations does not scale with the square root of the number of objects used to perform the fit. The method is also vulnerable to any bias that might affect the estimate of the mode of the luminosity function. If however the mode of the luminosity function can be reliably determined, the PFP relation can provide distance estimates with an accuracy comparable to the FP relation, with the advantage that the use of photometric parameters alone reduces drastically the observational requirements of the PFP, in comparison with those of the FP relation. This practical advantage makes the PFP a very economical distance indication method.

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1. Introduction

Techniques for the measurement of redshift–independent distances play a fundamental role in cosmology. Ideally, they would rely on the use of a "standard candle", i.e. a class of easily discernible objects of constant intrinsic properties. In most extensively applied techniques, e.g. those that use the Tully–Fisher (TF) relation for spirals (Tully & Fisher 1977) and the $D_n - \sigma$ or Fundamental Plane (FP) relation for spheroidals (Dressler *et al.* 1987; Djorgovski & Davis 1987), the standard candle concept is replaced by an empirically calibrated scaling relation (see also Jacoby *et al.* 1992 for a review). TF, $D_n - \sigma$ and FP all correlate a photometric, distance-dependent parameter with a kinematic, distance-independent one. Distance[3] estimates for a single galaxy are obtained with a typical uncertainty that varies between 12 and 25%. Because of this relatively high accuracy, these relations have been extensively used in mapping deviations from the universal expansion up to $cz \sim 10,000$ km s^{-1}. More recently they also have been used to study the evolution of the stellar population in high-redshift galaxies (z from 0.2 to 0.6), taking advantage of the dependence of the zero-point of both the TF and the FP relation on the galaxy mean mass-to-light ratio (see for example Vogt *et al.* 1993, Bershady 1996, van Dokkum & Franx 1996, Vogt *et al.* 1996).

From the observational view-point, the ingredients of TF, $D_n - \sigma$ and FP are analogous. Magnitudes (for TF), radii and surface brightnesses (for $D_n - \sigma$ and FP) require optical photometric data of similar quality. For a given nearby target ($z < 0.1$), a ten minute exposure of a high efficiency CCD on a 1m class telescope generally suffices. Rotational widths (for TF) or velocity dispersion (for $D_n - \sigma$ and FP) are, on the other hand, much more demanding. Larger telescopes are required than those necessary for the photometry, as well as significantly longer exposures. While the photometry of a TF, $D_n - \sigma$ or FP program can be economically acquired, the spectroscopy requires an observational investment of roughly one order of magnitude higher cost.

An economical and ubiquitously applicable distance-indication method, based entirely on photometric parameters, would be an extremely valuable tool for observational cosmology, if it were to achieve an accuracy comparable to those characteristic of the TF and FP relations. The Kormendy relation (Kormendy 1977) has been used as an economical substitute for the FP relation (Pahre *et al.* 1996). However its large scatter, and the fact that the residuals in the relation correlate with the galaxy luminosity (or, equivalently, with the galaxy velocity dispersion), make this relation extremely sensitive to bias effects, such as the cluster population incompleteness bias for cluster samples, or the Malmquist bias for field samples. Other extensively used photometric distance indicators are based on the determination of a characteristic magnitude,

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[3] Because of the uncertainty on the value of the Hubble constant, and because the number of nearby galaxies that could be used for an absolute calibration of the template relations is very small, the TF and FP relations are most commonly used to derive relative distances. Therefore here the term "distance" is used as an abbreviation for the more appropriate "recession velocity corrected for peculiar motions".

like the magnitude of the brightest galaxy in a cluster (Sandage 1972, Sandage & Hardy 1973, Hoessel 1980, Lauer & Postman 1994), or the peak of a Gaussian luminosity function (LF). The latter has been commonly employed using globular clusters or planetary nebulae within a single galaxy (see Jacoby *et al.* 1992), but it could be used with cluster E and S0 or spiral galaxies, that have a Gaussian LF (Sandage *et al.* 1985). Similarly, the LF of the global galaxy population in a cluster could be used, adopting the magnitude M_* in a Schechter LF (Schechter 1976) as a standard candle. The reliability of this application is obviously dependent on the degree of universality of the LF for clusters of galaxies. Still unexplored is another purely photometric, and potentially very useful, technique, based on a family of relations between a galaxy effective radius, effective surface brightness, and broadband colors discovered by de Carvalho & Djorgovski (1989).

Here we propose to use jointly the Kormendy relation and any one of the methods that can provide a characteristic magnitude for a cluster sample, to derive a modified version of the FP relation, based entirely on photometric parameters. We define for each galaxy ΔM as the difference between the galaxy's magnitude and the sample characteristic magnitude, and use ΔM, a distance–independent parameter, in substitution of the velocity dispersion in the FP relation. We illustrate the characteristics of such a Photometric Fundamental Plane (PFP) with a sample of 405 early-type galaxies in the Coma, A1367, and A2634 clusters. The characteristic magnitude for each cluster sample is obtained from the peak of the Gaussian LF that best approximates the sample magnitude distribution. This procedure is quite similar to the one previously used by de Carvalho & Djorgovski (1989), with the difference that those authors used broadband colors as a substitute for the velocity dispersion in the FP relation. The main advantage of the PFP relation is the improved accuracy it provides with respect to both the Kormendy relation and the method used to derive the sample characteristic magnitude. Such accuracy however depends on the reliability of the characteristic magnitude. First, and most important, any observational bias that affects the measurement of this magnitude will affect the PFP relation as well. Second, the uncertainty with which this magnitude is derived becomes a systematic uncertainty in the derivation of the PFP zero point. Therefore the accuracy of this derivation does not scale with the square root of the number of objects used in the fit, but is limited to a fraction of the uncertainty in the determination of the characteristic magnitude.

This paper is organized as follows: in section 2 we discuss the data used to obtain the PFP relation. The derivation of the PFP and its accuracy for distance determinations are discussed in section 3, while the discussion and conclusions are in section 4. Distance-dependent parameters are computed assuming $H_\circ$=100 h km s^{-1}Mpc^{-1} .

2. The data

As part of a study aimed at the cross–calibration of the TF and FP techniques, we obtained I band CCD images of early-type galaxies in 10 nearby clusters, including Coma, A1367, and A2634, with the 0.9m telescope of the Kitt Peak National Observatory (KPNO), during 3 observing runs between 1994 April, and 1995 September. The telescope was used with the f/7.5 secondary, field corrector and T2KA CCD chip (2048 x 2048 pixels), to obtain a field of view of 23′ x 23′, with a spatial scale of 0.68″ per pixel. The median effective seeing (the median FWHM of the stellar profiles) for these observations was 1.6″. All frames were obtained with 600 seconds integration time. Observations of Landolt fields (Landolt 1992), both at I and at R band, were repeated many times during each night, at airmasses between 1.2 and 2.5, to obtain the photometric zero point calibration and the atmospheric extinction coefficient. The mean uncertainty in the zero point calibration at I band was 0.021 magnitudes.

Complete details on the observations and the data reduction procedure will be presented elsewhere (Scodeggio 1997, Scodeggio *et al.* 1997b). Here we briefly summarize those details. All CCD frames were reduced using standard IRAF[4] procedures, and surface photometry measurement were obtained using the GALPHOT surface photometry package written for IRAF/STSDAS[5] by W. Freudling, J. Salzer, and M.P. Haynes. All frames were bias-subtracted, flat-fielded, and sky background-subtracted using the mean number of counts measured in 10-12 regions of "empty" sky. The uncertainty in the sky background is typically 0.2%. All pixels contaminated by the light of foreground stars or nearby galaxies, or by cosmic rays hits, were blanked, and excluded from the final steps of surface photometry.

Photometric measurements were obtained for all early-type galaxies with an available redshift measurement, and that are to be considered cluster members according to the criteria described by Giovanelli *et al.* (1997a). In addition a small number (64 galaxies out of the total 405) of galaxies that do not have redshift measurements available was included in the sample, because their size and luminosity make them likely cluster members. The 2-dimensional light distribution of each galaxy was fitted with elliptical isophotes, using a modified version of the STSDAS *isophote* package, maintaining as free parameters the ellipse center, ellipticity and position angle, and incrementing the ellipse semi-major axis by a fixed fraction of its value at each step of the fitting procedure. The fitted parameters yield a model of the galaxy light distribution, which is used to compute integrated magnitudes as a function of semi-major axis. For each galaxy the effective radius r_e and the effective surface brightness μ_e (the mean surface brightness within r_e) were obtained by fitting the radial surface brightness profile with a de Vaucouleurs $r^{1/4}$ law. 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 and μ_e is 5% and 0.06 mag., respectively. Total magnitudes were obtained independently from the $r^{1/4}$ fit, by extrapolating the $r^{1/4}$ fit to infinity (E galaxies), or

[4]IRAF (Image Reduction and Analysis Facility) is distributed by NOAO, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.

[5]STSDAS (Space Telescope Science Data Analysis System) is distributed by the Space Telescope Science Institute, which is operated by AURA, under contract to the National Aeronautics and Space Administration.

by extrapolating to infinity the exponential profile that fitted the outer parts of the galaxy light profile (S0 and S0a galaxies), and adding the flux corresponding to the extrapolated part of the profile to the one measured within the outermost fitted galaxy isophote. The median uncertainty in the determination of the total magnitude is 0.06 mag.

Standard corrections were applied for Galactic extinction, using Burstein & Heiles (1978) prescriptions, and $A_I = 0.45 A_B$, for the cosmological k-correction term (which was taken to be $2.5\log(1+z)$ because of the flat spectrum of early-type galaxies in the far red), and for the surface brightness $(1+z)^4$ cosmological dimming. Both r_e and μ_e were corrected for the effects of seeing following the prescriptions of Saglia *et al.* (1993, see in particular their figure 8).

3. The Photometric Fundamental Plane

3.1. Defining the relation

Well known correlations exist between early–type galaxy properties, such as that between luminosity and: r_e (Fish 1964), σ (Faber & Jackson 1976), and μ_e (Binggeli *et al.* 1984), and the relation between r_e and μ_e (Kormendy 1977). These correlations exhibit much larger scatter than can be accounted by measurement errors alone. The idea that early-type galaxies populate a plane in the 3–parameter space (r_e, μ_e, σ), independently introduced by Djorgovski & Davis (1987) and by Dressler *et al.* (1987), led to a significantly reduced scatter with respect to the Faber–Jackson or Kormendy relation, and made possible its use as a redshift-independent distance indicator.

Clusters of galaxies have been favorite targets for FP studies because they provide both an environment rich in early-type galaxies and large samples of objects all roughly at the same distance. Recent studies of that nature include those of Guzmán *et al.* (1993), Jørgensen *et al.* (1996) and our own (Scodeggio *et al.* 1997a). There is remarkable quantitative agreement in the FP calibration of those studies. In particular, the last two show that the r.m.s. scatter of the residuals in $\log r_e$, is $\simeq$0.085, or 20% uncertainty on the distance. For comparison, the Tully-Fisher relation has a dispersion of $\simeq$0.25–0.45 magnitudes (equivalent to a distance uncertainty of 12–24%, depending on the galaxy's rotational velocity; Giovanelli *et al.* 1997b).

The Kormendy (1977) relation between r_e and μ_e has been recently used by Pahre *et al.* (1996) as an economical substitute of the FP in two high redshift clusters, to obtain an improved version of the classical Tolman test for the expansion of the Universe. The scatter in the Kormendy relation is fairly large, and little use can be found for it as a distance indicator for single galaxies. However the disadvantage of the large scatter can be partly offset by the advantage of having a relation between two purely photometric parameters, when the relation is applied to clusters of galaxies. In a rich cluster, the large number of objects can statistically compensate for the large scatter in the relation in deriving the cluster distance. In Figure 1 we present the Kormendy relation for 405 E and S0 galaxies in the Coma, A1367, and A2634 clusters. The least squares, direct linear fit to this data set[6] is given by

$$\log R_e = 0.284(\mu_e - 19.45) + 0.495 - \log h \tag{1}$$

where R_e is in kiloparsec, and is computed placing each galaxy at the distance indicated by the cluster redshift, in the CMB reference frame. In doing this we are ignoring the possible effect of peculiar motions on the derivation of R_e, because the peculiar velocities of Coma, A1367 and A2634 have been shown to be quite small (Giovanelli *et al.* 1997b, Scodeggio *et al.* 1997a). The r.m.s. scatter in $\log R_e$ is 0.19, equivalent to an uncertainty of 0.95 mag in the distance modulus of a single galaxy. However, the statistical uncertainty in the fit zero point, because of the large sample being used, is only 0.010, equivalent to 0.05 mag, or to a distance uncertainty of 170 $\mathrm{km\,s^{-1}}$ at the distance to the Coma cluster.

Figure 2 shows the well known fact that the residuals from the Kormendy relation (1) are not random: they correlate very well with the galaxy magnitude, or, equivalently, with the galaxy velocity dispersion, bright galaxies exhibiting systematically positive residuals. We remark that the magnitudes used here are derived directly from the observed galaxy light distributions, and are therefore measured independently from the r_e and μ_e parameters. Because of the combination of the large scatter with residuals that are correlated with the galaxy luminosity, the Kormendy relation is severely affected by the cluster population incompleteness bias (Teerikorpi 1987, Sandage 1994a,b). The measured zero point and dispersion of the Kormendy relation depend on the limiting magnitude of the sample, as can be inferred from Figure 2 if we imagine the removal of all galaxies fainter than a certain limit. It is therefore very important to derive accurate bias corrections before using the Kormendy relation for cosmological applications like redshift-independent distance measurements.

It is clear that the two correlations shown in Figure 1 and 2 can be combined to produce a global relation in the 3-parameter space of $\log R_e$, μ_e, and M. This could be used, in principle, as a distance indication relation, where μ_e would be the distance-independent parameter, and $\log R_e$ and M would be the distance-sensitive parameters, derived from the observed $\log r_e$ and m assuming all galaxies are at the distance indicated by the cluster redshift. Unfortunately, the best fitting plane to the $\log R_e$, μ_e, M relation is given by

$$\log R_e = -0.13\ M + 0.26\ \mu_e + const. \tag{2}$$

and the combination of distance-dependent parameters $\log R_e + 0.13\ M$ is quite close to the distance-independent combination $\log R_e + 0.2\ M = \log r_e + 0.2\ m$. Equivalently, the best fitting plane (2) is almost parallel to the distance-independent plane

$$m = \mu_e + 5 \log r_e + const. \tag{3}$$

[6]This is likely to be a biased estimate of the true relation between $\log R_e$ and μ_e, because the fitting does not take into proper consideration the correlation between the measurement errors for the two parameters, but a detailed discussion of the Kormendy relation is beyond the purpose of this paper.

that would be populated by a perfectly homologous family of early-type galaxies, making the relation (2) of little practical use for distance determinations. However, if a characteristic magnitude could be defined in a distance-independent way for each cluster sample, this relation could be re-written in terms of the magnitude difference ΔM with respect to the characteristic magnitude, instead of the galaxy total magnitude. In this way a relation completely analogous to the FP relation could be obtained, using only photometrically derived parameters, since magnitude differences are distance-independent quantities.

3.2. The characteristic magnitude

A number of methods are available for the determination of a characteristic magnitude for a cluster sample, using only photometric data. Sandage (1972), and Sandage & Hardy (1973) have used the luminosity of the first ranked galaxy in a cluster to study the linearity of the Hubble flow out to very large distances. These authors claim that all such galaxies have approximately the same luminosity, with a dispersion of only 0.28–0.32 magnitudes (depending on the sample used). A modified version of this distance-estimation method was proposed by Hoessel (1980), and has been used most recently by Lauer & Postman (1994) to study the motion of Abell clusters with $cz \leq 15,000$ km s^{-1}. The uncertainty associated with this method has been estimated to be approximately 16%, or 0.35 magnitudes (Lauer & Postman 1994). Also LF's have been used as distance indicators. Well known is the use of the globular clusters and planetary nebulae LF (see Jacoby *et al.* 1992, and references therein) to derive redshift-independent distances for individual galaxies. The same technique can be applied to the galaxy LF in a cluster, provided that such LF is universal. Since giant E and S0 galaxies and spiral galaxies have been shown to have a Gaussian LF (Sandage *et al.* 1985), its peak M_{peak} can provide an accurate estimate of a characteristic magnitude. Similarly, fitting a Schechter LF (Schechter 1976) to the entire cluster population might provide a characteristic magnitude, in terms of the parameter M_*. Typical statistical uncertainties associated with the determination of M_{peak} and M_* are 0.2 and 0.3 magnitudes, respectively (see, for example, Jacoby *et al.* 1992, and Marzke *et al.* 1994).

Here we use a Gaussian fit to the LF of E and S0 galaxies to determine the characteristic magnitude for our cluster samples. The fit is performed using a maximum likelihood method (Malumuth & Kriss 1986), combining the 3 cluster samples, and excluding the brightest galaxy in each cluster from the fit. As in the case of the Kormendy relation, we compute absolute magnitudes assuming that each galaxy is at the distance indicated by the cluster redshift, in the CMB reference frame, and ignoring the effect of possible peculiar motions (known, as we said, to be quite small) on the redshift-distance conversion. The best fitting Gaussian LF yields $M_{peak} = -20.55$, with a dispersion of 1.25 magnitudes. This is in good agreement with the location of the peak observed in the Coma cluster LF by Biviano et al. (1995) and with the Gaussian LF obtained by Sandage *et al.* (1985) for a complete sample of E and S0 galaxies in the Virgo cluster, when an average (B–I) color of $\simeq 2.15$ for early-type galaxies is assumed. Figure

3 shows the results of the maximum likelihood fitting. In Fig. 3a the stair-step line represents the observed integral magnitude distribution, while the smooth curve is derived integrating the best fitting Gaussian. The inset show the best fitting Gaussian parameters, and the 68% (1σ) and 95% (2σ) joint confidence contours for those parameters. In Fig. 3b the histogram shows the differential magnitude distribution, with bins of width 0.4 mag, and the solid line curve shows the best fitting Gaussian. The completeness limit for the sample is shown by the vertical dashed line. The statistical uncertainty in the determination of the Gaussian peak is $\simeq 0.22$ mag. However it still remains to be demonstrated that the location of this peak does not change systematically as a function of cluster parameters like the dynamical evolution state, the richness, or the density of the intra-cluster medium.

3.3. The PFP and its accuracy

Defining $\Delta M = M - M_{peak}$, we see the E and S0 galaxies populating a plane in the purely photometric 3-parameter space ($\log R_e$, μ_e, ΔM), which we term the Photometric Fundamental Plane or PFP. Figure 4 shows an edge-on view of the PFP for the combined sample of Coma, A1367, and A2634 E and S0 galaxies. The best fitting plane, obtained averaging the results of the 3 possible fits that can be performed using one parameter as the dependent variable and the remaining two as the independent ones, is given by the relation

$$\log R_e = -0.13\ \Delta m + 0.264(\mu_e - 19.45) + 0.464 - \log h \tag{4}$$

We remark that the coefficients derived here for equation (4) should be considered only provisional, because of the difficult statistical problem of fitting a relation among parameters that do not have zero covariance. From this point of view the PFP case is very similar to the FP one, because measurement errors in $\log R_e$ and μ_e are strongly correlated, but they have negligible correlation with the measurement errors in ΔM, because total magnitudes are determined independently from the $r^{1/4}$ fit used to determine $\log R_e$ and μ_e.

A hint of non-linearity in the relation is apparent. However, the use of a quadratic relation produces a fit that is not significantly better than the one obtained using equation (4). A much larger sample will be required to settle this point. The r.m.s. scatter in $\log R_e$ about the PFP plane is 0.096, which is approximately half the scatter shown by the Kormendy relation, and very similar to the scatter shown by the FP relation, as discussed above. This scatter, however, is not the only source of uncertainty in the determination of a cluster distance with the PFP. The uncertainty with which the characteristic magnitude is determined introduces a systematic uncertainty in the determination of the PFP zero-point, that must be added to the statistical uncertainty produced by the scatter. Because this last term scales approximately with the square root of the number of data-points, for a large sample the systematic uncertainty due to the characteristic magnitude determination becomes the dominant source of error in a cluster distance determination. However, the value of the ΔM coefficient in the PFP is such that the effect of this systematic uncertainty on distance determinations performed with the PFP is less severe than it would be on the equivalent determination based solely on the characteristic magnitude. In the latter case the distance uncertainty σ_d is related to the characteristic magnitude uncertainty σ_M by the usual $\sigma_d/d = 0.2 \ln 10\ \sigma_M$, whereas in the PFP case the relation (considering only the characteristic magnitude contribution) is $\sigma_d/d = 0.13 \ln 10\ \sigma_M$, which is $\simeq 1.5$ times smaller.

Figure 5 shows a comparison of the accuracy in distance determinations that can be obtained using the Fundamental Plane, the PFP, and the Kormendy relation, as a function of sample size. We assume that in all cases statistical uncertainties scale with the square root of the number of objects used in the fit. The horizontal dashed lines give the accuracy achieved using the FP with a fixed sample size of 10, 20, or 30 galaxies, typical of the samples currently being used for distant and nearby clusters. The scatter in the FP is assumed to be 0.085 (0.43 mag in distance modulus; see Jørgensen *et al.* 1996, and Scodeggio *et al.* 1997a). The two solid line curves give the accuracy achieved using the PFP, for two different values of the uncertainty associated with the determination of the characteristic magnitude (0.25 mag for the upper curve, and 0.15 mag for the lower curve), for a scatter in the PFP of 0.096 (0.48 mag in distance modulus). The dotted line gives the accuracy obtained with the Kormendy relation, for a scatter of 0.19 (0.95 mag in distance modulus), and assuming that the sample completeness bias corrections do not introduce further uncertainties. In this sense, and also because our sample is incomplete at the fainter magnitudes and therefore we are under-estimating the true scatter in the Kormendy relation, this line should be considered an over-optimistic estimate of the accuracy achievable with the Kormendy relation.

4. Discussion and Conclusions

As in the case of the relations described by de Carvalho & Djorgovski (1989), the PFP can be understood as a generalization of the fundamental plane relation of early-type galaxies. Although our understanding of the processes of galaxy formation and evolution is still relatively limited, the mass of a galaxy appears to be the fundamental regulating parameter. Because of this, many observable quantities, like the galaxy luminosity, velocity dispersion, metallicity, and broad-band colors, are correlated with the mass, and therefore with each other. The precise form of those correlations is not always well constrained, but a subset exists, including the FP, the PFP and the relation suggested by de Carvalho & Djorgovski, that appears to yield a tighter description of early-type galaxies, within the limits imposed by measurement uncertainties and the intrinsic scatter present among FP-like relations.

The PFP can be a useful tool for observational cosmology. Its most positive characteristics are the relatively modest observational requirements, combined with its potential accuracy. The PFP relation requires only the photometric observations necessary also for the FP relation, without any need for spectroscopic observations. The characteristic magnitude required by the method can be derived from the photometric observations as well, in the form of the mode of the LF, or directly using the magnitude of the $n^{\rm th}$ brightest cluster member. This requirement, however, limits the applicability of the method to clusters of galaxies, and places the ultimate limit to its accuracy.

The accuracy of the PFP zero-point is constrained by the uncertainty in the measurement of the characteristic magnitude. We have seen that, at best, the uncertainty in the PFP zero point can be ∼60% of the uncertainty in the characteristic magnitude. Moreover, the PFP is affected not only by the bias intrinsic to the derivation of a template PFP relation, but its zero point is sensitive to biases that might affect the characteristic magnitude. Correlations are known to exist between the luminosity of the brightest galaxy in a cluster and the cluster Bautz-Morgan type (Sandage & Hardy 1973), and also the cluster X-ray luminosity (Hudson & Ebeling 1997). The universality of the LF for clusters is still very much debated. Therefore extreme care will be required for the application of the PFP for distance determination. However the properties of the method used to derive the characteristic magnitude could be in principle derived from the same data used to obtain the PFP relation, and should provide the opportunity to perform stringent consistency checks.

If the characteristic magnitude can be constrained to within 0.3 magnitudes or less, the PFP can offer an accuracy in distance measurements comparable to that of the FP, for a typical FP cluster sample, requiring only one fifth to one tenth of the telescope time. Also important is the fact that the imaging observations do not require a 4-5 meter class telescope (or 8-10 meter telescope, for high redshift clusters), but can be obtained with a 1 meter class telescope.

Finally, one important point must be made regarding the use of the PFP relation at low and high redshift. At low redshift, where the relation would be used to measure deviations from the Hubble flow, the characteristic magnitude must be derived separately for each cluster. At high redshift, instead, where the relation might be used to study evolutionary changes in the mass-to-light ratio of early-type galaxies, peculiar velocities have a negligible effect on the characteristic magnitude. Different cluster samples at the same redshift could thus be combined, improving the determination of the characteristic magnitude, and the accuracy of the PFP method.

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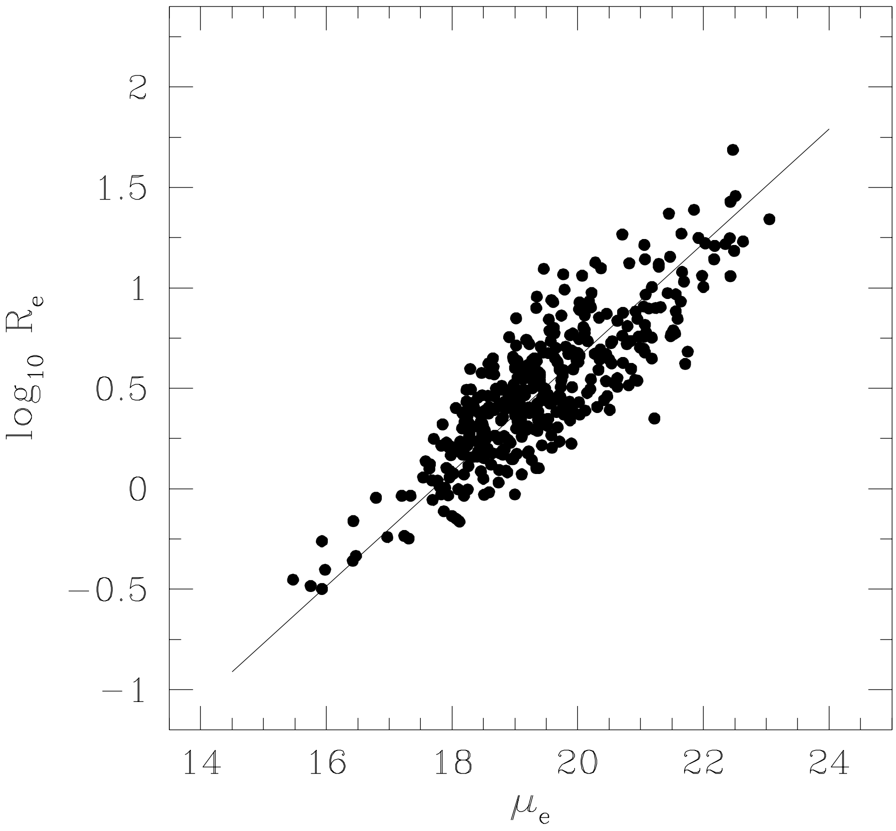


Fig. 1.— The Kormendy relation between the logarithm of the effective radius (in kiloparsec) and the effective surface brightness, for 405 early-type galaxies in the Coma, A1367, and A2634 clusters. The solid line is the best fit to the correlation (equation 1).

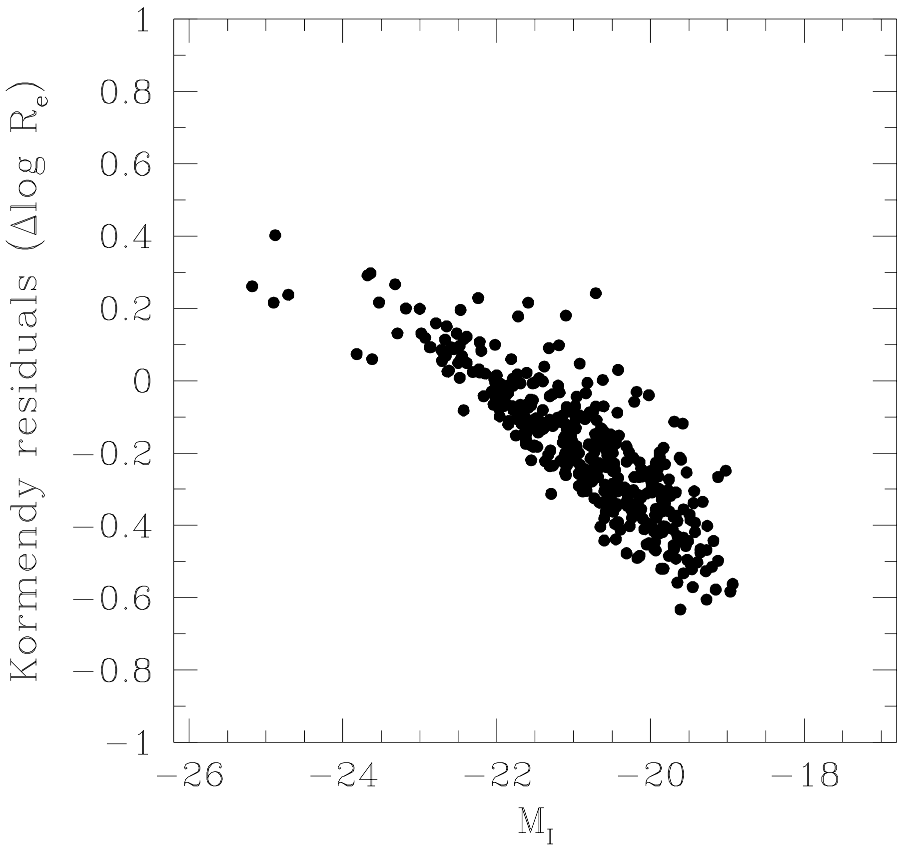


Fig. 2.— The residuals from the best line fit to the Kormendy relation (equation 1), plotted as a function of the galaxy magnitude.

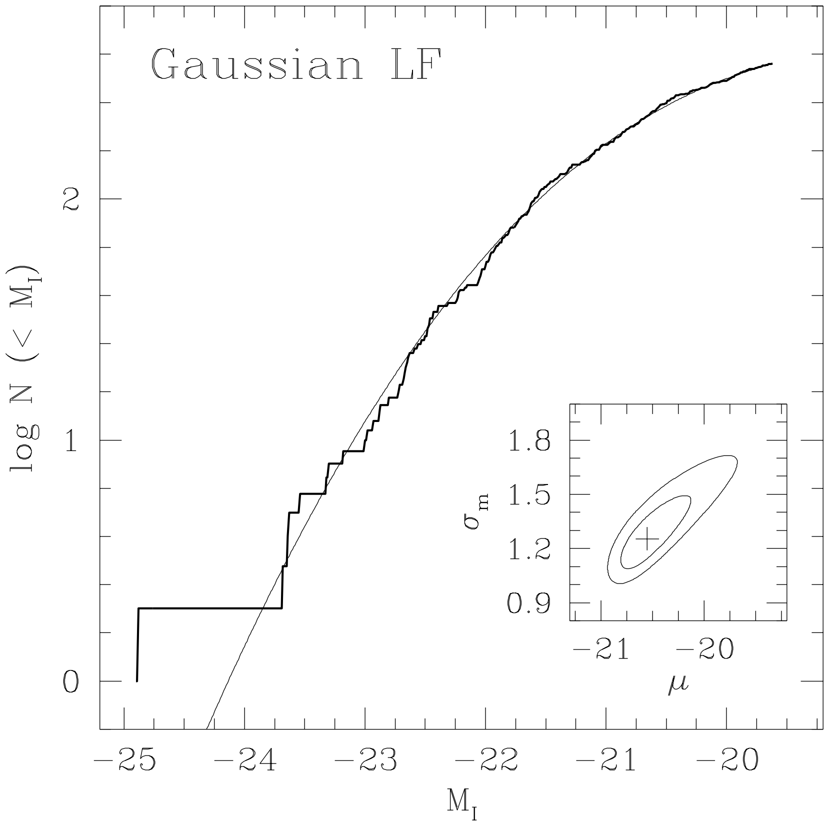
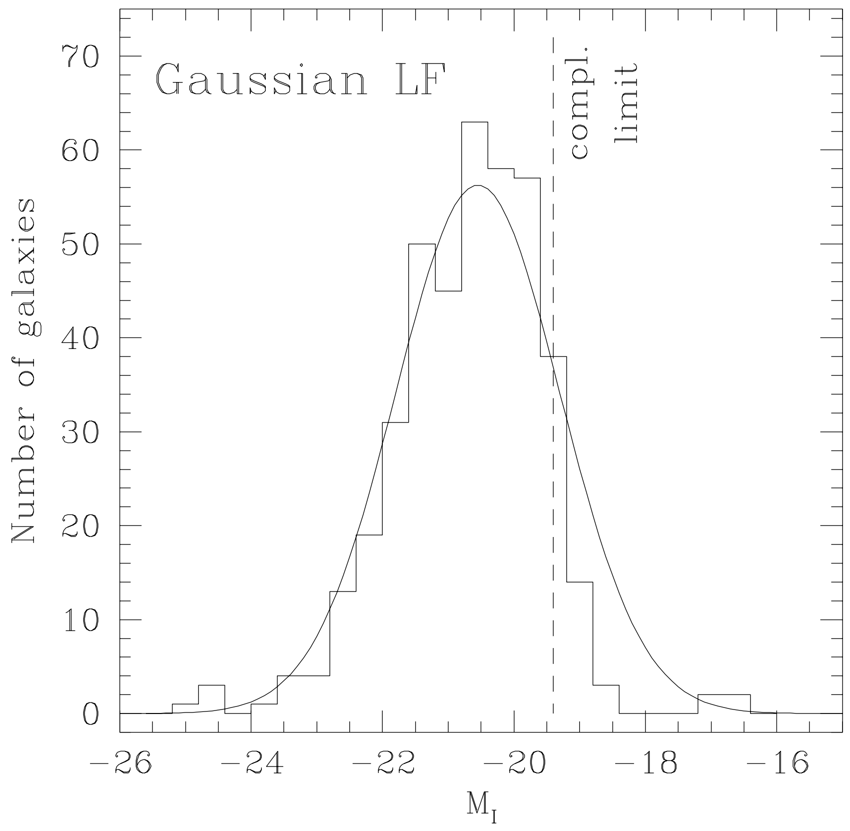


Fig. 3.— Maximum likelihood Gaussian luminosity function fit to the magnitude distribution of the combined sample of early-type galaxies. The fitting was performed excluding the brightest galaxy in each cluster. (a) The stair-steps line gives the observed integral magnitude distribution, while the smooth curve is derived integrating the best fitting Gaussian. The inset show the best fitting Gaussian parameters, and the 68% (1σ) and 95% (2σ) joint confidence contours for those parameters. (b) The histogram shows the differential magnitude distribution, within bins of width 0.4 mag., and the solid line curve shows the best fitting Gaussian. The completeness limit for the sample is shown by the vertical dashed line.



Gaussian LF
compl. limit
Number of galaxies
M_I
0
10
20
30
40
50
60
70
−26
−24
−22
−20
−18
−16

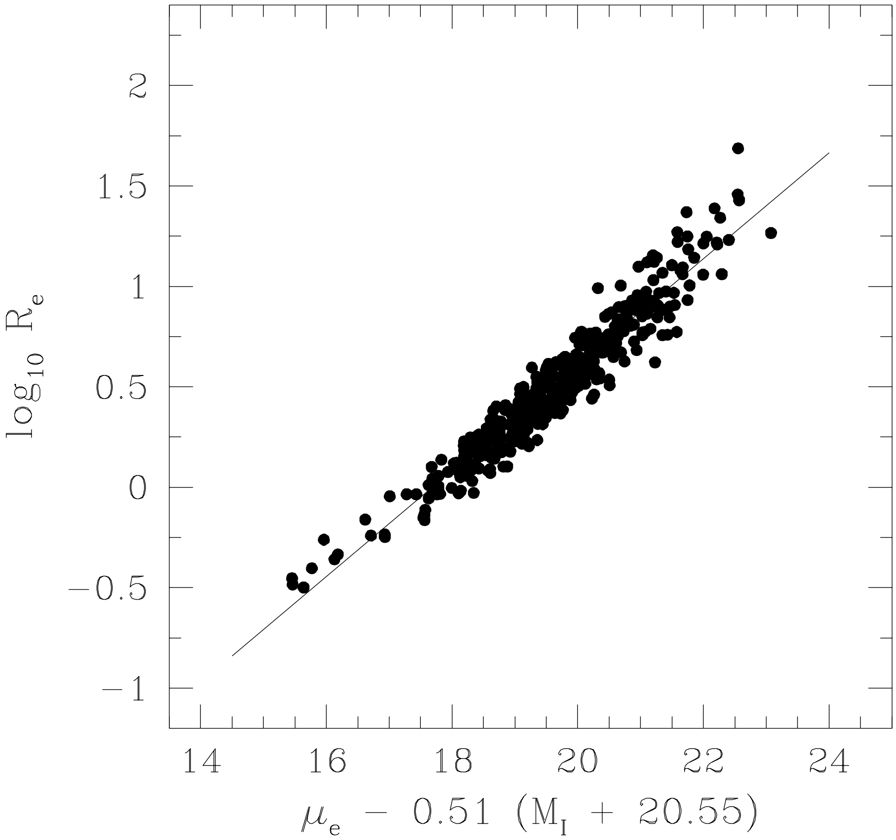


Fig. 4.— Edge-on view of the PFP. The same galaxies are plotted as in Fig. 1. The solid line is the projection of the best fitting plane (equation 4).

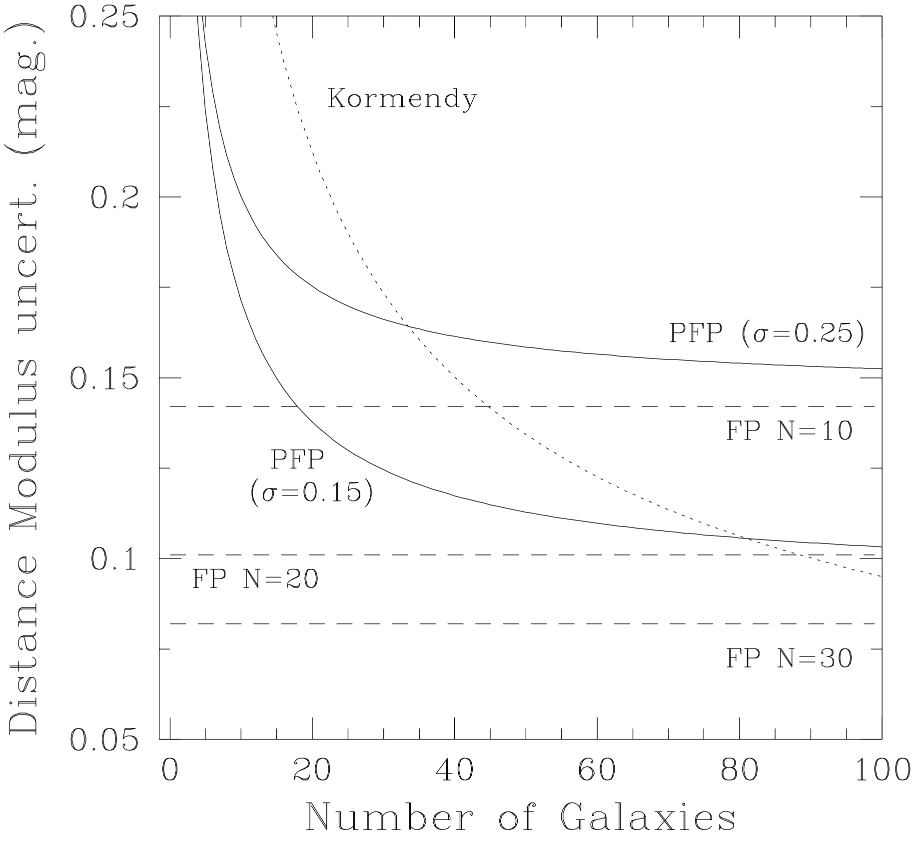


Fig. 5.— Comparison of the accuracy in a distance modulus estimate, as a function of sample size, that can be obtained using the PFP, Kormendy, and FP relation. The horizontal dashed lines give the accuracy achieved using the FP with a fixed sample size of 10, 20, or 30 galaxies (the scatter in the FP is assumed to be 0.085, or 0.43 mag.). The two solid line curves give the accuracy achieved using the PFP, for two different values of the uncertainty associated with the determination of the characteristic magnitude, for a scatter in the PFP of 0.096, or 0.48 mag. The dotted line gives the accuracy obtained with the Kormendy relation, for a scatter of 0.19, or 0.95 mag.