ASTRONOMY FROM WIDE-FIELD IMAGING

Part Twelve:

PROPERTIES OF NEARBY GALAXIES

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GLOBAL PROPERTIES OF NEARBY GALAXIES†

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1. Introduction

Surface photometry of nearby galaxies is among the research areas that gained most from the recent advances in 'wide-field imaging'. In fact, the demand for an accurate measure of the night-sky level all around the target galaxy — a key step in galaxy surface photometry; see Fig. 1 in Capaccioli & de Vaucouleurs (1983) — calls for at least some images covering a field wider than the size of the object under study. So far, the small field of most CCD cameras attached to the Cassegrain foci of medium-size telescopes has prevented both the mapping of the galaxian outskirts and, a fortiori, a direct measurement of the sky background μ_s on the galaxy image itself. Indirect methods to estimate μ_s — blank-sky exposures, matching of growth curves to photoelectric integrated magnitudes, assumptions on the shape of the galaxian light profiles — have proven ineffective and/or methodologically questionable (Capaccioli 1989). Until large-format CCD chips or mosaics are routinely used, the only way out of these problems is either the use of focal reducers, whose optical complexity may however be incompatible with photometric accuracy, or of large-field photographic plates.

We have devised a technique to perform surface photometry of galaxies, named 'global mapping' (GM), which couples unsaturated CCD frames with large-field deep photographic images (Capaccioli & Caon 1989). At state-of-the-art accuracy, it allows the mapping of a 'large' galaxy from its centre out to the isophote at $\mu_B \sim 28$ mag arcsec^{-2}, i.e. down to the ultimate limit set by the statistical fluctuations in the distribution of sub-threshold celestial sources (Capaccioli & de Vaucouleurs 1983). The internal errors are $\lesssim 0.1$ mag down to $\mu_B \simeq 26$.

In this paper we shall examine the reasons which prompted us to carry out, once more, the photometry of a sample of Virgo and Fornax early-type galaxies, discuss the solutions provided by our GM technique, and give a short account of the main astrophysical results so far achieved.

† This paper is dedicated to the memory of 'Pepe' Sersic, one of the pioneers of galaxy surface photometry.

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2. Motivations for a New Photometric Mapping of Nearby Galaxies

Increasing evidence has been recently accumulated that kinematically hot galaxian components (KHGCs = pressure-dominated systems such as ellipticals, bulges and early-type dwarfs) share some remarkable common properties, reflected in the existence of the so-called *Fundamental Plane* (FP — Djorgovski & Davis 1987; Dressler et al. 1987). In the global-parameters space (defined by luminosity, radius, surface brightness, velocity dispersion, colours, metallicity etc.), KHGCs do not fill the available volume, but are rather confined onto a two-dimensional surface, which becomes a plane after the proper coordinate transformations. The FP also implicitly contains important derived parameters, such as the mass and the mass-to-luminosity ratio, and provides powerful distance-indicator relationships for early-type galaxies (cf. Djorgovski et al. 1989). On the other hand, the variables which describe the shape of the light distribution, as ellipticity, isophotal twist, isophote shape descriptors etc., are believed not to correlate with the FP, or even among themselves.

In spite of the vast popularity gained by the FP, its universality has been questioned with regard to zero-point, slope, and thickness, and the existence of some differences between field and cluster ellipticals is still debated (see de Carvalho & Djorgovski 1992). A surprising fact and a matter of concern is also that opposite conclusions about the properties of the FP are drawn from approximately the same data-set.

We have investigated the reasons for such discordant results and opposite conclusions, realising that the data-sets used so far in the FP venture have problems in relation to the following aspects:

Statistical completeness: galaxy samples are generally magnitude-limited; that is, only objects brighter than a given apparent luminosity are included. A clear example of the consequences of such a bias is Kormendy's (1977) direct relation between effective radius R_e and corresponding surface brightness μ_e, suggesting that ellipticals as a whole form a uniparametric family. As we shall show below, this relation, founded on a set strongly biased toward intrinsically luminous objects, tells us only part of the true story.

Methodology: global photometric parameters (effective radius and surface brightness, total luminosity) which, according to their original definition (de Vaucouleurs 1961), are model-independent, often happen to be confused with the scale parameters of the best fitting $r^{1/4}$ law, in most cases applied to a limited portion of the galaxy light profile (that inside the CCD frame). This methodologically questionable practice also carries on the implicit assumption that ellipticals are homologous systems, i.e. that they have the same luminous structure — notice that homology is a basic ingredient in the interpretation of the FP through the Virial Theorem. We find instead that light profiles of early-type galaxies show a wide range of shapes, very well described by a generalized de Vaucouleurs law (Section 6). More importantly, the light profile shape is directly correlated with the galaxy luminosity and size.

Accuracy: the photometric mapping is often limited by the small field of view of the detector, and light profiles are therefore distorted by uncertain sky-background subtraction. For instance, the brightest galaxies in the Virgo and Fornax clusters can reach effective diameters as large as 0.1 degrees, comparable with the field-of-view of a typical CCD used at a medium-size telescope; this means that up to 50% of the galaxy light may fall outside the CCD frame, preventing the measurement of the blank-sky level directly on the galaxy image.

In order to circumvent the above problems, we need a new and homogeneously processed data-set of 'model-free' photometric and geometric parameters for a luminosity-limited sample of equally distant objects, based on a technique capable of mapping galaxies over their whole extension. Methodological homogeneity is desirable for reducing the galaxy-to-galaxy effects of those steps of the photometric processing which are somewhat arbitrary (e.g. the extrapolation procedure for deriving total magnitudes).

3. The 'Global Mapping' Technique

The key feature of GM is the coupling of unsaturated CCD frames with sky-limited Schmidt plates. We first determine the photographic sky-level from a digital map (PDS scanning) encompassing a large enough blank-sky region around the object in study. After masking out the galaxy and other interfering objects, the background is modelled by a two-dimensional polynomial. With an accuracy of 0.3% density units, the error on the galaxian light distribution is < 0.1 mag down to 4 mag below the night-sky level. The photographic image is then linearized by the proper calibration curve, the sky background subtracted out, and the galaxian signal normalized to the sky level. After registering the CCD and photographic images to the same orientation by common stars or features, the cross-sections along the main and the intermediate isophotal axes are extracted for both images.

The background level of the CCD image is determined by requiring that the CCD light profiles match the corresponding photographic profiles (in the unsaturated range), leaving no trend in the residual differences $\Delta\mu(r) = \mu_{pg} - \mu_{CCD}$. The comparisons between circular growth curves, $m(r)$, built with sky-subtracted CCD images, and the available integrated photoelectric measurements gives the CCD zero-point μ_s(CCD) for every galaxy, from which the corresponding photographic zero-point μ_s(pg) is computed adding $\Delta\mu(r)$ to μ_s(CCD). The agreement among the individual values of μ_s(pg) for galaxies on a same Schmidt plate is remarkable. The small scatter ($\sigma \simeq 0.04$ mag) indicates that no other sources of errors enter this procedure, besides the uncertainty in the zero-point determination and in the matching of CCD and photographic images. It also allows us to adopt the average value μ_s(pg) of the plate to calibrate galaxies lacking photoelectric measurements.

Finally, CCD and photographic profiles are combined together both for the luminosity and the geometry of the isophotes. The key point here is that, even if the accuracy of the determination of the CCD sky-level is not much better than usually achieved with CCD frames only (at least for objects not completely filling the frame), in the GM technique the photographic profiles replace and complement the CCD data from where the latter are effected by the uncertain background subtraction.

In view of the methodological and technical problems listed in the previous section, it is not surprising that the photometric parameters provided by GM differ significantly from literature data. Actually, in the application of this technique to a luminosity-limited sample of 80 early-type galaxies in the Virgo and Fornax clusters, Caon et al. (1990, 1993) found larger values for the total luminosities and effective radii of the brightest galaxies ($B_T \lesssim 11.0$), while a good agreement exists for the fainter objects (Fig. 1). In agreement with Capaccioli et al. (1988), they attributed this discrepancy to the practice of adopting standard growth curves or fitting light profiles with a $r^{1/4}$ formula even to galaxies so large that their outer luminosity distribution remains unknown.

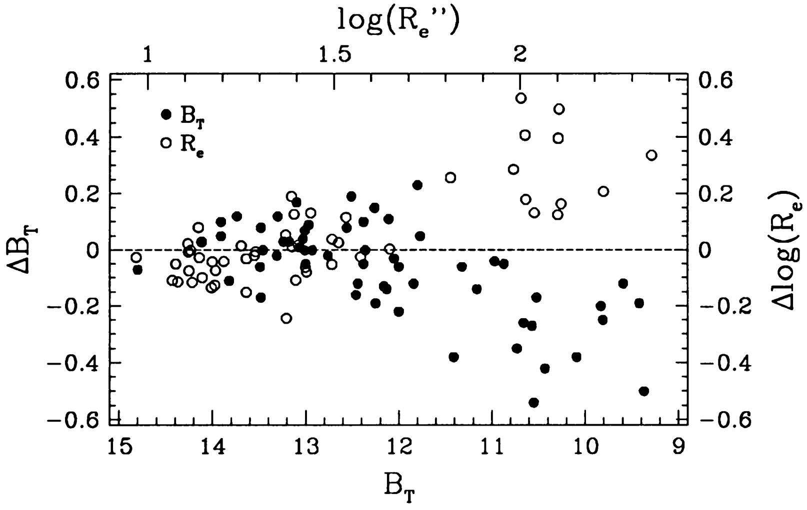

Figure 1. 'Global mapping' measurements of the total luminosity B_T (filled dots) and effective radius R_e (empty dots) are compared with the values listed in RC3 (de Vaucouleurs et al. 1991). While for galaxies fainter than $B_T \simeq 11.5$ and smaller than $R_e \simeq 55''$ ($\simeq$ 5 kpc) there is a good agreement with literature values, the other galaxies are measured systematically brighter and larger in size.

We shall explicitly remark here that the total luminosities — hence the effective radii, defined as the sizes of those isophote encircling half the total luminosity — are ill-defined parameters because of the required extrapolation of the luminosity distribution beyond the observational threshold (typically ~ 27.5 B-mag arcsec^{-2}). For a deep mapping, however, the extrapolation term is estimated to contribute less than 15% to L_T. The corresponding absolute uncertainties on the effective parameters, computed using $r^{1/4}$ models, are $\delta \log R_e < 0.08$ and $\delta\mu_e < 0.4$. It goes without saying that the relative errors are drastically reduced by the use of a homogeneous extrapolation procedure.

As a test of reliability and effectiveness, the GM methodology and the 'bulge fitting' technique, needed to extract the KHGC from a composite galaxy, were successfully applied by Capaccioli et al. (1987, 1990a) to the two standard galaxies NGC 3379, the prototype of the E class, and NGC 3115, an S0 seen nearly on-edge.

Before describing the consequences of the GM 'campaign' by Caon et al. (1990, 1993), we shall first review some recent findings in the field of early-type galaxies.

4. Families of Elliptical Galaxies

The discovery that isophotes of elliptical galaxies often depart from perfect ellipses has opened the question on whether such deviations are merely morphological details or signatures of the galaxy structure, hence tracers of the formation and evolution history (Capaccioli 1987; Carter 1987).

Bender et al. (1989) were the first to search systematically for correlations between isophotal shapes and global parameters. By performing the Fourier expansion of the radial differences between isophotes and the best fitting ellipses of a fair sample of galaxies, they showed that a_4, the coefficient of the cos(4θ) term, correlates with several photometric, kinematic, and physical parameters. Boxy galaxies ($a_4 < 0$) are usually strong X-ray and radio emitters. Their shape, possible triaxial, is due to anisotropic pressure. They often show signatures typical of merging and accretion phenomena. On the other hand, disky ellipticals ($a_4 > 0$) look like galaxies, and are believed to populate one end of the disk-to-bulge sequence of lenticular galaxies toward vanishingly small disks (see also Capaccioli et al. 1988).

Although quite attractive, the above scenario is still controversial. Recent N-body simulations (Stiavelli et al. 1991; Governato et al. 1993) indicate that the same galaxy may appear either boxy or disky depending on the specific view angle, therefore casting some doubts on the significance of the correlations found by Bender and collaborators. Also, these correlations are suspected to weaken when more careful analysis is carried out on larger and statistically more significant samples.

Moreover, even in the simplest cases ('true' disky galaxies), the results of the isophotal shape analysis may be strongly blurred by the effects of the inclination of the principal plane of the object onto the line-of-sight (Capaccioli et al. 1990a; Rix & White 1990). For instance, Capaccioli et al. (1987) showed that the faint disk of NGC 3115 (6% of L_T) would remain undetected, were the galaxy seen close to face-on. Also, Capaccioli et al. (1990b) were able to demonstrate that NGC 3379, where some features typical of stellar disks had been already detected, seems indeed a disky galaxy whose flat component escaped detection because of the unfavourable angle of view. Along this line, Capaccioli et al. (1990c) postulated that NGC 3115 and NGC 3379 share the same structure, and appear diverse only because of the different view-angles. On this ground they estimated the intrinsic shape of the bulge, finding that while the short-to-long axis ratio is nearly constant, $c/a \simeq 0.5$, the intermediate-to-long axis ratio varies from $b/a = 0.9$ in the inner regions to 0.75 in the outer ones, a fact which may give important clues about the mechanisms of galaxy formation and evolution.

5. The Effective Parameters Plane

Capaccioli et al. (1992, 1993) have re-analysed the distribution of KHGCs in the (log R_e, μ_e) plane (Fig. 2) starting from the set of global photometric parameters measured by Caon et al. (1990, 1993) for the luminosity-limited sample of Virgo and Fornax E and S0 galaxies, and by d'Onofrio (1991) for the bulges of 35 Virgo spirals. At variance with the previous results by Kormendy (1977) and others, they found that KHGCs separate into two distinct groups. The first one, named the 'ordinary' family, consists of galaxies fainter than $M_B \simeq -19.3$ ($\Delta = 18.3$ Mpc for both clusters). For objects of given luminosity, the effective parameters range in a wide interval, a fact not accounted for either by measurement errors or by projection effects, and quite important for understanding the failures of some intrinsic shape tests. Furthermore, independently of their luminosity, these galaxies do not grow larger than $R_e \simeq 3$ kpc. The second group ('bright' family) is formed by galaxies brighter than $M_B \simeq -19.3$. They are well separated from the 'ordinary' galaxies, and define a uniparametric sequence well represented by the Kormendy relation. They also seem to produce a marked secondary peak in the luminosity function, at variance with the claim by Binggeli et al. (1988) of a bell-shaped luminosity function for both

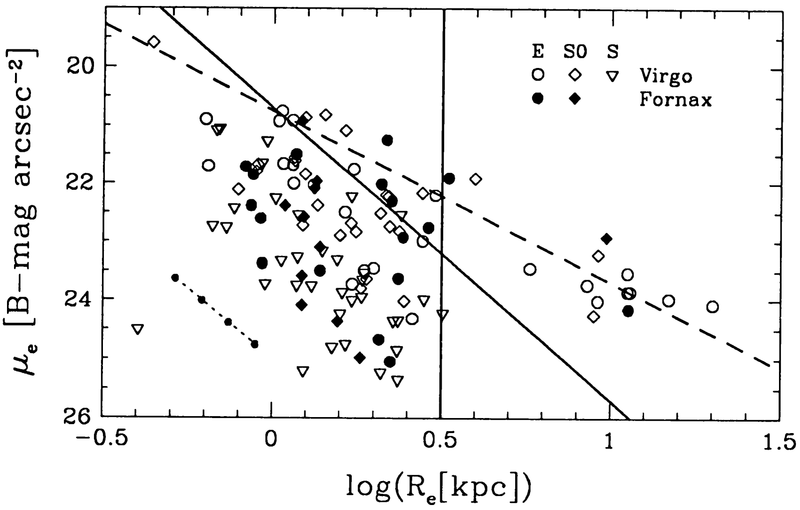

Figure 2. Sample of 87 Virgo galaxies (ellipticals and bulges of S0s and spirals) and of 28 Fornax (Es and S0s), showing some sort of bimodal distribution in the (log R_e, μ_e) plane. The upright solid line log $R_e = 0.5$ is an estimate of the upper boundary to the effective radius for the so-called 'ordinary' family (see text). The diagonal solid line marks the locus of constant luminosity $M_B = -19.3$ for homologous galaxies. The dashed line is the Kormendy (1977) relation, holding for the brightest group. The drift due to an error on the total luminosity B_T is indicated by the dotted line (the distance between two ticks corresponds to $\delta B_T = 0.1$ mag).

Virgo cluster and field E and S0 galaxies.

These findings, as well as the dependence on R_e of several structural galaxian parameters (isophotal shape, colour gradients, metallicity, dust and gas content, radio and X luminosity), markedly different in the two families, indicate that, while 'ordinary' galaxies constitute an inbred family, 'bright' ones are probably the result of accretion and merging processes (Capaccioli et al. 1993).

6. The Shape of Light Profiles

The existence of a dichotomy in the global parameters of KHGCs suggests that the light (and mass) distribution inside galaxies also should be different according to the galaxy membership to each family. In other words, the common assumption of structural *homology* appears in contrast with the above findings. We notice that such an assumption is supported observationally by the claimed universality of the de Vaucouleurs $r^{1/4}$ law (e.g. Burkert 1993), which also found a justification in the results of numerical simulations of the dissipationless collapse of protogalaxies. So far, deviations of the light profiles from the perfect $r^{1/4}$ model were interpreted as due to the presence of sub-components (faint disks, rings, ovals ...) or to tidal effects.

Prompted by these considerations, we have investigated in detail the shapes of the light profiles of our 80 Virgo and Fornax early-type galaxies. We found that a rather good

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parameterisation is provided by the generalized $r^{1/n}$ de Vaucouleurs law, $\mu(r) = a + b\, r^{1/n}$, where the exponent $1/n$ is let free rather than fixed to 1/4. For $n > 4$, the light profiles show an upward concavity in the ($r^{1/4}$, μ) plane; the contrary holds for $n < 4$.

It is obviously of paramount importance, for this kind of study, that the light profiles are accurately measured and that they extend outwards as much as possible. In fact, the use of a too limited portion of the light profile (such as that inside a CCD frame) could let the progressive change of slope in the ($r^{1/4}$, μ) frame remain undetected, while deviations from the $r^{1/4}$ best-fit might be interpreted as the result of an inaccurate background subtraction.

As apparent in Fig. 3, n is directly correlated with the galaxian size, varying from $n = 1$ for the smallest galaxies ($R_e \simeq 0.5$ kpc) to $n = 20$ for the largest ones ($R_e \simeq 20$ kpc). The de Vaucouleurs law ($r^{1/4}$) law loses its universality, but fixes the boundary between the 'ordinary' and the 'bright' galaxian families.

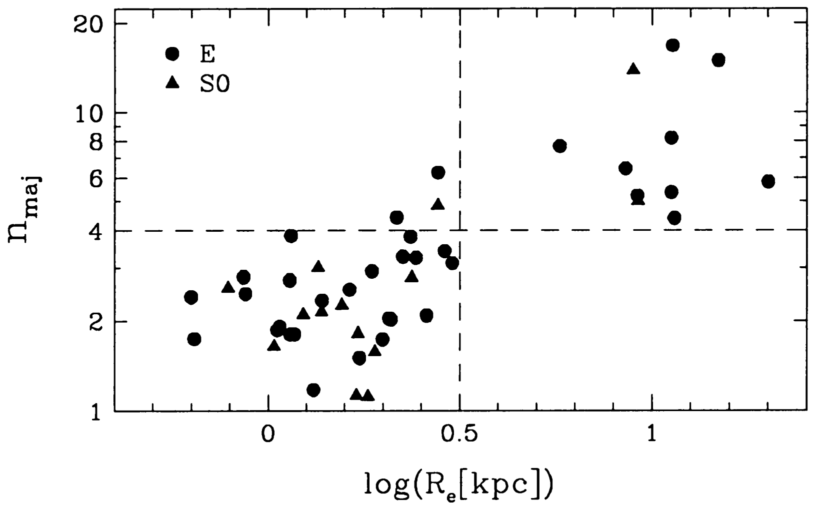

Figure 3. The correlation with R_e of the exponent n of the generalized de Vaucouleurs law is shown for the Caon et al. (1990, 1993) sample of Virgo and Fornax early-type galaxies. The horizontal and vertical dashed lines indicate the locus $n = 4$ and the $R_e = 3$ kpc cutoff between the 'ordinary' and 'bright' galaxian families respectively.

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