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Families of galaxies in the μ_e–R_e plane

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ABSTRACT

Using a complete sample of Virgo cluster galaxies and a larger set of heterogeneous literature data, we show that ellipticals, early-type dwarfs, and bulges of S0s and of spirals form two distinct families in the plane of the effective parameters, R_e and μ_e. The 'ordinary' family is composed of all galaxies fainter than $M_B \simeq -19.3$. Their effective parameters range over a wide interval for the same total luminosity: R_e varies by at least ~ 0.7 dex and μ_e by 3.5 mag. Moreover, the interval spanned by R_e is the same at any luminosity (down to $M_B \simeq -12.0$), with a sharp upper boundary at $R_e \simeq 3$ kpc.

The 'bright' family is composed of the brightest cluster members and the host galaxies of QSOs. Their effective radii extend up to $\simeq 300$ kpc, and are directly related to the effective surface brightness: $\mu_e \simeq 3 \log R_e + \text{constant}$. There are indications that the objects belonging to this family have probably undergone merging phenomena.

The existence of the above dichotomy has a bearing on the use of the Fundamental Plane to probe extragalactic distances, and increases interest in the $(\log R_e, \mu_e)$ plane as a diagnostic diagram for galaxy formation and evolution.

Key words: galaxies: elliptical and lenticular, cD – galaxies: fundamental parameters – galaxies: spiral.

1 INTRODUCTION

The long-debated question (Brosche 1973) of how many physical parameters are necessary to describe elliptical galaxies has been answered in recent years only. At first, observations seemed to indicate that E galaxies and spheroidal components (bulges) form a single-parameter family. In particular, the central velocity dispersion was discovered to depend on the total luminosity, $L_T \propto \sigma_c^\alpha$ (Faber & Jackson 1976), and the effective radius and surface brightness, R_e and μ_e, were found to be mutually dependent, $\mu_e \simeq 3 \log R_e + \text{constant}$ (Kormendy 1977).

These results were questioned by several authors. Terlevich et al. (1981) showed that the residuals from the Faber–Jackson relation correlate with the metallicity indicator Mg_2, while de Vaucouleurs & Olson (1982) stated that the same residuals depend on the mean surface brightness. Both studies brought up the case of the existence of a second (hidden) parameter. In this vein, benefitting from a large sample of early-type galaxies with photometric and kinematical data, Djorgovski & Davis (1987, hereafter DD87) showed that galaxies populate a thin plane in a 3D space, named the 'Fundamental Plane' (FP), having the total luminosity, the central velocity dispersion and the mean surface brightness $\langle I \rangle_e$ as axes. The thickness of the plane is fully accounted for by observational errors, and the position of each galaxy above or below the plane is independent of any of the shape parameters such as flattening profile, isophotal twisting, velocity anisotropy and detailed radial run of the light profiles. In this picture, the Faber–Jackson and μ_e–R_e relations are projections of the FP on to coordinate planes.

The above results are of importance in that the existence of a FP shows that the structural properties of galaxies span a narrower range than expected from models, indicating that some regulating mechanisms must be at work (Djorgovski, de Carvalho & Han 1989). This fact, together with the value of the exponents in the equations defining the FP, provide basic information and physical constraints on galaxy formation processes.

Being magnitude limited, the DD87 sample is biased toward intrinsically bright objects and not representative of the global galaxy population. Most importantly, the scale parameters were obtained by fitting a $r^{1/4}$ law to the bright part of the galaxy light profiles, which are possibly also distorted by uncertain background subtraction on small-field CCD frames.

Prompted by these considerations, we decided to construct a new data base of 'model-independent' photometric parameters for a large and deep luminosity-limited sample of early-type galaxies (Caon, Capaccioli & Rampazzo 1990, hereinafter CCR; Trevisani 1991) and bulges of spirals (D'Onofrio 1991) belonging to the Virgo cluster, and use it to reanalyse the relationship between μ_e and R_e. Since the early-type galaxies of Virgo are nearly at the same distance from us (cf. Tonry, Ajhar & Luppino 1990), their scale parameters do not suffer from the uncertainties affecting sparse and/or distance-unconstrained samples.*

For now we must refrain from commenting on the FP, since central velocity dispersion measurements are available only for 40 per cent of our sample galaxies.

With literature data added to ours in order to extend the sample toward both brighter and fainter luminosities, we show here that spheroids (E galaxies and bulges of all luminosity classes) populate two different regions of the ($\log R_e$, μ_e) plane, and we argue that this segregation probably corresponds to the existence of two physically distinct families of objects. The first consists of ordinary ellipticals, bulges and early-type dwarfs. For a fixed total luminosity, these galaxies exhibit a fairly large spread in surface brightness, $\Delta\mu_e \simeq 3.5$ mag, which is mostly intrinsic (i.e. not accounted for by measurement errors, nor by projection effects). They are always fainter than $M_B \simeq -19.3$ mag ($H_0 = 70$ km s^{-1} Mpc^{-1}) and smaller than $R_e \simeq 3$ kpc, a limit independent of L_T.

The second family, composed of the brightest cluster galaxies (BCG) and of objects hosting QSOs and Seyfert nuclei, populates a narrow strip in the ($\log R_e$, μ_e) plane, which extends over more than 1 dex in R_e and has slope $d\mu_e/d\log R_e \simeq 3$. There are indications that this distribution is related to merging processes.

2 THE ($\log Re$, μ_e) PLANE FOR THE VIRGO SAMPLE

The distribution of early-type galaxies in the ($\log R_e$, μ_e) plane has already been investigated by Capaccioli & Caon (1991; Paper I) for a sample of 33 E and non-barred S0 galaxies belonging to the Virgo cluster. We have enlarged that sample by adding 19 early-type galaxies in the southern region of Virgo (Trevisani 1991) and 54 spirals also belonging to the cluster (D'Onofrio 1991). With respect to the membership list by Binggeli, Sandage & Tammann (1985), the present early-type sample is 80 per cent complete to a total apparent magnitude $B_T = 14.0$, i.e. to an absolute magnitude $M_B = -17.3$, if a distance modulus $(m-M) = 31.3$ is adopted (Capaccioli et al. 1990); the spiral sample is also complete to 80 per cent, but within $B_T = 13.5$. In both cases the missing objects lie mostly at the cluster outskirts, not covered by our plate material.

Following the 'global mapping' strategy (Capaccioli & Caon 1989), based on the coupling of B-band CCD images with deep Schmidt photographs for both the Es and S0s, we were able to compute the parameters R_e and μ_e of the effective isophote (encircling half the total luminosity) in a model-independent way – they are not the parameters of the $r^{1/4}$ or any other empirical fitting law. For galaxies where the disc is made evident by the study of the geometry of the isophotes, effective parameters are those of the bulge component only (for details on our technique of bulge–disc decomposition, see CCR and Capaccioli & Caon 1992).

Spirals were instead decomposed into the sum of a $r^{1/4}$ bulge plus an exponential disc, obtaining meaningful results for 35 objects (D'Onofrio 1991).

The errors on the effective parameters for the early-type galaxies, related to the uncertainty on $B_T(|\delta B_T| < 0.1)$, are estimated to be $|\delta \log R_e| < 0.08$ and $|\delta\mu_e| < 0.4$ mag (Paper I).

For spirals, errors are more difficult to quantify, being caused mainly by the uncertainty in the decomposition and by the inadequacy of the photometric model for reproducing the actual luminosity behaviour of the galaxian components (cf. Schombert & Bothun 1987).

In Fig. 1, which plots the distribution of our total sample of 87 Virgo cluster galaxies in the ($\log R_e$, μ_e) plane, we recognize two distinct groups of galaxies, which are described in the following subsections.

2.1 The 'ordinary' group

The 'ordinary' group appears confined within a strip bounded by lines of constant luminosity, $L_T \propto I_e R_e^2$, the lower boundary being just the cut-off of our sample. Spheroids of the same total luminosity span the ranges $\Delta\mu_e \simeq 3.5$ mag and $\Delta \log R_e \simeq 0.7$. The distribution has an upper limit at $M_B \simeq -19.3$ and a vertical boundary at $\log R_e \simeq 0.45$. There is no apparent segregation of morpho-

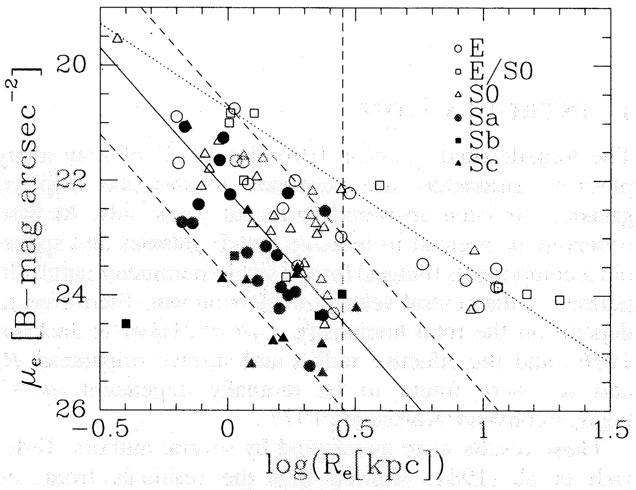

Figure 1. Distribution of 87 Virgo ellipticals and bulges of S0s and spirals in the ($\log R_e$, μ_e) plane. The adopted distance modulus is 31.3 mag. Morphological types are shown by different symbols. The locus of the points for galaxies with fixed luminosity $M_B = -17.8$ and obeying the same scaling law $L_T \propto I_e R_e^2$ is shown as a solid line; dashed lines correspond to a luminosity shift $\Delta M_B = \pm 1.5$. The vertical dashed line at $\log R_e = 0.45$ is a by-eye estimate of the upper boundary to the effective radii for the 'ordinary' group. The dotted line represents the HK relation.

*Larger systematic effects may plague the group of NGC 4472 (Binggeli, Tammann & Sandage 1987) and the spiral sample (Tully & Shaya 1984).

logical types, except for the fact that, on average, bulges of spirals are fainter than those of S0s and ellipticals.

2.2 The 'bright' group

The brightest galaxies in our sample form a well-separated group ('bright' family) characterized by very large effective radii ($\langle R_e \rangle = 10.5$ kpc) and relatively low effective surface brightness ($\langle \mu_e \rangle = 23.8$ B-mag arcsec^{-2}). It is precisely this group that, together with the brightest objects in the range of R_e typical of the 'ordinary' group, defines the single parameter relation

$$\mu_e = 2.94 \log R_e + 20.75, \qquad (1)$$

reported by Hamabe & Kormendy (1987, hereafter the HK relation), with zero-point adjusted to our Virgo cluster distance.

2.3 The luminosity function

A second point that we want to make with our data concerns the luminosity function (LF) of early-type galaxies. We confirm the finding of Paper I that, at variance with previous studies showing that E and S0 galaxies both in the field and in the Virgo cluster have bell-shaped LFs (see fig. 1 in Binggeli, Sandage & Tammann 1988), our Virgo sample exhibits a bimodal distribution with a secondary (quasi-Gaussian) bump at very high luminosities, with centre at $M_B \simeq -21.2$ and FWHM = 1.7 mag (see Fig. 2).

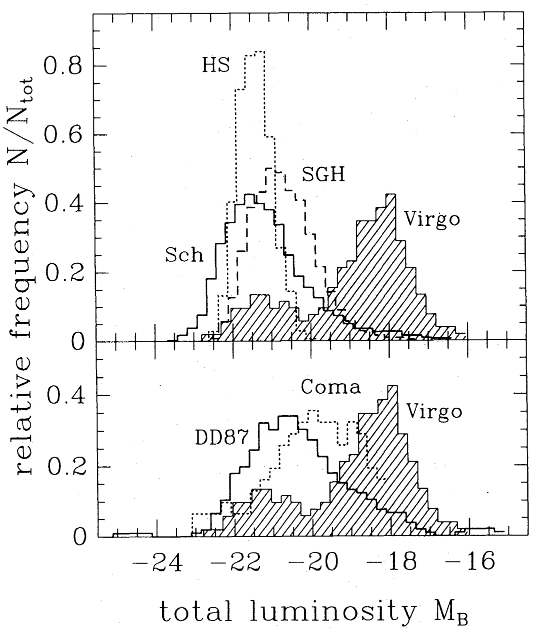

Figure 2. Bottom panel: the luminosity function for the 52 early-type galaxies of our Virgo sample (shaded histogram) is compared with the LF for the Coma sample studied by Jørgensen et al. (1991, dotted line) and with the LF for the sample of DD87 (solid line). Upper panel: the LFs of the BCG samples populating the ($\log R_e$, μ_e) plane. HS = Hoessel & Schneider (1983, dotted line); SGH = Schneider, Gunn & Hoessel (1985, dashed line); Sch = Schombert (1987, solid line). Data have been registered to the same distance scale and photometric band, and smoothed by a running window 1.0 mag wide, moved in steps of 0.25 mag.

Indeed, the total luminosities of our brightest objects are systematically in excess (by up to 0.5 mag) over most of the literature values (for detailed comparisons, see CCR). We attribute the source of this discrepancy to the common practice of applying standard growth curves or fitting laws (e.g. the $r^{1/4}$ function) to obtain integrated magnitudes for galaxies whose outer light profiles remain unknown (as in most CCD photometry of bright galaxies).

3 THE ($\log R_e$, μ_e) PLANE WITH LITERATURE DATA ADDED

In order to extend the luminosity range and morphological types of our sample toward both brighter (BCG, QSO) and fainter (early-type dwarf) galaxies, we have compiled a catalogue of structural parameters from the literature, aiming also at cross-comparing different sources. Basic information on literature data has been reported in Capaccioli et al. (1992).

The different data sets have been homogenized to the B band and to the same distance scale ($H_0 = 70$ km s^{-1} Mpc^{-1}). The main source of disagreement among the various authors is in the methods used to derive the effective parameters. In fact, the representation of light profiles by empirical models provides parameters which depend upon the fitting procedure or the fitted surface brightness range. An example is displayed in Fig. 3: the observed luminosity profile of the elliptical galaxy NGC 4621 is compared with $r^{1/4}$ models, making use of our 'global mapping' effective parameters and of those given by Kormendy (1977). It is evident that, while Kormendy's interpolation describes quite well the inner part of the luminosity profile, out to $r \sim 80$ arcsec, where $L/L_T = 0.45$, it fails in modelling the outer region where the profile becomes shallower; the $r^{1/4}$ model with our parameters is indeed more representative of the global photometric behaviour. We also note that differences in R_e of up to 0.5

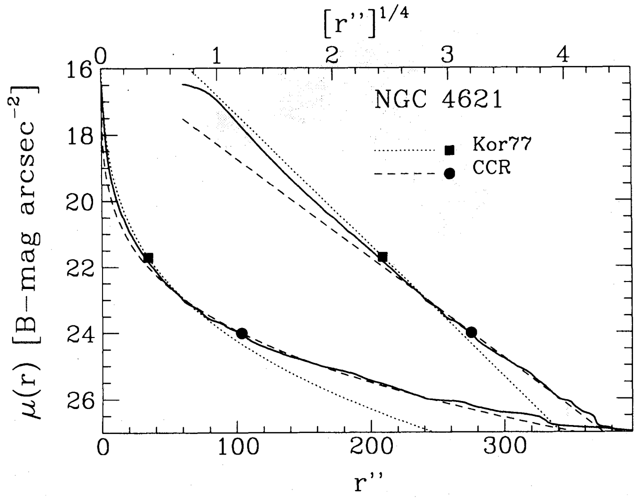

Figure 3. The observed equivalent light profile of NGC 4621 (from CCR) is compared with $r^{1/4}$ models drawn using (i) our model-free effective parameters (dashed line), and (ii) those adopted by Kormendy (1977, dotted line), after rescaling to a common distance. The same light profile and the $r^{1/4}$ models are plotted both in linear units (left-hand curves, bottom scale) and in $r^{1/4}$ units (right-hand curves, upper scale). Dots mark the values of the effective parameters for the two models.

dex and in μ_e of up to 3 mag for the same galaxy are found in the literature (see fig. 7 of Capaccioli et al. 1992).

In spite of their heterogeneity in quality and characteristics of the environment, literature data further support the existence of two distinct families of galaxies in the ($\log R_e$, μ_e) plane. BCGs all lie in a quite narrow strip (slightly curled), which follows approximately the single parameter HK relation (1), with slope $\simeq 3$ (computed for $\log R_e > 1$), and an rms scatter of about 0.5 mag in μ_e at fixed R_e (Fig. 4). The strip extends to $R_e \simeq 300$ kpc. This behaviour is characteristic of each single BCG sample. In particular, data from Schombert (1987) show a segregation according to the morphological type, D and cD galaxies having the faintest surface brightnesses and largest effective radii.

The brightest Virgo ellipticals are superposed on this sequence, but they span a quite small range in effective parameters, as already noted. Furthermore, the LFs of BCG samples (Fig. 2) are peaked at the same absolute magnitude as the secondary bright bump found in our Virgo sample.

Interestingly enough, the representative points of host galaxies of QSOs (Malkan 1984; Malkan, Margon & Chanan 1984) overlap those of BCGs in the ($\log R_e$, μ_e) plane, despite the fact that the accuracy of the effective parameters is rather poor.

We have extended our study toward very faint luminosities using data for 220 Virgo dwarf ellipticals and S0s kindly made available by Drs B. Binggeli and L. M. Cameron, in advance of publication. The representative points of these galaxies, also plotted in Fig. 4, lie just below our 'ordinary' group, within the same boundary in R_e. Dwarfs seem thus the natural extension of such a group toward fainter luminosities and fainter effective surface brightnesses.

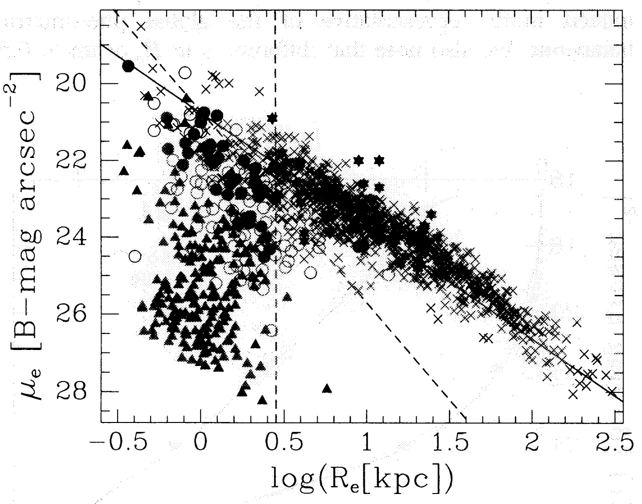

Figure 4. The ($\log R_e$, μ_e) plane after the addition of literature data. Open circles represent the spiral samples of Kent (1985) and D'Onofrio (1991); filled circles are Es and S0s from CCR and Trevisani (1991); filled triangles are data from Binggeli & Cameron (1992); crosses are data from Schneider et al. (1983), Thomsen & Frandsen (1983), Malumuth & Kirshner (1985), Hoessel & Schneider (1985), Michard (1985), Schombert (1987) and Capaccioli, Piotto & Rampazzo (1988); starred symbols are galaxies hosting a QSO and Seyferts from Malkan (1984) and Malkan et al. (1984). The oblique dashed line is that of constant luminosity, $M_B = -19.3$, i.e. the upper limit of the 'ordinary' group; the solid line represents the HK relation.

There are two features in Fig. 4 which appear quite remarkable:

(1) galaxies with luminosities differing by as much as 3 dex none the less share the same range of R_e, and

(2) whatever their luminosity, 'ordinary' galaxies do not grow larger in size than a rather well-defined maximum, $R_e \simeq 3$ kpc.

4 DISCUSSION AND CONCLUSION

The distribution in the ($\log R_e$, μ_e) plane of our Virgo sample galaxies and of the literature data reveals the existence of two distinct families. The first, the 'ordinary' group, is composed of ordinary Es and S0s and of early-type dwarfs, which lie in a well-defined region with $20 \lesssim \mu_e \lesssim 28$ B-mag arcsec^{-2} and $-0.4 \lesssim \log R_e$ (kpc) $\lesssim 0.45$, bounded at $M_B \simeq -19.3$. While the lack of objects with fainter effective surface brightness is probably due to a selection effect and we have insufficient information to establish the reality of the left boundary in R_e, the right boundary at $R_e \simeq 3$ kpc is likely to be an intrinsic property of the family. The striking result is that galaxies with the same effective radii span a luminosity range of 3 dex and the sharp upper cut-off in R_e is independent of the total luminosity. This property had already been recognized by Disney et al. (1990) for dwarf galaxies. In fact, once their data are reduced to our system of effective parameters, they define the same upper limit of $\simeq 3$ kpc.

The 'bright' family is formed by the most luminous galaxies, which cluster approximately along the HK relation (equation 1). Nine of the 10 Virgo galaxies belonging to this group have boxy or non-classifiable isophotes. The samples of Bender, Döbereiner & Möllenhoff (1988), Peletier et al. (1990) and Jørgensen, Franx & Kjærgaard (1991) confirm the fact that 'bright' galaxies are mostly boxy, while discy objects preferentially belong to the 'ordinary' group.

If, as many pieces of evidence indicate, the boxy appearance in luminous galaxies is the result of merging events (see Bender 1990), we may wonder how merging affects the position of the merger product in the ($\log R_e$, μ_e) plane. Following Hoessel (1980), the evolution in size as a function of mass is governed by the equation $\delta R_e/R_e = k\,\delta M/M$, where M is the total mass, and k is a parameter in the interval $1<k<2$, depending on the mechanism of the merging process. Including the definition for the scale parameters, $L \propto I_e R_e^2$, and assuming that the mass-to-light ratio is a power-law function of the mass, $M/L \propto M^{\gamma}$, the representative points of merger products are found to move along lines of slope

$$\frac{d\,\mu_e}{d\,(\log R_e)} = 2.5\left(2 - \frac{1-\gamma}{k}\right). \qquad (2)$$

For typical values of k and $\gamma (0 \leq \gamma \leq 0.2)$, $\delta\mu_e/\delta \log R_e$ ranges from 2.5 to 4.0. This interval is centred almost at the slope of equation (1), a fact which gives further support to the merging scenario for the 'bright' family. The high frequency of multiple nuclei among BCGs also goes in this direction.

We notice the interesting position of the galaxies hosting an active nucleus (Malkan 1984; Malkan et al. 1984). Although for these objects significant errors can be present due to seeing effects and strong selection effects may exist, the association of host galaxies of QSOs with the line of mergers is remarkable.

In summary, we suggest that the $(\log R_e, \mu_e)$ plane for E galaxies and bulges may be viewed as the 'logical equivalent' to the HR diagram for stars: it marks the locus occupied by galaxies at the end of dissipative collapse (the 'ordinary' family) and traces the evolutionary tracks of objects which have experienced significant merging (the 'bright' family).

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