Structure of early-type galaxies: 2D fit of the light distribution for a complete volume-limited sample

E. Iodice (iodice@sissa.it)
International School for Advanced Studies, Trieste - Italy

M. D’Onofrio (donofrio@pd.astro.it)
Dipartimento di Astronomia - Università di Padova - Italy

M. Capaccioli (capaccioli@na.astro.it)
Dipartimento di Scienze Fisiche - Università di Napoli Federico II - Italy
Osservatorio Astronomico di Capodimonte, Napoli - Italy

Abstract. We outline the results of a two-dimensional (2D) fit of the light distribution of early-type galaxies belonging to a complete volume-limited sample, and briefly discuss the significant correlations among the structural parameters. In particular we reconfirm that the lack of structural homology is likely a characteristic of hot stellar systems.

Keywords: galaxies: photometry - galaxies: structure

1. Introduction

The luminosity distribution of ellipticals and bulges of S0 galaxies has been modelled for long using the $r^{1/4}$ formula (de Vaucouleurs 1948), which is characterized by just two scale parameters, the effective radius $R_e$ and the effective surface brightness $\mu_e$ of the isophote encircling half of the total light. More recently Caon et al. (1993) showed that a generalized de Vaucouleurs formula, $r^{1/n}$, obtained by adding a free exponent $n$ (Sersic, 1968), not only gives a better fit to the light profiles (which is expected in view of the larger number of parameters), but it provides also an interesting correlation between shape ($n$) and total luminosity ($L \sim I_e R_e^2$), which in turn suggests that the family of elliptical galaxies is not homologous.

The main criticism moved to this result is that the observed trend of $n$ with $R_e$ may be due to the presence of hidden disks embedded in elliptical galaxies: the larger is this disk, the smaller comes the value of $n$.

Caon et al. (1993) had obtained their result by fitting the main-axes light profiles using just the $r^{1/n}$ law. In view of the above criticism, we decided to pinpoint the question by adopting a 2D fitting procedure allowing the presence of the disk; 2D is needed in order to strongly couple and exploit the different projection properties of components.
such as disk and bulge which are expected to have quite different intrinsic thickness.

A non-linear least square fit minimizing the $\chi^2$ has been applied to the same volume-limited sample of Caon et al. (1993): it contains $\sim 80$ early-type galaxies belonging to either the Virgo or the Fornax cluster. This sample is $\sim 80\%$ complete down to $B_T \sim 14$ mag, equivalent to $M_B \sim -17.3$ if we assume a distance modulus $\Delta \mu = 31.3$ for both clusters.

In the following we outline the adopted methodology and summarize the results of this work (D’Onofrio et al., in preparation).

2. The 2D fit

Our 2D fitting models are based on the superposition of up to two components, each one characterized by concentric and coaxial elliptical isophotes with constant flattening. One such component may be thought as the projection of a spheroid with finite intrinsic thickness, thus mimicking a bulge. For this component only we allow a moderate degree of boxiness/diskiness. The other component is thought to be a disk.

**Model 1** is the 2D extension of the one used in their work by Caon et al. (1993). It consists of a spheroidal component only whose projected light distribution follows the generalized de Vaucouleurs law:

$$\mu_b(x, y) = \mu_e + k \left( \frac{r_b}{r_e} \right)^{1/n} - 1$$

with $k = 2.5(0.068n - 0.142)$ and $r_b = \left[ x^c + \frac{y^c}{(b/a)^c_b} \right]^{1/c}$; $c$ is the parameter accounting for some boxiness/diskiness ($c > 2$ for boxy isophotes and $c < 2$ for disky isophotes).

**Model 2** is made by the superposition of a bulge-like component with a $r^{1/4}$ light distribution (same as eq. 1, with $n = 4$) to an exponential disk represented as:

$$\mu_d(x, y) = \mu_0 + 1.086 \left( \frac{r_d}{R} \right)$$

with $r_d = \left[ x^2 + \frac{y^2}{(b/a)_d} \right]^{1/2}$.

**Model 3** is a generalization of model 2; the light distribution of the bulge follows a $r^{1/n}$ law, but the disk remains exponential.
Figure 1. Plot of the effective surface brightness $\mu_e$ versus the logarithmic effective radius $\log(R_e)$ for the bulge component. The bulges of spiral galaxies studied by de Jong (1996) are marked by asterisks. Filled circles and triangles mark the best fit for E and S0 galaxies, open pentagons and triangles the fair fits, open squares and open squares with a cross the poor fits. The solid line represents a constant absolute magnitude $M_B = -19.3$.

In summary, the structural parameters involved in these models are: the effective surface brightness $\mu_e$ and the effective radius $R_e$ of the spheroid, the free exponent $n$ when considered, the central surface brightness $\mu_0$ and the scale length of the disk $h$ if included, the apparent axial ratios $b/a$ for the bulge and the disk components, and the boxiness/diskiness parameter $c$.

A number of simulations on artificial galaxies have been performed in order to test the tool and to unveil the systematic effects that influence the model parameters; in particular the seeing, which produces strongly biased results even after proper convolution of the model, and can be taken care only by masking out the central area of the galaxies. The simulations also provided a more correct estimate of the errors of the model parameters.

3. Result of the fit

The three adopted models do not provide the same accuracy in reproducing the light distribution of early-type galaxies. By examining the
Figure 2. Plot of the effective radius $\log(R_e)$ of the bulge component versus the exponent $n$ of the generalized de Vaucouleurs law (symbols as in Fig.1). Open circles represent the data from Caon et al. 1993.

reduced $\chi^2$, the 2D residuals, and by comparing the geometry of the model (ellipticity and $a_4$ profiles) with the real galaxies, we concluded that the $r^{1/n} + \text{exp}$ model has to be preferred to either the simple $r^{1/n}$ and the $r^{1/4} + \text{exp}$ models. Model 1 is comparable to model 3 in reproducing dwarf elliptical galaxies ($M_B > -17$). Model 2 often produces extended luminous halos not observed in the real objects.

It is evident that the reduced $\chi^2$ by itself does not guarantee the physical significance of the best-fit solution for models with different numbers of parameters. We performed also an F-test of the best-fit $\chi^2$ distributions, in order to verify whether the variances are different even from a statistical point of view. Actually, however, we may try to attach a physical meaning to the most complex and best-fitting model, that of $r^{1/n} + \text{exp}$, only after analyzing and falsifying the correlations among the different parameters.

In general the best fitting model does not work in the inner seeing-dominated region ($< 1''$) and in the outer parts, where an extended luminous ‘halo’ is often found, but it is good in the intermediate regions for a large range of $\mu$. 
4. Analysis of the bulge parameters

We confirm the correlation between the effective radius $R_e$ and the effective surface brightness $\mu_e$. The $\mu_e - \log(R_e)$ relation (Fig. 1) shows a family of large bulges with $R_e > 3$ kpc and with low surface brightness $\mu_e$, as found by Capaccioli et al. (1992). The separation between ordinary and bright galaxies is well visible, even if the gap between the two families is less clear. The bulges of spirals all belong to the ordinary family ($R_e < 3$ kpc).

Fig. 2 shows the $n - \log(R_e)$ relation. The open circles represent the old distribution, found by Caon et al. (1993) for the same sample of galaxies by fitting the equivalent light profiles. The dashed line marks the value $n = 4$ of the de Vaucouleurs law. By comparing the old relation with the new one, we observe that there is not a variation within the errors of the parameters.

The $n$ parameter spans a wide range of values ($1 < n < 10$): low values are typical of exponential bulges (already known to exist in spiral galaxies), while high values are found in bright and large galaxies.

This result confirms that the different values of $n$ are not due to the presence of a disk, but that there is a clear trend in the values of $n$ with the galaxy size (and therefore with the total luminosity) for
Figure 4. Logarithmic plot of the scale length $R_e$ of the bulge versus the scale length $h$ of the disk components (symbols as in Fig. 1). The dashed lines mark the seeing dominated regions.

the spheroidal components. It follows that the non-homology is likely a characteristic of hot stellar systems.

5. Analysis of the disk parameters

Our best fit solutions tell us that in quite a few ($\sim 25\%$) elliptical galaxies there is a central exponential component. This is not surprising for the disky ellipticals, in which an ‘embedded disk’, generally smaller and brighter than normal disks in S0’s and spirals, gives a characteristic disky shape to the isophotes (Capaccioli et al., 1990, Scorza & Bender, 1995). However, we found an inner exponential component (with bright $\mu_0$ and small $h$) also in the bright, boxy ellipticals.

We verified a posteriori that such small and bright ‘disks’ are a first order approximation of the inner cores of elliptical galaxies, well described by the ‘Nuker law’ (Lauer et al. (1995), Byun et al. (1996) and Faber et al. (1997)).

Fig.3 shows the central surface brightness $\mu_0^c$ (corrected for inclination assuming a zero-thickness disk), plotted versus the scale length log($h$) of the detected ‘disks’. The distribution of values is large: it goes from small and bright ‘disks’ ($\mu_0^c < 19$, $h < 0.63$ kpc), many of them hosted by luminous E galaxies, to less luminous and great disks, preferably found in S0 and low luminosity ellipticals. The disk
parameters of normal spirals (from de Jong, 1996) are also included in the diagram for comparison.

It seems that the whole distribution follows approximately the lines of constant disk luminosities (dashed lines). The spiral disks of de Jong’s sample are brighter than the early-type disks of our sample and extend towards fainter \( \mu_0 \) and longer scale length \( h \). The distribution of \( \mu_0 \) does not peak around the Freeman value (solid line) (Freeman, 1970, van der Kruit, 1987).

In Fig. 4 we plotted the effective radius \( \log(R_e) \) of the bulge component versus the scale length \( \log(h) \). It is apparent there is a correlation between these parameters, but with two separated trends, one for the bulge dominated systems (upper part of the diagram), and another for the disk dominated galaxies (bottom part of the diagram).

It seems also that galaxies with very small bulges and disks \( (R_e \sim h < 0.6 \text{ kpc}) \) as well as systems with large \( R_e \) and \( h \) \( (> 2 \text{ kpc}) \) do not exist. We note that the lack of objects with large size cannot be a bias, since our sample is complete in luminosity.

6. Conclusions

By applying a full 2D fit of the light distribution of a volume-limited sample of early-type galaxies we obtained the following results:

1. The luminosity distribution of bright E galaxies is well represented by the superposition of an inner exponential component and a large outer bulge. This inner structure is characterized by a high central surface brightness and a small scale length. It is likely that the detected component is the core of the galaxy. It seems important, however, that this component follows the same photometric properties of normal disks, although shifted in zero point.

2. The distribution of \( \mu_0 \) for all detected ‘disks’ is a function of the scale length \( h \). The slope of the relation is that of constant disk luminosities. The central surface brightness \( \mu_0 \) spans a wide range of values, in contrast with the claimed constant value.

3. The effective radii of the bulges and the scale lengths of the ‘disks’ are correlated: this suggests a possible coupling during the galaxy formation between the two components, and that the angular momentum should be an important parameter for the Hubble sequence.
4. The effective radius $R_e$ correlates with $\mu_e$ and with the exponent $n$ of the generalized de Vaucouleurs law. The existence of two families of spheroids is confirmed as well as the increasing of $n$ for large luminous bulges. This suggests that elliptical galaxies are not homologous systems.

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Address for Offprints: iodice@sissa.it