Carnegie Observatories Astrophysics Series, Vol. 1:
Coevolution of Black Holes and Galaxies, 2004
ed. L. C. Ho (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium1/proceedings.html)

Inner and Outer Photometric Structure of Elliptical Galaxies

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Abstract

The Nuker model, when applied to the inner regions of "core" galaxies, is shown to produce systematic biases in the determination of the core "break-radii". These radii can easily be (and often have been, see Trujillo et al. 2004) over-estimated by more than 100%. Moreover, due to curvature in the outer profiles of early-type galaxies (i.e., beyond the break-radius), none of the Nuker model parameters are found to be robust quantities. A new empirical model that simultaneously describes both the inner *and* outer light-profiles of elliptical galaxies (and bulges in general) is presented. It consists of a Sérsic function with an inner power-law and a variable transition region.

1.1 Introduction

The Nuker model was designed to match the inner few (∼3-10) arcseconds of predominantly nearby, early-type galaxy light-profiles; it was never intended to describe an entire profile. The model consists of a double power-law with a variable transition region between the inner and outer power-laws; it can be written as

$$I(r) = I_b 2^{(\beta-\gamma)/\alpha} \left(\frac{r}{r_b}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}, \tag{1.1}$$

where the intensity at the break-radius r_b, separating the two power-laws, is denoted by I_b. The inner power-law slope is denoted by γ and the outer power-law slope is denoted by β. A fuller description of the above model can be found in the review contribution from Lauer (these Proceedings).

Of course, it was known from the start that the outer profiles (beyond the core break-radii) in elliptical galaxies have a de Vaucouleurs $r^{1/4}$-like shape, and hence the Nuker model would be unable to describe their entire profile. However, what was not explored was how the curvature in the outer profile might actually bias the Nuker parameters. This has been investigated in Graham et al. (2003b) and is reported here. It is revealed that the break-radii derived from the Nuker model, even when applied to simulated core galaxies without noise, can be more than 100% larger than the true break-radii. It turns out that because of parameter coupling, none of the Nuker model parameters are stable quantities.

The Sérsic model, on the other hand, was developed to fit the entire profile of elliptical galaxies (and bulges in general); however, due to the presence of depleted galaxy cores (and various other nuclear components) the Sérsic model cannot always describe the very inner region. It therefore seemed appropriate to develop a new empirical model consisting of an

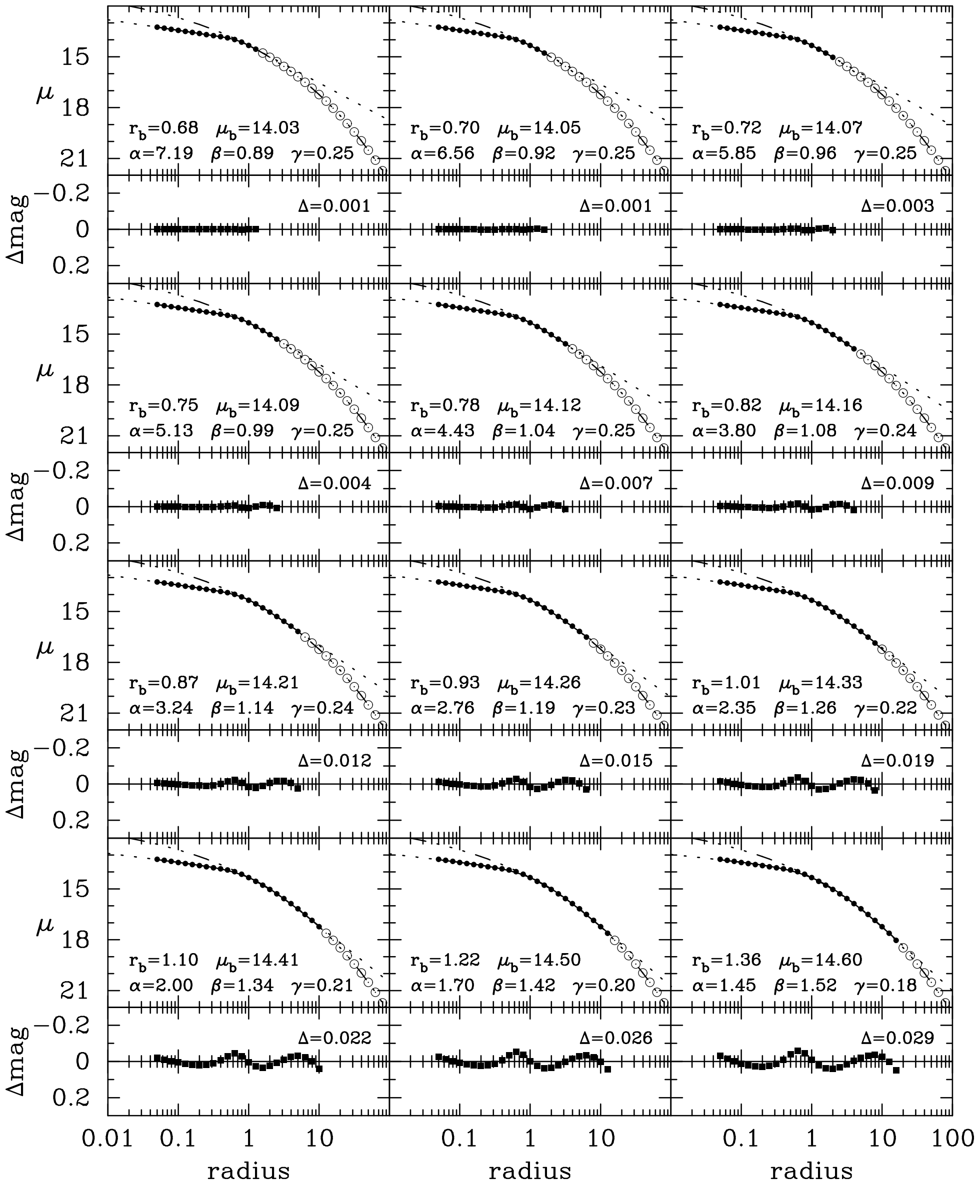

Fig. 1.1. A model "core" galaxy is shown, along with the best-fitting Nuker law (dotted lines). The galaxy model light-profile is always the same, although a progressively larger radial range is fitted by the Nuker law in each panel until the scatter (Δ) reaches 0.03 mag — the average value reported by the Nuker team. The galaxy model consists of an outer de Vaucouleurs profile (dash-dot-dot-dot curve) having $r_e = 25$ arcseconds and an inner power-law with a negative logarithmic slope of 0.25. The break-radius is 0.65 arcseconds and μ_b=14.0 mag arcsec^{-2}, a value of $\alpha = 8.0$ (see equation 1.2) has been used. Although every fit looks acceptable, the derived Nuker parameters (inset in figure) can be seen to vary systematically; the break-radius finally increasing more than 100% of its true value.

inner power-law, a transition region, and an outer Sérsic model. It is hoped this can be used to connect the inner and outer structure of elliptical galaxies. Fuller details of this model can be found in Graham et al. (2003b) and Trujillo et al. (2004). Below is the content of the 10 minute talk given (by A.G.) at the Conference.

1.2 Stability of the Nuker Model Parameters

In a simple exploration into the stability of the Nuker model parameters, the Nuker model has been fitted to a simulated galaxy in which we know the true break-radius. The synthetic galaxy light-profile was constructed to resemble a typical "core" galaxy having an outer $r^{1/4}$ profile with effective radius $r_e = 25$ arcseconds, a well-resolved break-radius of 0.65 arcseconds at $\mu = 14$ mag arcsec^{-2}, and an inner power-law with slope $\gamma = 0.25$.

As the actual radial extent fitted by the Nuker model is increased to values typically used by Rest et al. (2001, $\sim$ 10 arcseconds), Figure 1.1 reveals how the Nuker model break-radius marches steadily outward. When the mean difference between the synthetic data and the Nuker model reaches ~ 0.03 mag arcsec^{-2} (the average value reported by the Nuker team in their fits), the derived break-radius is more than twice the true break-radius. Due to the curvature in the outer profile (small as it is over the limited radial range fitted), coupling of the parameters results in systematic changes far greater than those expected from random errors. Byun et al.'s (1996, their Figure 6) covariance error analysis (for a constant fitted radial range) revealed that the 10σ χ^2 ellipses span typically $\pm 6\%$ of the fitted Nuker model break-radius. Systematic errors therefore dominate over random errors; this is further illustrated with an analysis of a representative galaxy taken from the sample of Rest et al. (2001; see figure 1.2).

The more an outer profile (beyond the core region) resembles a power-law, that is, the less curvature in the outer profile, the less severe this bias should be. Caon, Capaccioli, & D'onofrio (1993; see also Graham et al. 1996) revealed that bigger galaxies have higher Sérsic $r^{1/n}$ n-values than smaller galaxies. For large values of n ($>$ 10-15) and small radial ranges, the Sérsic function looks like a power-law. Consequently, the Nuker model should be more accurate when applied to brightest cluster galaxies (Laine et al. 2003, and these proceedings). However, it is of course of importance to examine the reliability in even these cases by varying the radial range to which the Nuker model is fitted (as done in Figure 1.1 and 1.2), rather than using a constant 3 or 10 arcsecond range.

1.3 A New Empirical Light-Profile Model

Modifying the Nuker model through the transformation of the outer power-law to a Sérsic function, or similarly, modifying the Sérsic model through the inclusion of an inner power-law, our new (radially global)* empirical light-profile model is given by the expression

$$I(r) = I' \left[1 + \left(\frac{r_b}{r}\right)^{\alpha}\right]^{\gamma/\alpha} \exp\left\{-b_n[(r^{\alpha} + r_b^{\alpha})/r_e^{\alpha}]^{1/(\alpha n)}\right\}, \tag{1.2}$$

where r_b is the break-radius separating the inner power-law having logarithmic slope γ from the outer Sérsic function having a shape parameter n and effective half-light radius r_e. The

* The presence of additional components, such as nuclear star clusters, bars, rings, or outer large-scale disks can be dealt with by adding additional models to accommodate for their structural form — just as a bulge+disk model is used to describe a spiral galaxy.

quantity b_n is a function of n and can be approximated by $2n - 1/3$ for values of n greater than ~ 1 (Graham 2001). The value of r_e is then the effective half-light radius of the outer $r^{1/n}$ profile beyond the transition region, and not the half-light radius of the new model. The effective surface brightness of the outer Sérsic profile is obtained by putting $r = r_e$ and $r_b = 0$ in equation 1.2, while r_b retains its value in equation 1.3 below.

The intensity I_b at the break-radius r_b can be evaluated from the expression

$$I' = I_b 2^{-(\gamma/\alpha)} \exp\left[b_n (2^{1/\alpha} r_b / r_e)^{1/n}\right]. \tag{1.3}$$

The final parameter, α, controls the sharpness of the transition between the inner (power-law) and outer (Sérsic) regimes — higher values of α indicating sharper transitions. In practice (see Trujillo et al. 2004), a sharp transition ($\alpha > 3$) may be preferable; high values of α also minimize possible coupling of the parameters, which may compromise the inner profile slope (as can happen with Nuker model fits, see, for e.g., Rest et al. 2001, and references therein). We advocate keeping α fixed at some large constant value; this reduces equation 1.2 to a 5 parameter equation capable of describing the full radial extent of elliptical galaxy light-profiles.

1.4 Application to Real Profiles

In Trujillo et al. (2004), this new model is applied to a sample of $\sim$20 bona fide elliptical galaxies from the Lauer et al. (1995) and Rest et al. (2001) galaxy sample. Two representative galaxy profiles, modeled with equation 1.2, are presented here. In Figure 1.3, the inner $r < 15$ arcseconds are the (deconvolved) profiles from Rest et al. (2001), while the outer points are from the full WFPC2 mosaic of the same exposures (see Trujillo et al. 2004, for full details).

The "power-law" galaxy NGC 5831 is shown to be well described by the 3-parameter Sérsic function over almost its entire observed radial range (0.1 arcseconds to $\sim 3r_e$) — the 5 Nuker parameters only describe its inner region. Rest et al. (2001) had derived a break-radius $r_b = 1.78$ arcseconds, where as we resolve no (partially evacuated) core. Importantly, Trujillo et al. (2004) reveal that all the so-called "power-law" galaxies that we modeled are in fact simply "Sérsic" galaxies over their entire radial extent. That is, the so-called "power-law" class of galaxies can (most probably) be done away with, subsumed into regular $r^{1/n}$ elliptical galaxies that do not have cores.

Moreover, Graham et al. (2003b) show how the Nuker model, with its 5 parameters, is capable of mimicking the 3-parameter Sérsic function over small radial ranges. That is, application of the Nuker model can result in apparently good fits with artificial (non-zero and non-infinite)* break-radii for profiles which actually have no physical cores. The use of the 3 Sérsic parameters to describe the entire radial extent of these systems, rather than 5 parameters to describe only the inner profile, is recommended.

In Figure 1.3, NGC 3348 clearly displays a flattening of the inner profile relative to the outer Sérsic profile; this break is well matched by our new model. Rest et al. (2001) classified this galaxy as a "core" galaxy with break-radius $r_b = 0.99$ arcseconds; we find $r_b = 0.45$ arcseconds, and attribute the difference to the process illustrated in Figure 1.1. Indeed, Trujillo et al. (2004) find that the new model yields break-radii which are, on average, half the size of the published values derived using the Nuker model. It would appear that the

* The Nuker model is equivalent to the $r^{1/n}$ model when $r_b \to \infty$, $\gamma = 0$, and $\alpha = 1/n$ (Byun et al. 1996).

break-radii of the Nuker model simply indicate where the change in the logarithmic profile slope of the Nuker model is a maximum, and not the actual physical break-radius of a galaxy.

1.5 Conclusions

Due to curvature in the light-profiles of early-type galaxies beyond their core region, none of the 5 Nuker model parameters are robust quantities; they vary systematically with the fitted radial range. These parameters are therefore unable to represent any physically meaningful quantity. A new empirical model which modifies the Nuker model by transforming its outer power law into a Sérsic function is developed and suggested for the use of modeling the entire radial extent of elliptical galaxies. Due to the curvature of the Sérsic function, this new model does not suffer from the same systematic biases that the Nuker model does.

Application of this new model has revealed that the so-called "power-law" galaxies can have their entire radial extent described with the 3-parameter Sérsic model, while "core" galaxies appear to be "Sérsic" galaxies with impoverished cores. A new definition for a "core" is therefore advocated as as a deficit in central flux relative to the outer Sérsic profile.

It is known that the Sérsic shape parameter n is strongly related with the mass of a galaxies central supermassive black hole (SMBH; Graham et al. 2001, 2003a; Erwin et al., these Proceedings). Application of our new model not only provides a measurement of the shape (n) of a galaxies global light-profile (beyond the core region), but simultaneously provides an estimate to the size of the partially evacuated core, thereby promising new insight into the formation of elliptical galaxies and SMBHs.

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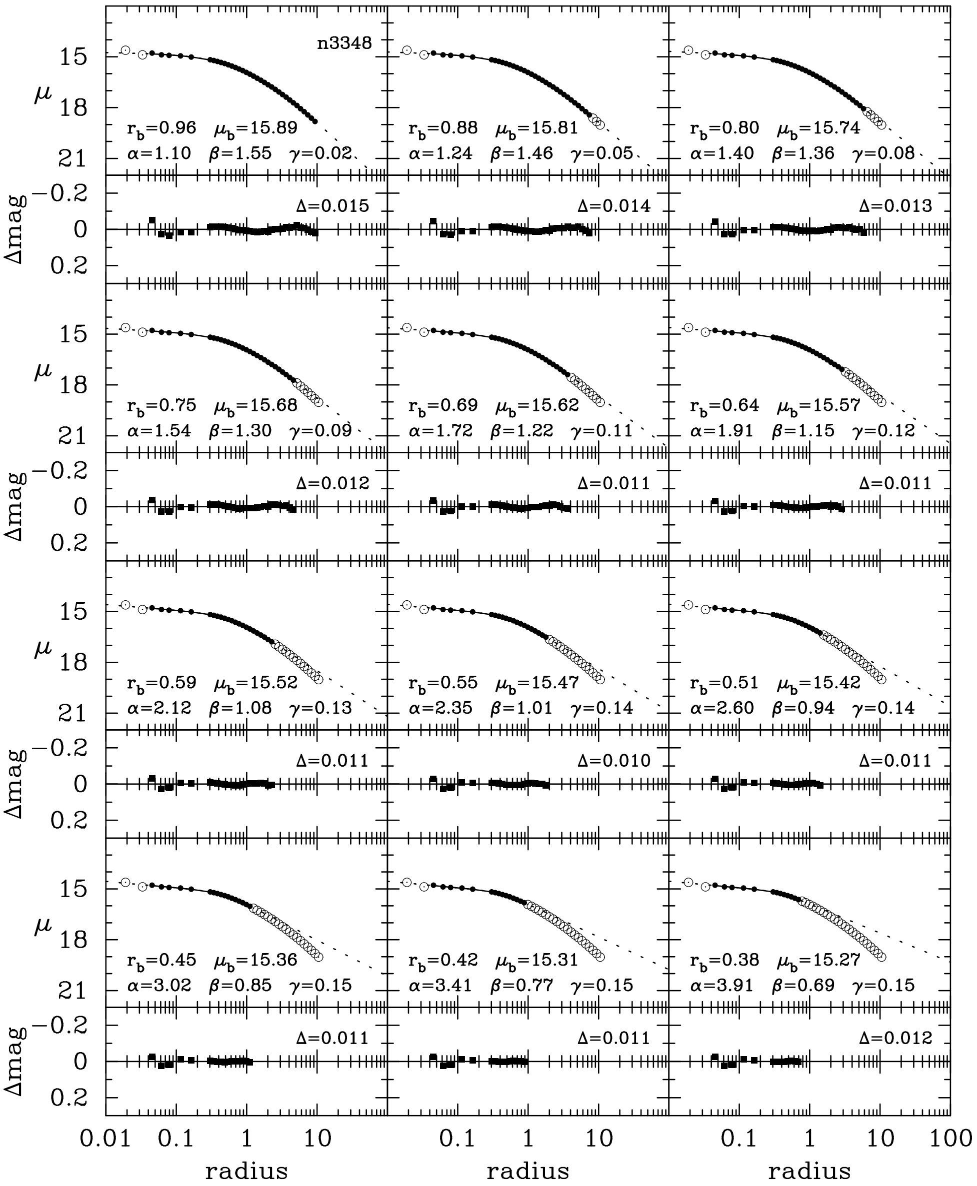

Fig. 1.2. Nuker-model fits (solid and dotted lines), using progressively smaller radial ranges, are applied to the major-axis F702W surface-brightness profile of NGC 3348 (from Rest et al. 2001). The radial extent of the fitted data (filled circles) decreases from left to right and top to bottom. Although every fit looks acceptable (the r.m.s. scatter Δ mag for each fit is given in each panel), as we saw in figure 1.1, the actual Nuker model parameters (inset in figure) vary systematically with the fitted radial extent. Rest et al. (2001) reported a break radius $r_b = 0.99''$ for this galaxy, based on their Nuker-model fit. (Figure taken from Graham et al. 2003b).

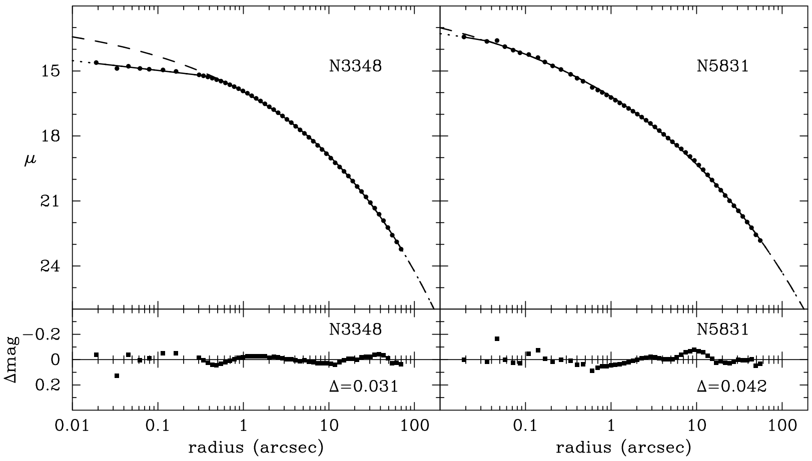

Fig. 1.3. Two *HST* major-axis surface-brightness profiles of elliptical galaxies. The solid lines are fits using the new empirical model of equation 1.2, with inner and outer extrapolations indicated by the dotted lines. Inward extrapolations of the outer Sérsic-like part of the model, past the break-radius, are indicated by the dashed lines. In NGC 3348, which Rest et al. (2001) classified as a "core" galaxy with break-radius $r_b = 0.99''$, there is a clear inner break from the Sérsic profile; we find $r_b = 0.45''$. For NGC 5831, a "power-law" galaxy according to Rest et al. (2001) with $r_b = 1.78''$, our best fit is essentially a pure Sérsic model. (Figure taken from Graham et al. 2003b).