Mon. Not. R. Astron. Soc. **000**, 1–6 (2001) Printed 1 April 2002 (MN LaTeX style file v2.2)

The Photometric Plane of Elliptical Galaxies

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Received 2002 January 10; Accepted 2002 March 28

ABSTRACT

The Sérsic ($r^{1/n}$) index n of an elliptical galaxy (or bulge) has recently been shown to correlate strongly ($r = 0.8$) with a galaxy's central velocity dispersion. This index could therefore prove extremely useful and cost-effective (in terms of both telescope time and data reduction) for many fields of extragalactic research. It is a purely photometric quantity which apparently not only traces the mass of a bulge but has additionally been shown to reflect the degree of bulge concentration. This paper explores the affect of replacing the central velocity dispersion term in the Fundamental Plane with the Sérsic index n. Using a sample of early-type galaxies from the Virgo and Fornax clusters, various (B-band) 'Photometric Planes' were constructed and found to have a scatter of 0.14-0.17 dex in $\log r_e$, or a distance error of 38-48 per cent per galaxy (the higher values arising from the inclusion of the S0 galaxies). The corresponding Fundamental Plane yielded a 33-37 per cent error in distance for the same galaxy (sub-)samples (i.e. ~15-30 per cent less scatter). The gains in using a hyperplane (i.e. adding the Sérsic index to the Fundamental Plane as a fourth parameter) were small, giving a 27-33 per cent error in distance, depending on the galaxy sample used. The Photometric Plane has been used here to estimate the Virgo-Fornax distance modulus; giving a value of $\Delta\mu = 0.62 \pm 0.30$ mag (cf. 0.51$\pm$0.21, HST Key Project on the Extragalactic distance Scale). The prospects for using the Photometric Plane at higher redshift appears promising. Using published data on the intermediate redshift cluster Cl 1358+62 (z=0.33) gave a Photometric Plane distance error of 35-41 per cent per galaxy.

Key words: distance scale – galaxies: elliptical and lenticular, cD – galaxies: fundamental parameters – galaxies: kinematics and dynamics – galaxies: photometry – galaxies: structure

1 INTRODUCTION

Studies of supermassive black holes and the elliptical galaxies (and bulges) at whose centers they reside have revealed that the Sérsic (1968) index n can be used just as effectively for predicting the mass of the black hole as the velocity dispersion of the stars (Graham et al. 2001). Aside from the physical insight this provides into the formation of galaxy and black hole alike, it also has important practical consequences: relatively expensive spectroscopic observations can be replaced with (photometrically uncalibrated) images. Furthermore, the issue of aperture corrections for velocity dispersion measurements is bypassed completely.

This paper explores whether or not the 'Fundamental Plane' (Djorgovski & Davis 1987; Dressler et al. 1987) remains as thin (or at an acceptable/useful thickness) when the central velocity dispersion term is replaced with the Sérsic index n, producing what is called a 'Photometric Plane'. The Photometric Plane of course has a huge economical bonus in terms of telescope time. It has the potential to be an extremely cost-effective option for studies of peculiar velocity flows that use elliptical galaxies as tracers of motion (e.g., Müller et al 1999; da Costa et al. 1999; Smith et al. 2001; Gibbons, Fruchter & Bothun 2001) and for studies into the evolution of ellipticals galaxies which have, to date, used the Fundamental Plane (e.g. Jørgensen et al. 1999; Kelson et al. 2000c; Treu et al. 2001). The Photometric Plane may also potentially be used, just as the Fundamental Plane is, for many types of elliptical galaxies, such as: low redshift radio galaxies (Bettoni et al. 2001), ellipticals in compact groups (de la Rosa, de Carvalho & Zepf 2001), and even many gravitational lens galaxies (Kochanek et al. 2000).

Khosroshahi et al. (2000a) constructed a near-infrared Photometric Plane from a sample of 42 Coma elliptical galaxies and the bulges of 26 early-type disk galaxies

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taken from the field (Khosroshahi, Wadadekar & Kembhavi 2000b). Their Photometric Plane was constructed using the Sérsic index n, the effective radius $r_{\rm e}$ and the central bulge surface brightness μ_0 derived from the best-fitting $r^{1/n}$ model. The authors claimed that the scatter about their (elliptical only) Photometric Plane implied an error of 53 per cent in the derived distance to any single galaxy. Möllenhoff & Heidt (2001) modelled 40 early-type spiral galaxy bulges and computed a correlation coefficient $r = 0.91$ between $\log n$ and a linear combination of μ_0 and $\log r_e$. Although they did not give an estimate to the scatter, a strong correlation clearly exists.

In the present analysis, the Photometric Plane will be derived using a well known sample of Virgo and Fornax elliptical galaxies for which the required data has already been published. Importantly, both the Photometric Plane *and* the Fundamental Plane will be derived for exactly the same galaxy sample, enabling a direct comparison of the scatter about the two planes. The usefulness of the Photometric Plane will subsequently be tested by computing the Virgo-Fornax distance modulus and comparing the result with the latest estimate from the *HST Key Project on the Extragalactic Distance Scale*.

Section 2 introduces the data which has been collated from the literature. The construction and analysis of the Photometric and Fundamental Planes for the full galaxy sample (and various sub-samples) is presented in Section 3. A hyperplane using all three Sérsic (photometric) parameters plus the central velocity dispersion is also introduced here. The analysis is discussed in Section 4, and a brief comparison and/or discussion is made of several other purely photometric relations such as the Kormendy relation, the scalelength-shape ($r-n$) relation of Young & Currie (1994) and the 'Entropic Plane' (Lima Neto et al. 1999). Lastly, the Photometric Plane of the intermediate redshift cluster Cl 1358+62 (z=0.33) is constructed and shown to have comparable scatter to the local Photometric Plane.

2 KINEMATIC AND PHOTOMETRIC DATA

The photometric data for the present investigation have been taken from table 2 of Caon, Capaccioli & D'Onofrio (1993) and table A1 of D'Onofrio, Capaccioli & Caon (1994). The data is discussed further in Caon, Capaccioli & Rampazzo (1990) and Caon, Capaccioli & D'Onofrio (1994a). In essence, it consists of a (B-band) magnitude-limited sample of elliptical and non-barred S0 galaxies which is 100 per cent complete down to B_T=15 mag for the Fornax cluster and 80 per cent complete down to B_T=14 mag for the Virgo cluster. These tables give the *model-independent* equivalent half-light radii ($r_{\rm e} = \sqrt{a_{\rm e}b_{\rm e}}$, where $a_{\rm e}$ and $b_{\rm e}$ are the half-light radii of the semi-major and semi-minor axis) and the B-band surface brightness at this radius ($\mu_{\rm e}$). These two quantities will therefore be used together with the *equivalent-profile* Sérsic index $n_{\rm eq}$ (n hereafter). The equivalent axis rather than the major-axis was selected because more galaxies have tabulated values of $n_{\rm eq}$ than $n_{\rm maj}$. Typical erorrs for the value of n are around 25%, or 0.10 dex for $\log n$.

No attempt has been made here to re-model the light profile data as this task was very recently performed by D'Onofrio (2001a, 2001b). Using his new data produced consistent results (see section 4) with the data referred to above.

The trend of increasing central bulge intensity with increasing bulge luminosity (and n) which holds for spiral galaxy bulges (Khosroshahi et al. 2000b), and dwarf elliptical and ordinary elliptical galaxies (Jerjen & Binggeli 1997; Graham, Trujillo & Caon 2001) breaks down for the high-luminosity ellipticals (see, e.g. Faber et al. 1997, their figure 4). This is likely due, at least in part, to the presence of 'cores' in bright elliptical galaxies (Ferrarese et al. 1994; Lauer et al. 1995). Consequently, the (extrapolated) central surface brightness derived from a Sérsic model may not always be realised, especially for those galaxies with large values of n. As the present investigation will use several bright elliptical galaxies, the central surface brightness (used by Khosroshahi et al. 2000a and Möllenhoff & Heidt 2001) will therefore not be used here. Instead, the mean surface brightness within the effective half-light radius will be used. Values of $\mu_{\rm e}$ have been converted[1] into $<\mu>_{\rm e}$, the mean surface brightness within $r_{\rm e}$, in units of mag arcsec^{-2}. This is what is typically used for constructing the Fundamental Plane. When expressed in linear units, this term shall be denoted $\Sigma_{\rm e}$.

Central velocity dispersion measurements (σ_0) have been taken from Hypercat[2]. In order to make a direct comparison between the Fundamental Plane and the Photometric plane, only galaxies for which central velocity dispersion measurements and $n_{\rm eq}$ are available have been used. This resulted in a final sample of 19 Es and 11 S0s from the Virgo cluster, and 8 Es from the Fornax cluster. This is therefore in no sense a statistically complete galaxy sample. The collated data set is given in Table 1.

The central velocity dispersion has been plotted against the equivalent- (and major-) axis Sérsic index in Figure 1. It is worth stating the obvious here: these are two completely independently derived quantities. Despite this, and the heterogeneous nature of the velocity dispersion data, for the elliptical galaxy sample the Spearman rank-order correlation coefficient is r_s=0.82 when using $n_{\rm eq}$ and r_s=0.83 when using $n_{\rm maj}$. Obviously n is not simply some random third parameter in the $r^{1/n}$ model which produces better profile fits. Quite the contrary, the Sérsic index not only traces the mass of a galaxy (given that central velocity dispersion is a reliable estimate of mass) but is also known to quantify a galaxy's degree of concentration (Trujillo, Graham & Caon 2001; Graham, Trujillo & Caon 2001). The existence of colour gradients does however mean that n will unfortunately be a function of bandpass, whereas stellar velocity dispersion should not. On the other hand, central velocity dispersion measurements can be affected by many things (decoupled kinematics such as counter-rotating cores, galaxy rotation, apertures sizes and seeing conditions) to which n is less sensitive.

[1] See, e.g., Appendix A of Graham & Colless 1997.
[2] Hypercat can be reached at http://www-obs.univ-lyon1.fr/hypercat/

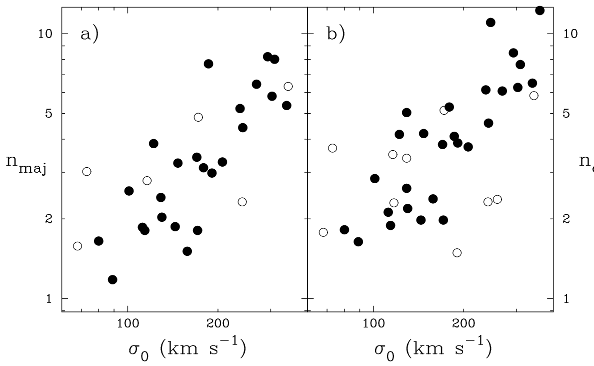

Figure 1. a) Major-axis and b) equivalent-axis Sérsic index n plotted against the central galaxy velocity dispersion. Elliptical galaxies are marked with filled circles, while S0 galaxies are denoted by open circles.

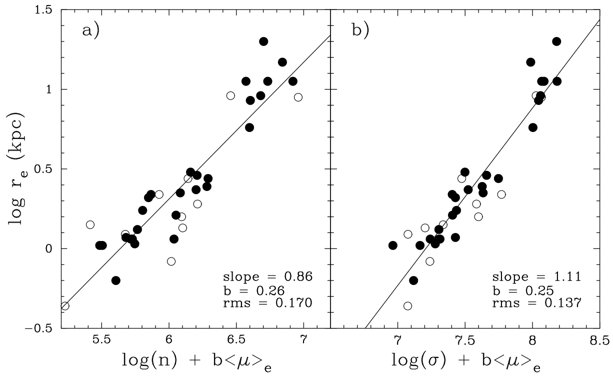

Figure 2. a) Photometric Plane. b) Fundamental Plane. Both planes have been constructed by minimising the vertical residual in $\log r_e$.

3 THE FUNDAMENTAL AND PHOTOMETRIC PLANES

Performing a least-squares regression analysis which minimises the scatter in the distance-dependent quantity $\log r_e$ gave the Fundamental Plane relation $r_e \propto \sigma_0^{1.11\pm0.12}\Sigma_e^{-0.71\pm0.06}$ with a vertical scatter of 0.137 dex in $\log r_e$. This scatter translates to a 37 per cent error in distance per galaxy. The minimisation of $\log r_e$ on the two photometric parameters gave the Photometric Plane $r_e \propto n^{0.86\pm0.13}\Sigma_e^{-0.57\pm0.09}$, with a vertical scatter of 0.170 dex in $\log r_e$, or a 48 per cent error in distance (see Figure 2).

The above minimisation routine was tested on several galaxy sub-samples. Removing the 8 Fornax elliptical galaxies and using only the Virgo galaxies had no significant affect on the above results. In using only the elliptical galaxy sample from the Virgo and Fornax clusters (i.e. excluding the 11 S0 galaxies) also did not significantly alter the Fundamental Plane, but the Photometric Plane changed to $r_e \propto n^{0.75\pm0.17}\Sigma_e^{-0.75\pm0.12}$, with a vertical scatter of 0.153 dex in $\log r_e$, or a 42 per cent distance error per galaxy. Use of the velocity dispersion data from McElroy (1995) was also explored and found not alter the above results beyond the 1σ significance level.

Using the complete sample of Virgo and Fornax galaxies and treating all variables equally (see, e.g., Feigelson & Babu 1992), rather than minimising the residuals of just one variable (as done above), yielded the Photometric Plane $r_e \propto n^{0.89\pm0.14}\Sigma_e^{-0.60\pm0.09}$ and the Fundamental Plane $r_e \propto \sigma_0^{1.22\pm0.11}\Sigma_e^{-0.74\pm0.08}$. A consistent result was obtained after the exclusion of the S0 galaxies, and the separate exclusion of the Fornax galaxies. This Fundamental Plane is also, as one might expect, in complete agreement with the multivariate analysis performed by D'Onofrio et al. (1997), where they obtained $r_e \propto \sigma_0^{1.26\pm0.09}\Sigma_e^{-0.70\pm0.03}$ for their Virgo cluster data.

Given the tight correlation between n and σ_0, one might not expect there to be any significant gains in using all four

Table 1. The (B-band) photometric parameters given in columns 3-5 have been taken from table 2 and table A1 in Caon et al. (1993) and D'Onofrio et al. (1994) respectively, with the distinction that the mean surface brightness $<\mu>_e$ has been computed from the surface brightness μ_e following Caon et al. (1994b). The value of $\log r_e$ and n correspond to that of the equivalent profile. Unlike the Sérsic index n, the values of r_e and μ_e were derived by the above authors independently of the Sérsic $r^{1/n}$ model. The central velocity dispersion (final column) has been taken from Hypercat.

Galaxy Name	Morph. Type	$<\mu>_e$ mag arcsec^{-2}	$\log r_e$ (kpc)	n	σ_0 km s^{-1}
N1339	E	20.46	0.07	1.98	171
N1351	E	21.50	0.39	4.20	147
N1374	E	20.94	0.35	3.74	207
N1379	E	20.93	0.32	2.19	130
N1399	E	22.16	1.05	12.24	359
N1404	E	19.77	0.34	4.60	242
N1419	E	20.20	-0.08	5.04	129
N1427	E	21.38	0.46	3.82	170
N4168	E	21.57	0.44	4.10	186
N4261	E	21.71	0.76	7.65	309
N4365	E	22.12	0.93	6.08	269
N4374	E	22.06	1.05	8.47	293
N4387	E	20.59	0.03	2.12	112
N4406	E	22.04	1.17	11.03	246
N4434	E	20.59	0.06	4.17	122
N4458	E	21.28	0.21	2.84	101
N4464	E	19.72	-0.20	2.61	129
N4472	E	22.44	1.30	6.27	303
N4473	E	20.66	0.48	5.29	179
N4478	E	19.72	0.02	1.98	144
N4486	E	21.88	1.05	6.51	339
N4550	E	19.93	0.02	1.82	80
N4551	E	20.67	0.06	1.89	114
N4564	E	20.63	0.24	2.38	158
N4621	E	22.39	0.96	6.14	237
N4623	E	21.09	0.12	1.64	89
N4660	E	19.53	0.06	3.87	191
N4339	S0	21.50	0.37	3.50	116
N4342	S0	18.48	-0.36	2.32	241
N4431	S0	22.65	0.28	1.78	68
N4459	S0	20.64	0.44	5.14	172
N4476	S0	21.03	0.13	3.70	73
N4552	S0	22.24	0.95	12.81	263
N4649	S0	21.63	0.96	5.84	343
N4281	S0	21.10	0.34	2.37	259
N4352	S0	21.78	0.20	2.30	117
N4570	S0	19.92	0.15	1.49	190
N4638	S0	19.55	0.09	3.39	129

parameters (i.e. $n, r_{\rm e}, <\mu>_{\rm e}$ and σ_0). Nonetheless, as the data is already at hand, a hyperplane was constructed and the scatter in $\log r_{\rm e}$ measured to be 0.125 dex (cf. 0.137 dex for the Fundamental Plane). Removing the 8 Fornax galaxies produced a scatter of 0.123 dex in $\log r_{\rm e}$, and the additional removal of the 11 S0 galaxies resulted in a scatter of only 0.105 dex in $\log r_{\rm e}$ about the hyperplane. This is equivalent to an error of 27 per cent in distance per galaxy, whereas the Fundamental Plane gave a scatter of 0.125 dex (33 per cent error in distance) for this reduced galaxy sample, and the Photometric Plane had a scatter of 0.141 dex (38 per cent error in distance).

The analysis above has been performed assuming that the Virgo and Fornax clusters reside at the same distance from us. The latest results from the *HST Key project on the Extragalactic Distance Scale* (Freedman et al. 2001) find a Virgo-Fornax distance modulus of 0.51±0.21 mag. This result is based on Cepheid distances to 5 spiral galaxies in the Virgo cluster and 3 spiral galaxies in the Fornax cluster.

We can quickly gauge the Photometric Plane's ability to estimate distances by adding some constant value to one clusters distance-dependent values of $\log r_{\rm e}$ (kpc) until the Photometric Plane of the combined Virgo+Fornax sample has a minimum scatter in $\log r_{\rm e}$. Both the E+S0 and the E-only galaxy samples were found to have a minimum scatter when the Fornax galaxy radii were increased by 0.06 dex, giving a Virgo-Fornax distance modulus of +0.30 mag and placing Fornax 15 per cent more distant than Virgo.

A more accurate approach is to use the Working-Hotelling (1929) confidence bands described, and further developed, in Feigelson and Babu (1992). This technique has previously been applied to Fundamental Plane data in Graham (1998) to determine the intercept offset along the $\log r_e$ axis between the Virgo and Fornax Fundamental Planes and is described there. The method allows for the fact that an error in slope to the fitted data will cause a greater discrepancy at the ends of the relation, and hence the method gives more weight to central data points. For our full galaxy sample, the Virgo and Fornax Fundamental Planes were found to have an offset of 0.114±0.067 dex in $\log r_{\rm e}$, implying a Virgo-Fornax distance modulus of 0.57±0.34 mag. The Photometric Planes had an offset of 0.117±0.088 dex in $\log r_{\rm e}$, implying a distance modulus of 0.59±0.44 mag. The largish error can, in part, be attributed to the presence of only 8 galaxies in our Fornax cluster sample. Including those galaxies without velocity dispersion estimates but with measurements of n, the Virgo-Fornax distance modulus derived from the Photometric Plane was found to be 0.62±0.30 mag[3].

4 DISCUSSION

It had been our intention to analyze the Photometric Plane using those galaxies studied by Tonry et al. (1997) in their measurements of surface brightness fluctuations (SBF) for determining galaxy distances. However, with regard to their data reduction process they write: "Finally, we make a mask of the obvious stars and companion galaxies in the cleaned image and determine the sky background by fitting the outer parts of the galaxy image with an $r^{1/4}$ profile plus sky level." Unfortunately, this procedure is flawed because of its assumption that all elliptical galaxies have outer $r^{1/4}$ profiles. Any real departures from an $r^{1/4}$ profile in the actual galaxy light profile will be largely erased by their tunable sky-level. This of course has many consequences: for example, colour gradients will be erroneous.

This explains the strange behaviour of the $r^{1/4}$ models fitted to this data by Kelson et al. (2000a). While their models match the outer light-profiles very well, they fail to the fit the inner regions of almost every galaxy. Although fitting an $r^{1/4}$ model to an $r^{1/n}$ profile may not effect the $r_{\rm e}$ and $\Sigma_{\rm e}$ combination in the standard Fundamental Plane (Trujillo et al. 2001), the erroneous construction of an $r^{1/4}$ profile from an $r^{1/n}$ profile is another issue. This may possibly explain why the Fundamental Plane analysis of Kelson et al. (2000a) gave a notably different Hubble constant to the other techniques employed by the *HST Key Project on the Extragalactic Distance Scale* team[4], and certainly rules out our hope to derive a Photometric Plane from these data.

D'Onofrio (2001a,b) recently performed a two-dimensional fit to the light distributions of the magnitude-limited galaxy samples discussed in section 2. He fitted both seeing-convolved $r^{1/n}$ and seeing-convolved ($r^{1/n}$ + exponential) models. Using the parameters from his $r^{1/n}$ models fitted to the 'genuine' elliptical galaxies, and the Sérsic bulge parameters from the ($r^{1/n}$ + exponential) models fitted to the 'genuine' S0 galaxies gave a Photometric (and Fundamental) Plane consistent (at the 1σ-level) with that derived above using the full galaxy sample of 38 objects mentioned in section 2. Using only the elliptical galaxies from D'Onofrio (2001) gave a level of scatter equivalent to that found previously; inclusion of the S0 galaxies resulted in an increased scatter. It should however be noted that the analysis by D'Onofrio (2001a,b) took into account several errors which can affect the structural parameters and in many ways this new data set is to be preferred. The planes constructed using both data sets are, reassuringly, the same.

It is of course of interest to know what the prospects are for the Photometric Plane at higher redshifts. Fortunately we have been able to immediately address this question using published Sérsic model parameters from galaxies in the z=0.33 cluster Cl 1358+62 (Kelson et al. 2000b, their table 1). Kelson et al. fitted seeing-convolved Sérsic models to their z=0.33 galaxy light profiles. Performing a regression that minimised the residuals in $\log r_{\rm e}$ for the combined E, E/S0 and S0 galaxy sample gave a scatter of 0.150 dex (an error of 41 per cent in distance[5]), the same as obtained above for the Virgo/Fornax elliptical galaxy sample. This is an extremely encouraging result, which could well be pursued with new (and old) cluster samples spanning a range of redshifts (e.g. Fasano et al. 2002).

While the Photometric Plane used here can be viewed as a variant of the Fundamental Plane, in which the Sérsic

[3] The results given at the start of this section did not change significantly when a Virgo-Fornax distance modulus of 0.6 was applied because there are only 8 Fornax galaxies.

[4] The use of aperture velocity dispersions within widely varying fractions of each galaxy's effective radius (as also used here) may have also been a contributing factor.

[5] A distance error of 35 per cent was obtained when the later galaxy types used by Kelson et al. (2000b) were included here.

index n has replaced the velocity dispersion, it can also be seen as an extension to the scalelength–shape[6] relation of Young & Currie (1995; 2001). The scatter in $\log r_{\rm e}$ about the $\log r_{\rm e}$–$\log n$ relation for the present data sample is 0.35 dex, while the scatter we have computed about the Kormendy relation between $\log r_{\rm e}$ and $< \mu >_{\rm e}$ is 0.25 dex[7]. As we have seen above, using all three photometric parameters resulted in a tighter correlation.

Concerns of parameter coupling in the fitting of the Sérsic model, and henceforth spurious correlations in our Photometric Plane, can largely be laid to rest (see also Trujillo et al. 2001). We have used both the model-independent effective radius, and surface brightness at this radius, obtained directly from the image with no recourse to the Sérsic model. The Sérsic index n has of course come from the best-fitting $r^{1/n}$ model and this was used to convert $\mu_{\rm e}$ into $< \mu >_{\rm e}$. However, the scatter about our Photometric Planes are the same no matter which of these two surface brightness terms we use.

One big advantage in replacing the Fundamental Plane with a a relation based on purely photometric quantities is the considerable reduction in observational time and data analysis. This has of course been recognised before, and led Scodeggio, Giovanelli & Haynes (1997) to replace the stellar velocity dispersion term in the Fundamental Plane with the difference between the magnitude of a galaxy and that of the mode of the Gaussian luminosity function of the E/S0 galaxies. This method could however only be applied to galaxy clusters whose E/S0 luminosity function could be reliably determined. Additionally, the accuracy for distance determinations did not scale with the square root of the number of objects used to perform the fit. Nonetheless, this was an interesting venture into the use of a purely photometric distance indicator for early-type galaxies.

Assuming an isotropic velocity dispersion tensor, the absence of rotational energy, a constant mass-to-light ratio and a constant specific entropy for elliptical galaxies, Lima Neto et al. (1999) presented theoretical arguments for the existence of what they termed an 'Entropic Plane'. This is a two-dimensional plane within the three-dimensional space of photometric parameters $\ln \Sigma_0$, $\ln h$ and $F(n)$, where Σ_0 is the central intensity of a bulge, h is the radial scalelength (rather than half-light radius), and $F(n)$ is a function of the Sérsic index n.

Analyzing a sample of ordinary elliptical and dwarf spheroidal galaxies (with values of n less than 4) taken from the rich clusters Coma and ABCG 85, and also from the group NGC 4839, Lima Neto et al. (1999) showed that the tilt to their observed Entropic planes did not quite match the value expected from theory. Márquez et al. (2000) subsequently identified one likely cause for the offset: Elliptical galaxies do not have a constant specific entropy but a value which increases with galaxy luminosity. This conclusion was reached using the same data sample used in Lima Neto et al. (1999) and was further supported by simulations of hierarchial merging galaxy formation. One may well expect the level of entropy (disorder) to increase through mergers. Nonetheless, despite this and other likely systematic differences with luminosity[8], a relatively tight plane was found to exist within a purely photometric set of parameters. The physical grounds for this are pursued further in Márquez et al. (2001). Additional insight may come from the statistical mechanics of violent relaxation (Lynden-Bell 1967) which have been invoked to explain the range of elliptical galaxy light-profile shapes, such that n increases as the luminosity (mass) does (Hjorth & Madsen 1995).

Highly accurate analytical expressions have recently been formulated to model the mass-density profiles of stellar systems having $r^{1/n}$ profiles when seen in projection. The model presented in Trujillo et al. (2002), for example, not only surpasses the accuracy of the Dehnen model in describing a deprojected de Vaucouleurs $r^{1/4}$ profile, but importantly has an error of well under 0.1% for any value of n ranging from 0.5 to 10. It is hoped as models of galaxy merging and evolution advance, they will shed light onto the origin of the Photometric Plane. Recently Aguerri, Balcells & Peletier (2001) showed through N-body simulations that the growth of spiral galaxy bulges via the merger of a dense satellite results in an increase of a bulge's Sérsic index n. They explained how this was due to two effects. Firstly, the survival of the dense satellite increased the bulge's nuclear density once it settled at the bulge center (but see Holley-Bockelmann & Richstone 2000). Secondly, the merger process resulted in the heating of the outer bulge, increasing the stellar density at larger radii. Both of these affects describe a light profile whose shape is evolving toward higher values of n. How, or rather why, the Sérsic index n changes for elliptical galaxies is a somewhat open question.

To conclude, the Photometric Planes studied here display $\sim$15-30 per cent more scatter than the Fundamental Planes corresponding to the same galaxy sample. Due to the strong (r_s=0.82) correlation between the Sérsic index n and the central stellar velocity dispersion, hyperplanes which use all three photometric parameters plus the velocity dispersion have 11-18 per cent less scatter than the Fundamental Plane. The scatter in $\log r_e$ about the Photometric Plane translates to a distance error of $\sim$38-48 per cent per galaxy. A scatter of 35-41 per cent was found for the z=0.33 cluster Cl 1358+62. The offset in $\log r_{\rm e}$ between the Virgo and Fornax Photometric Planes constructed using galaxies without velocity dispersion measurements gave a distance modulus of 0.62$\pm$0.30, implying the Fornax cluster is, on average, 33$\pm$15 per cent more distant. This result is in good agreement with other accurate distance determinators, and indicates the applicability of the Photometric Plane to practical situations. Although the Fundamental Plane appears to have less scatter than the Photometric Plane, it is recommended authors

[6] Given the results of Figure 1, the luminosity–shape ($L-n$) relation of Young & Currie (1994) can be understood as a variant of the luminosity–velocity dispersion relation of Faber & Jackson (1976).

[7] These values reduced to 0.28 dex and 0.21 dex when using only the Virgo Elliptical galaxies.

[8] Low luminosity elliptical and S0 galaxies are known to contain significant rotation (e.g., Davies et al. 1983; Prugniel & Simien 1994, 1996; Busarello et al. 1997; Graham et al. 1998), and dwarf elliptical galaxies are generally believed to be anisotropic (Bender, Burstein & Faber 1992). The issue of a constant M/L ratio with luminosity remains somewhat undecided, or at least has not yet been universally agreed upon (see, e.g., Prugniel & Simien 1997).

construct the Photometric Plane and check if its level of accuracy is sufficient for their needs before pursuing additional (expensive) kinematical data.

5 ACKNOWLEDGEMENTS

I am happy to thank Nicola Caon for his corrections and comments on this work.

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