Black Holes: from Stars to Galaxies – across the Range of Masses
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The Inner Workings of Early-Type Galaxies: Cores, Nuclei and Supermassive Black Holes

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Abstract. Recent years have seen dramatic progress in the study of the core and nuclear properties of galaxies. The structure of the cores has been shown to vary methodically with global and nuclear properties, as cores respond to the mechanisms by which galaxies form/evolve. The dynamical centers of galaxies have been found capable of hosting two seemingly disparate objects: supermassive black holes (SBHs) and compact stellar nuclei. In a drastic departure from previous beliefs, it has been discovered that both structures are common: galaxies lacking SBHs and/or stellar nuclei are the exception, rather than the norm. This review explores the connection between cores, SBHs and stellar nuclei in early-type galaxies, as revealed by the ACS Virgo Cluster Survey.

Keywords. galaxies: elliptical and lenticular, cD, galaxies: dwarf, galaxies: fundamental parameters, galaxies: kinematics and dynamics, galaxies: photometry, galaxies: structure, galaxies: nuclei, galaxies: bulges

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1. Introduction

Cores, a term we will use loosely to describe the central few hundred parsec region of a galaxy, represent an integral part in our understanding of the global galactic structure, for very good reasons. Cores act as recording devices of a galaxy history. Dynamical timescales are shorter here than elsewhere in the galaxy; the morphology, dynamics and history of star formation and chemical enrichment of the cores are a sensitive tracer of the gas, dust and dense stellar systems, either intrinsic or accreted through merging events, that are drawn to the bottom of the potential well throughout cosmic times. Furthermore, core and global properties are linked through a number of scaling relations. In particular, those involving supermassive black holes (SBHs) – which are almost always associated with galactic cores – underscore the importance of nuclear feedback in galaxy evolution (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Graham et al. 2001; Ferrarese 2002; Haring & Rix 2004).

The study of galactic cores received a tremendous push forward with the deployment of the Hubble Space Telescope. HST images brought into focus a plethora of structural features, including nuclear stellar disks, bars, "evacuated" regions (possibly scoured out by the evolution of SBH binaries), and an entire spectrum of dust features - from small irregular patches to large, organized dust disks. In early-type galaxies, cores were found to fall in two distinct classes: those with a shallow surface brightness profile, and those whose surface brightness kept increasing, in roughly a power-law fashion, to the innermost radius accessible given the resolution limit of the instrument (Ferrarese et al. 1994; Lauer et al. 1995,2005; Ravindranath et al. 1996; Rest et al. 2001). Galaxies falling into the first class have become known (somewhat unfortunately) as "core" galaxies, galaxies falling into the second class as "power-law". The division between the two classes was found to correlate neatly with galaxy luminosity, with core galaxies being exclusively bright giant ellipticals, while fainter galaxies are (with few exceptions) classified as power-laws. The stark separation between the two classes has been attributed to differing formation/evolutionary histories. Power-law galaxies have been claimed to be the result of dissipation during galaxy formation, with some authors further claiming that all power-law galaxies host stellar disks; while core-galaxies are believed to be the result of the merging of fainter (power-law) galaxies, and of their central SBHs.

Dynamical detections of SBHs exist in approximatively three dozen galaxies (see Ferrarese & Ford 2005 for a review); indeed, balancing the SBH mass function from the QSO epoch to the present day requires virtually all local galaxies brighter than a few $0.1L^*$ to host a SBH (e.g. Shankar et al. 2004; Marconi et al. 2004). Recent observations, however, have made it clear that SBHs are not the only objects to enjoy a priviledged position at a galaxy's dynamical center. Stellar nuclei, or nuclear star clusters, have recently been detected in a large fraction (70% to 90%) of galaxies of all Hubble types and luminosities (Böker et al. 2002; Lotz et al. 2004; Grant et al. 2005). Follow-up spectroscopy of stellar nuclei in spiral galaxies (Walcher et al. 2005,2006; Rossa et al. 2006) has shown them to be massive, dense objects akin to compact star clusters. Luminosity-weighted ages range from 10 Myr to 10 Gyr, younger than the age of the galactic disk, and with the younger clusters found preferentially in the later type spirals.

This review explores the connection between cores, nuclei and supermassive black holes in light of recent results from the ACS Virgo Cluster Survey (ACSVCS), the largest HST imaging survey designed specifically to provide an unbiased characterization of the core structure of early-type galaxies.

2. The ACS Virgo Cluster Survey

The ACSVCS (Côté et al. 2004) consists of HST imaging for 100 members of the Virgo Cluster, supplemented by imaging and spectroscopy from WFPC2, Chandra, Spitzer, Keck and KPNO. The program galaxies span a range of ≈ 460 in B-band luminosity and have early-type morphologies: E, S0, dE, dE,N or dS0. All images were taken with the Advanced Camera for Surveys (ACS; Ford et al. 1998) using a filter combination roughly equivalent to the g and z bands in the SDSS photometric system. The images cover a $\approx 200'' \times 200''$ field with $\approx 0''.1$ resolution ($\approx$8pc at the distance of Virgo, 16.5 Mpc).

This review summarizes results from the subset of ACSVCS papers which deal with the morphology, isophotal parameters and surface brightness profiles for early-type galaxies (Ferrarese et al. 2006a), their central nuclei (Côté et al. 2006) and scaling relations for nuclei and SBHs (Ferrarese et al. 2006b). Other ACSVCS papers have discussed the data reduction pipeline (Jordán et al. 2004a), the connection between low-mass X-ray binaries and globular clusters (Jordán et al. 2004b), the measurement and calibration of surface brightness fluctuation distances (Mei et al. 2005ab), the connection between globular clusters and ultra-compact dwarf galaxies (Haşegan et al. 2005), the luminosity function, color distributions and half-light radii of globular clusters (Jordán et al. 2006ab; Peng et al. 2006a), and diffuse star clusters (Peng et al. 2006b).

3. The Core Structure of Early-Type Galaxies

Over the three-decade radial range between a few tens of parsecs and several kiloparsecs (i.e. to the largest radii covered by the ACSVCS images), the surface brightness profiles of the ACSVCS early-type galaxies are well described by a simple Sérsic model (Sérsic 1968) with index n increasing steadily with galaxy luminosity. Notable, and systematic, deviations from a Sérsic model are however registered in the innermost regions. For eight of the 10 brightest galaxies ($M_B \lesssim -20.3$) the measured inner profiles (typically within $0''.5$ to $2''.5$, corresponding to 40 to 200pc) are shallower than expected based on an inward extrapolation of the Sérsic model constrained by the region beyond. For these galaxies, the surface brightness profile is best fitted by joining the outer Sérsic profile to an inner, shallower, power-law component (such composite models are referred to as "core-Sérsic" Graham et al. 2003; Trujillo et al. 2004),

The opposite is seen in fainter galaxies, $\approx 80\%$ of which show a clear upturn, or inflection, in the surface brightness profile within (typically) the innermost few tens of parsec region (see Figure 1 of P. Côté, these proceedings). The upturn signals the presence a stellar nucleus that is most likely structurally distinct from the main body of the underlying galaxy. When a nucleus is present, the inner surface brightness is, by definition, larger than the inward extrapolation of the outer Sérsic model.

The picture that has emerged from the ACSVCS is therefore one in which, in moving down the luminosity function from giant to dwarf early-type galaxies, the innermost 100-parsec region undergoes a systematic and smooth transition from light (mass) "deficit" (relative to the overall best fitting Sérsic model) to light "excess". Although the subset of ACSVCS "core-Sérsic" galaxies coincides with the galaxies that were classified as "cores" in previous investigations, there are critical differences between our study and the ones that preceded it. Compared to previous work, the ACSVCS has emphasized the role of stellar nuclei; the fact that the frequency, luminosities and sizes of the ACSVCS nuclei are in remarkable agreement with those measured (using different techniques and assumptions) by recent independent surveys in both early and late type galaxies, supports the robustness of the ACSVCS analysis. Recognizing the nuclei as separate components has allowed us to revisit the issue of the division of early-type galaxies into "core" and "power-law" types. Such division was based on the fact that the distribution of the logarithmic slopes, $\gamma = -d\log I/d\log r$, of the inner surface brightness profile had been found to show various degrees of bimodality. Such bimodality is absent in the γ distribution of the ACSVCS galaxies. In agreement with previous studies, in galaxies brighter than $M_B \approx -20.3$, γ is indeed found to decrease with galaxy luminosity, while the opposite trend is seen for fainter galaxies, however, the transition is smooth, rather than abrupt. In a further departure from previous studies, we find that the low-γ end of the distribution (corresponding to the galaxies with the shallowest surface brightness profiles) is occupied mostly by the faintest dwarf stystems, rather than by the brightest giant ellipticals. We note here that the absence of a bimodal behaviour in γ does not automatically invalidate a picture in which brighter galaxies evolve mainly through merging while fainter systems are largely left untouched. Indeed, such picture does not necessarily explain the perceived stark separation of galaxies in "core" and "power-law" types for which it was formulated. The extent to which structural parameters are compromised by merging of galaxies (and their supermassive black holes) depends on the the masses of the progenitors (e.g., Bournaud et al. 2005; Milosavljevic & Merritt 2001); given a continuous distribution for the latter, combined with a galaxy luminosity function heavily biased towards low-mass systems, allows for the possibility of a smooth transition between progenitors and merger products.

4. Compact Stellar Nuclei in the ACSVCS

At the outset of the ACSVCS, it was known that at least $\approx$25% of the program galaxies contained nuclei, based on ground-based classifications from the VCC (Binggeli et al. 1985). Stellar nuclei in the ACSVCS images were identified by a variety of indicators, including direct inspection of the ACS frames, color changes in the $g-z$ color images, and sudden upturns in the surface brightness profiles. Based on these criteria, 60 to 80% of ACSVCS galaxies host stellar nuclei (with the precise fraction depending on galaxy magnitude), in line with the fraction reported in both spiral and elliptical galaxies based on recent high-resolution surveys (Carollo, Stiavelli & Mack 1998; Matthews et al 1999; Böker et al. 2002, 2004; Balcells et al. 2003; Lotz et al. 2004; Graham & Guzman 2003; Grant et al. 2005), but a factor ~ 3 higher than expected based on the VCC.

Our analysis shows that surface brightness selection biases in the VCC data are largely responsible for the difference: in galaxies with central g-band surface brightnesses lower than ≈ 20.5 mag arcsec^{-2}, the agreement between the ACSVCS and VCC is nearly perfect, while above 19.5 mag arcsec^{-2}, virtually all nuclei were missed by the ground-based survey. Selection effects might, of course, still be at work in the ACSVCS sample, implying that our estimate for the frequency of nucleation, $f_n \approx 60-80\%$, is almost certainly a lower limit on the true frequency. As will be discussed shortly, the luminosity and half-light radii of stellar nuclei correlate strongly with the magnitude of the host galaxy; it is therefore possible, for each galaxy classified as non-nucleated, to determine whether a nucleus, if present, could have gone undetected. Based on these tests, with very few exceptions, the only galaxies for which the existence of a nucleus can be confidently excluded are those brighter than $M_B \approx -20.3$ mag. These are the same galaxies with central light "deficits" for which the surface brightness profiles are well represented by "core-Sérsic" rather than Sérsic models (§3)

4.1. *Scaling Relations for Stellar Nuclei*

For 51 galaxies in the ACSVCS the sharp upturn in the surface brightness within $\approx 1''$ is conspicuous enough that a measurement of the nucleus' photometric and structural parameters is possible. These parameters are recovered by adding a central King model (King 1966) to the underlying Sérsic component when fitting the surface brightness profile.

The luminosity function of nuclei follows a Gaussian distribution with dispersion in the range $1.5-1.8$ mag and peak absolute $g-$band magnitude ≈ -10.7 mag, a factor $\approx 25\times$ brighter than the peak of the globular cluster luminosity function. With a half-dozen exceptions, nuclei in the ACSVCS galaxies are clearly spatially resolved (thereby ruling out an AGN origin), with individual sizes ranging from 62 pc down to the resolution limit of 2 pc, and a median half-light radius of $\langle r_h \rangle = 4.2$ pc. Unlike globular clusters, for which size is largely independent of magnitude, nuclear sizes are found to scale with luminosity according to the relation $r_h \propto \mathcal{L}^{0.50\pm0.03}$ (Figure 1, left panel).

One of the most credited models posits that the formation of nuclei proceeds trough the coalescence of globular clusters drawn to the bottom of the potential well by dynamical friction (e.g. Tremaine et al. 1975). While the size-magnitude relation observed for the ACSVCS nuclei is consistent with the prediction of such model (Bekki et al. 2004), a more complex picture is put forth by the observations that nuclei, again unlike globular clusters, display a color-magnitude relation (Figure 1, right panel). Monte Carlo simulations show that mergers of globular clusters through dynamical friction are unable to explain the observed color-magnitude relation; indeed the existence of this relation suggests that the chemical enrichment of nuclei is governed by local or internal factors, along the lines of the various "gas accretion" models (e.g. Mihos & Hernquist 1996). Note that the nuclei's color-magnitude relation is better defined for galaxies fainter than $M_B \approx -17.6$ mag, while the nuclei belonging to brighter galaxies frequently show very red colors, $(g-z) \sim 1.5$. If confirmed (measurements are more uncertain for these nuclei, due to the high

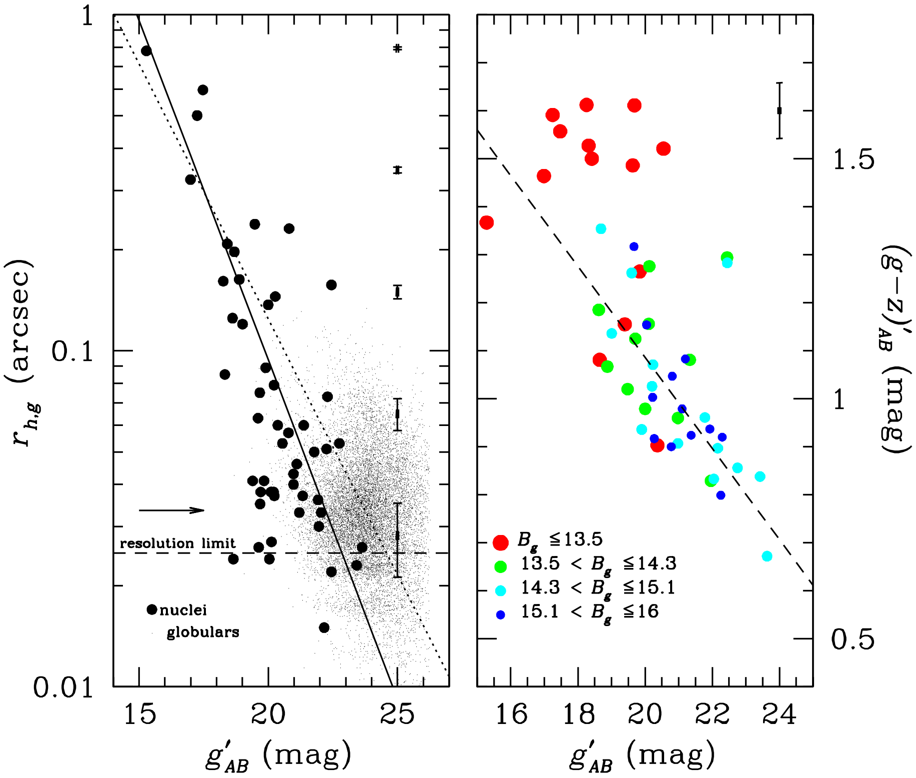

Figure 1. *(Left Panel)* The size-magnitude relation, in the $g-$band, for the 51 ACSVCS nuclei for which structural parameters could be measured (solid circles) and the sample of globular clusters from Jordán et al. (2006) (points). Typical errorbars for the nuclear sizes are shown in the right hand side of the panel. The arrow shows the "universal" half-light radius of $0''.033$ ($\approx$ 2.7 pc) for globular clusters in Virgo (Jordán et al. 2005), while the dashed line shows a conservative estimate for the resolution limit of the ACS images. The solid diagonal line shows the best fitting relation for the nuclei ($r_h \propto L^{0.5}$), while the dotted line shows the prediction of the globular cluster merging model of Bekki et al. (2004). *(Right Panel)* Color-magnitude diagram for the ACSVCS nuclei.The size of the symbol for the nuclei is proportional to the magnitude of the host galaxy, shown in the legend. The dashed line shows the the best fit relation for the nuclei of galaxies fainter than $B_T = 13.5$ mag.

underlying galaxy surface brightness), this observation might suggest that these nuclei may constitute a separate type of objects following a different formation route.

A third model, namely nuclear formation through two-body relaxation around a black hole, is inconsistent with the observation that nuclei are spatially resolved in most of the ACSVCS galaxies. Nuclei formed through this mechanism are predicted to extend to approximately 1/5 of the SBH sphere of influence (e.g. Merritt & Szell 2005), and would therefore be spatially unresolved by the ACS in all of the ACSVCS galaxies, clearly contradicting our observations.

Finally, we note that the luminosity function and size distribution of the ACSVCS nuclei shows remarkable agreement with those of the "nuclear star clusters" detected in spiral galaxies (Böker et al. 2002,2004). This points to a formation mechanism for the nuclei that is largely independent on both intrinsic and extrinsic factors, such as host magnitude and Hubble type, and immediate environment.

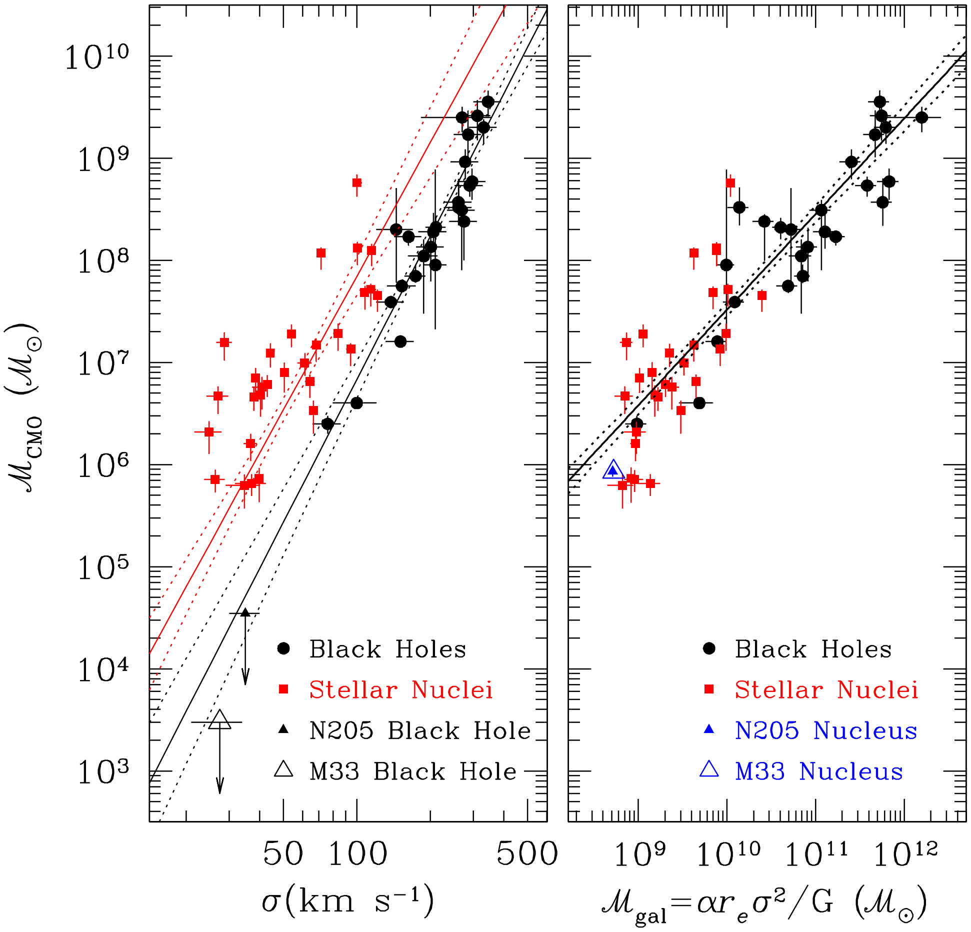

Figure 2. *(Left Panel)* Mass of the CMO (stellar nuclei as red squares and SBHs as black circles) plotted against the velocity dispersion of the host galaxy. The solid red and black lines show the best fits to the nuclei and SBH samples, respectively, with 1σ confidence levels shown by the dotted lines. *(Right Panel)* CMO mass plotted against galaxy virial mass. The solid line is the fit obtained for the combined nuclei and SBH sample.

5. Stellar Nuclei and Supermassive Black Holes

The ubiquitousness of SBHs and stellar nuclei, and their unique location at the dynamical centres of galaxies, are reasons to suspect that a connection between the two might exist.

The ACSVCS data strongly support this view. The left panel of Figure 2 (from Ferrarese et al. 2006b) shows a recent characterization of the relation between the masses of SBHs (black circles) and the stellar velocity dispersion of the host bulge, originally discovered by Ferrarese & Merritt (2000) and Gebhardt et al. (2000). The $\mathcal{M}-\sigma$ relation is one of the tightest, and therefore most fundamental, of the scaling relations for SBHs, and has been used extensively to constrain the joint evolution of SBHs and galaxies (e.g., Haehnelt 2004 and references therein). The ACSVCS stellar nuclei (shown as red squares) obey an $\mathcal{M}-\sigma$ relation with the same slope, although different normalization, as the one defined by SBHs. This is a notable and unexpected finding, suggesting close similarities in the formation and evolutionary history of these two radically different structures

(McLaughlin et al. 2006). Furthermore, when σ is combined with the effective radius r_e to produce a measure of the galaxy's virial mass, $\mathcal{M}_{gal} \propto \sigma^2 r_e/G$, SBHs and stellar nuclei are found to obey an identical $\mathcal{M}-\mathcal{M}_{gal}$ relation (right panel of Figure 2; see also Côté et al. 2006). Remarkably, the same relation is also found to hold in spiral galaxies (Rossa et al. 2006) and to extend to dEs as faint as $M_B \approx -11.7$ mag (Wehner & Harris 2006).

These findings can be summarized as follows: a constant fraction, $\mathcal{M}_{\rm CMO}/\mathcal{M}_{gal} \approx 0.2\%$, of a galaxy total mass is used in the formation of a nuclear structure, or "central massive object" (CMO). This holds true for galaxies spanning a factor 10^4 $M_\odot$ in mass, all Hubble types, luminosities and environments. In spite of their obviously different nature, SBHs and stellar nuclei are nothing but complementary incarnations of CMOs - they likely share a common formation mechanism and follow a similar evolutionary path throughout their host galaxy's history. From the prospective of a theoretical framework of galaxy evolution, the commonalities between SBHs and stellar nuclei imply that both are equally relevant: as the characterization of SBHs has been instrumental in furthering our understanding of galaxy evolution (via AGN feedback), so promises to be the characterization of stellar nuclei (via superwinds and stellar feedback).

Several questions remain unanswered at this stage. Perhaps the most intriguing is whether the formation of SBHs and stellar nuclei are mutually exclusive. Nuclei are not present in the brightest ACSVCS galaxies, the prototypical objects in which SBHs are expected to reside, and for which a "mass deficit" has been attributed to the evolution of supermassive black hole binaries (Milosavjevic & Merritt 2001). At the other extreme of the luminosity range spanned by the ACSVCS galaxies, NGC205 and M33, for which there is no evidence of a SBH (Merritt et al. 2001; Gebhardt et al. 2001; Valluri et al. 2003), host stellar nuclei that follow the same scaling relations as the nuclei detected in the ACSVCS galaxies (Figure 2, right panel). It is possible that nuclei form in every galaxy, but are subsequently destroyed in the brighest system as a consequence of the evolution of SBH binaries. Alternatively, it is possible that collapse to a SBH takes place preferentially in the brightest galaxies, while in fainter systems, the formation of a stellar nucleus is the most common outcome. In the latter case, nuclei could represent "failed black holes", low-mass counterparts of the SBHs detected in the brightest galaxies.

The ACSVCS collaboration is currently persuing several programs aimed at studying the dynamics and stellar population of the ACSVCS galaxies and nuclei; a similar investigation is underway for a sample of 43 early-type galaxies in the Fornax Cluster (Jordán et al. 2006). These projects promise to shed further light on the core structure of early-type galaxies, their nuclei and their inter-relation to SBHs.

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Parametric Representation of Surface Brightness Profiles: a Critical Comparison of Nuker and Core-Sérsic/Sérsic Models.

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Abstract. The parameterization of the surface brightness profiles of early-type galaxies has been instrumental in characterizing scaling relations and in defining the properties of these systems. In the study of the core properties (i.e. within the innermost few hundred parsecs), the most commonly used parameterization is given by the so called "Nuker" model (Lauer et al. 1995), described by an inner and outer power law joined at a "break" radius. In recent years, however, shortcoming of the Nuker model have started to become apparent (e.g. Graham et al. 2003). Indeed, Ferrarese et al. (2006) and Côté et al. (2006) found it necessary to adopt a different parameterization in their analysis of the surface brightness profiles of a sample of 100 early-type galaxies observed with the HST Advanced Camera for Surveys as part of the ACS Virgo Cluster Survey (ACSVCS). In the ACSVCS analysis, core-Sérsic or Sérsic models are claimed to provide good descriptions of the surface brightness profiles from parsec to kiloparsec scales, and are adopted in defining the properties of compact stellar nuclei. In this contribution, we present a more detailed comparison of Nuker and core-Sérsic/Sérsic models. This comparison is motivated by a recent astro-ph posting (Lauer et al., astro-ph/0609762) where, based on HST/WFPC1 or WFPC2 images of 22 of the ACSVCS galaxies, it is argued that the Sérsic and core-Sérsic models presented by Ferrarese et al. (2006) provide inadequate fits to the surface brightness profiles and that such models lead to the identification of spurious nuclear features. We show that the Lauer et al. criticisms are based on faulty assumptions and misrepresent the ACSVCS analysis. We further show that the Nuker model parameterization used by Lauer et al. not only fails to reproduce the surface brightness profiles on kiloparsec scales, but is also not a particularly good representation of the profiles of the ACSVCS galaxies on parsec scales. Indeed, we argue that, for several of the galaxies in common with the ACSVCS sample, the Nuker model fits of Lauer et al. were likely biased by the lower signal-to-noise ratio and limited spatial extent of the WFPC1 or WFPC2 data used in their analysis. These shortcomings are probably responsible for the fact that Lauer et al. failed to recognize and characterize the properties of stellar nuclei in many early-type galaxies.

1. Introduction

The ACS Virgo Cluster Survey (ACSVCS) is an HST project designed to study the globular cluster systems and core properties of early-type galaxies. The survey employed the Wide Field Channel (WFC) of the Advanced Camera for Surveys (ACS) to image, in the g and z bands, a representative sample of early-type (E, S0, dE, dE,N, S0 and

S0,N) confirmed members of the Virgo Cluster. The galaxies span a factor 460 in B-band luminosity and, at their nearly identical distance of 16.5 Mpc, are observed at the same high spatial resolution of 6.7 pc. In terms of sample size, completeness in both luminosity and morphological type, spatial resolution, radial coverage and data homogeneity, the ACSVCS represents the best sample of early-type galaxies observed with HST to date.

The core and global properties of the ACSVCS galaxies have been characterized in Ferrarese et al. (2006a, hereafter F06) and Côté et al. (2006, hereafter C06). In these papers, it was argued that Sérsic (Sérsic 1968) or core-Sérsic models (Graham et al. 2003) provide a superior description of the surface brightness profiles of early-type galaxies than the more commonly adopted "Nuker" model (Lauer et al. 1995), as this latter model fails to capture the curvature of galaxy brightness profiles on kiloparsec scales. It was further shown in the ACSVCS that the actual profiles vary in a smooth and predictable fashion as one moves down the luminosity function for early-type galaxies, as shown in Figure 1. Relative to the inward extrapolation of the Sérsic model that best fits the surface brightness profiles between a few tens to several thousands of parsecs, bright galaxies show a luminosity "deficit": i.e., their profiles are shallower and have lower surface brightness than expected based on a Sérsic characterization. Fainter galaxies, on the contrary, show luminosity "excesses" within the inner few parsecs relative to the Sérsic laws that best fit the profiles on larger scales. Such excesses are identified with stellar nuclei, and are often associated with a change in the $(g-z)$ color, an inflection in the surface brightness profile, and a change in the isophotal parameters (ellipticity and position angle) relative to the main body of the galaxy. When the main body of the galaxy is considered (i.e., excluding a nuclear component), the distribution of inner profile slopes, $\gamma = -d\log I/d\log r$, is found to be unimodal with the low-γ peak (corresponding to the shallowest profiles) occupied by the *faintest* galaxies in the sample. In defining γ, I is the intrinsic (prior to PSF convolution) intensity of the core-Sérsic or Sérsic model that best fits the global profile, and the derivative is measured at $0''\!.1$.

The analysis and interpretation presented in F06 and C06 have been criticized in a recent astro-ph posting (Lauer, Gebhardt, Faber, Richstone, Tremaine, Kormendy, Aller, Bender, Dressler, Filippenko, Green & Ho 2006, astro-ph/0609762). The Lauer et al. posting is divided into two parts. In the first four sections, the authors address the issue of bimodality in the distribution of the logarithmic slope, $\gamma = -d\log I/d\log r$, of the inner surface brightness profiles of early type galaxies. To this end, Lauer et al. compile γ values from the literature. However, galaxies were included only if γ was derived, in the original investigation, by fitting a Nuker model to the surface brightness profile measured from HST images. A total of 219 galaxies satisfy this criterion; these galaxies were observed as part of five independent projects, each employing a different instrument and/or filter combination, and analyzed by five independent groups, often with different methodologies (Lauer et al. 1995, 2005; Rest et al. 2001; Laine et al. 2002; Quillen et al. 2000; Ravindranath et al. 2001). Galaxies which were observed with HST, but for which Nuker model fits are not available in the literature, were simply excluded in the Lauer et al. analysis.

Based on their compilation, Lauer et al. find the distribution of γ to be bimodal, with the low γ peak (corresponding to shallow surface brightness profiles) occupied exclusively by the *brightest* galaxies in the sample, in contrast to the findings of F06. In the second part of their astro-ph posting, Lauer et al. investigate the cause of such discrepancy and claim that the results of F06 are invalidated by an inadequate analysis of the data. Specifically, Lauer et al. claim that: (1) the Sérsic and core-Sérsic models used by F06 to fit the profiles do a poor job at describing the data at small radii, thus leading to an

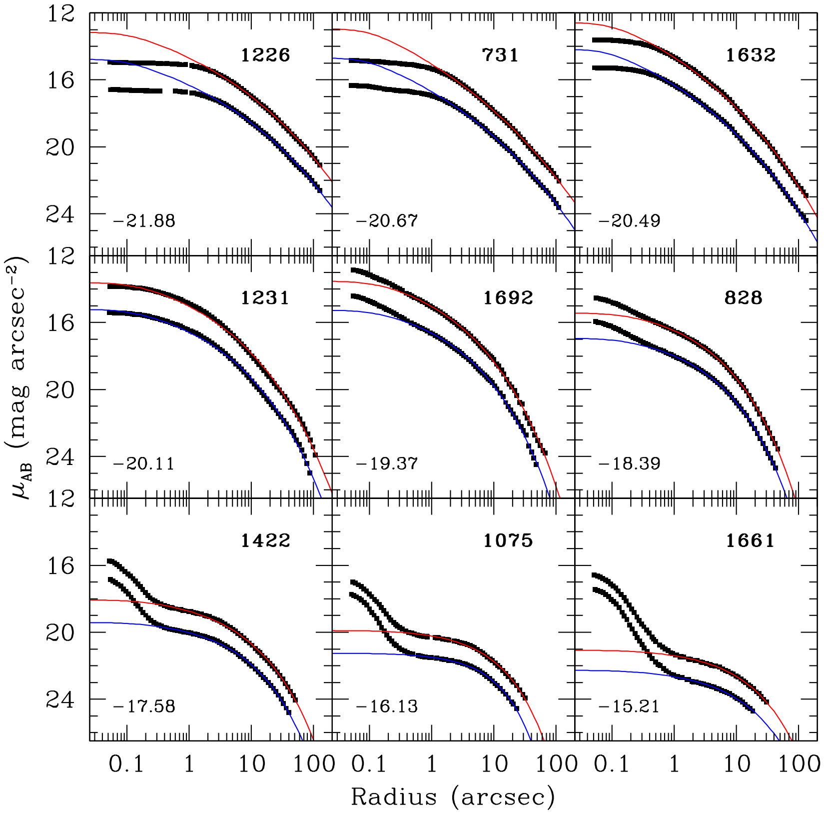

Figure 1. Representative surface brightness profiles for nine early-type galaxies from the ACSVCS. The galaxies span a factor of ~ 460 in $B-$band luminosity – the $B-$band magnitude is listed in the bottom left of each panel. For each galaxy, we show the azimuthally-averaged brightness profile in the g and z bands (lower and upper profiles, respectively). The solid curves show Sérsic models fitted to the profiles beyond $\sim 0''.2$-$2''$. Note the gradual progression from a central light "deficit" to "excess", with a transition at $M_B \sim -20$ (see Ferrarese et al. 2006a and Côté et al. 2006 for details).

incorrect measurement of γ; and (2) the inherent inadequacy of the Sérsic models fitted to most galaxies forces F06 to introduce "*ad hoc* stellar nuclei", exacerbating a bias in γ.

The issue of bimodality (or lack thereof) in the distribution of inner profile slopes will be addressed in several forthcoming papers. The present contribution focuses on the second part of the Lauer et al. posting, and is intended to correct factual errors, misleading and incorrect statements, and logical inconsistencies made in Lauer et al.. In order to better understand what follows, it is useful to clarify some of the differences in the approach followed by Lauer et al. and F06:

- *Sample selection.* The samples used by Lauer et al. and the ACSVCS sample differ dramatically in their selection function. No objective selection criteria describe the former, the only commonality between the Lauer et al. galaxies being the fact that they were observed with HST and that Nuker model parameters were available in the literature. The sample used by F06, on the other hand, is a representative (nearly magnitude limited) sample of 100 early-type galaxies located at a common distance of ≈ 16.5 Mpc, and observed with an identical observational set-up (HST/ACS F475W and F850LP). There are 27 galaxies in common between Lauer et al. and F06; however, in the compilation of Lauer et al. the surface brightness profiles for these galaxies were measured from WFPC1/F555W images (9 galaxies), WFPC1/F785LP images (1 galaxy), WFPC2/F555W images (12 galaxies), WFPC2/F702W images (3 galaxies) NICMOS2/F160W images (1 galaxy) and NIC3/F160W images (1 galaxy). Issues related to the sample selection will be discussed in more detail in §2.

- *Choice of parametrization of the surface brightness profile.* For the galaxies included in Lauer et al., the profile was parametrized using a Nuker model. F06 adopt a core-Sérsic model (Graham et al. 2003; Trujillo et al. 2004) for galaxies brighter than $M_B \approx -20.3$ ($\sim 10\%$ of the sample), and a Sérsic model (Sérsic 1968) for fainter galaxies.† When a stellar nucleus is present, as is the case for most galaxies fainter than $M_B \approx -20.3$, it is described as a PSF-convolved King model, added to (and fitted at the same time as) the Sérsic model representing the galaxy profile beyond the nuclear component (i.e., for radii larger than a few $0.''1$). There are several reasons why Nuker models were not adopted for the analysis of the ACSVCS data. Nuker model parameters have been shown to depend on the radial extent of the data that is being fitted (Graham et al. 2003), to the point that their physical interpretation is problematic (this is a particular concern in the case of a sample of galaxies at different distances, as in the compilation of Lauer et al.). Furthermore, Nuker models asymptote to power-laws on large scales, while real galaxies almost universally exhibit continuous curvature on a log-log plot. This critical point is lost for the galaxies in the Lauer et al. compilation, due to the small radial extent of the data. However, the ACS data analyzed by F06 (and supplemented, for the brightest galaxies, with ground based data) encompass the curvature of the profiles at kiloparsec scales, rendering the Nuker model a completely inadequate choice of parametrization.
- *Treatment of the data.* For the galaxies in the Lauer et al. compilation, Nuker models are fitted to deconvolved data (except for the galaxies drawn from the Ravindranath et al. 2001 sample, for which convolved models were fitted to data in the observational plane). F06, on the other hand, fit PSF-convolved models to ACS data in the observational plane. While there are pros and cons to both methodologies, the Lauer et al. claim that "recognizing subtle systematic failures of the models is considerably more difficult in the observed domain" is entirely unsubstantiated. Deconvolution of data is an inherently ill-posed process, and the instability is greater the lower the signal-to-noise (S/N) ratio of the data, or the larger the PSF compared to intrinsic physical scales (e.g. Craig and Brown 1986). Results can depend critically on the choice of regularization scheme, an issue not discussed by Lauer et al., and this is most true near the center where the intrinsic profiles vary rapidly on the scale of the PSF. Convolution of a noiseless model, on the other hand, is a well-posed mathematical operation with a unique solution. Deconvolution is appropriate when attempting to characterize the data in a non-parametric way (e.g. Merritt & Tremblay 1994), but when the goal is to compare data with empirical models, it is always more appropriate to project the model into the observed plane than vice versa (e.g. King 1975).
- *Identification of stellar nuclei.* Lauer et al. identify nuclei as upturns relative to the best fitting Nuker model. F06 identify nuclei as upturns relative to the best fitting Sérsic model, and from a variety of other indicators, including visual inspection of the images, and sudden changes in the isophotal parameters and color profiles within the inner few $0.''1$. As will be shown in §4, identification of stellar nuclei is less ambiguous in the case of

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† In what follows, for convenience we will refer to these models as the "ACSVCS models".

Table 1. Comparison of the Lauer et al. and ACSVCS Samples

Instrument	No. of Galaxies	Range in Distance (Mpc)	Range in M_B (mag)	Mean Spatial Resolution (pc)	Source
Lauer et al. 2006					
WFPC2/F555W	63	10.2 to 92.2	−18.0 to −23.6	8.2	Lauer et al. 2005
WFPC2/F702W	46	13.4 to 50.1	−18.4 to −22.3	10.6	Rest et al. 2001
WFPC2/F814W	60	38.2 to 209	−21.8 to −25.3	49.7	Laine et al. 2002
WFPC1/F555W	26	13.3 to 321	−15.6 to −23.8	27.1	Lauer et al. 1995 Faber et al. 1997
NIC2/F160W	9	12.9 to 73.3	−18.6 to −23.3	22.9	Quillen et al. 2000
NIC2/F160W or NIC3/F160W	15	3.5 to 56.0	−17.2 to −22.9	15.2	Ravindranath et al. 2001
Ferrarese et al. (2006a) (ACSVCS)					
ACS/F475W and F850LP	100	16.5	−15.1 to −21.8	6.7	Côté et al. 2004

the ACSVCS data, rather than the WFPC1 or WFPC2 data used by Lauer et al. This is due to the higher S/N, larger radial extent, and (compared to the WFPC1 data) higher resolution afforded by the ACS, as well as to the availability of color images.

- *Definition of* γ. Lauer et al. measure γ at either the resolution limit of the instrument (judged to be between $0''.02$ and $0''.1$) or the innermost radius that they deem to be unaffected by a nuclear component, whichever is largest. Although Lauer et al. do not tabulate the radii at which γ is measured for each galaxy, their figures indicate that these radii vary by at least a factor 10, from $0''.02$ to over $0''.2$. By contrast, F06 measure γ at a consistent angular scale of $0''.1$. Because of the common distance of the ACSVCS galaxies, this angular scale corresponds to the same physical scale, ~ 8 pc, for all galaxies. If a nucleus is present, the slope is measured from the inward extrapolation of the Sérsic model best fitting the profile in the region unaffected by the nucleus (generally a few $0''.1$ to $\lesssim 100''$).

2. Sample Comparison

A comparison of the Lauer et al. and the ACSVCS samples is given in Table 1. As mentioned above, the Lauer et al. analysis is based on a compilation of published Nuker model parameters fitted to surface brightness profiles of early-type galaxies by a variety of groups (Lauer et al. 1995,2005; Rest et al. 2001; Laine et al. 2002; Quillen et al. 2000; Ravinandranath et al. 2001). The only commonality between their galaxies is that all were observed with HST (albeit with different instruments and filters) and all were fitted using a Nuker model. Almost all galaxies have early-type morphologies, although a handful of spiral bulges are included. HST data for which a Nuker model fit was not available in the literature were excluded from the outset.

The Lauer et al. sample therefore consists of a not-easily characterizable mix of parameters measured by five independent groups, most, but not all, from deconvolved profiles of galaxies spanning a factor 100 in distance (Figure 2), observed with four different instruments and four different filters (from the V to H bands), spanning a factor five in angular resolution (from $0''.02$ to $0''.1$ according to the authors), and a factor 65 in spatial resolution (from 2.4 pc to 156 pc, Figure 3).

Comparing the sample used by Lauer et al. to that from the ACSVCS (Table 1), it is immediately evident that the ACSVCS sample: (1) is larger than any single sample previ-

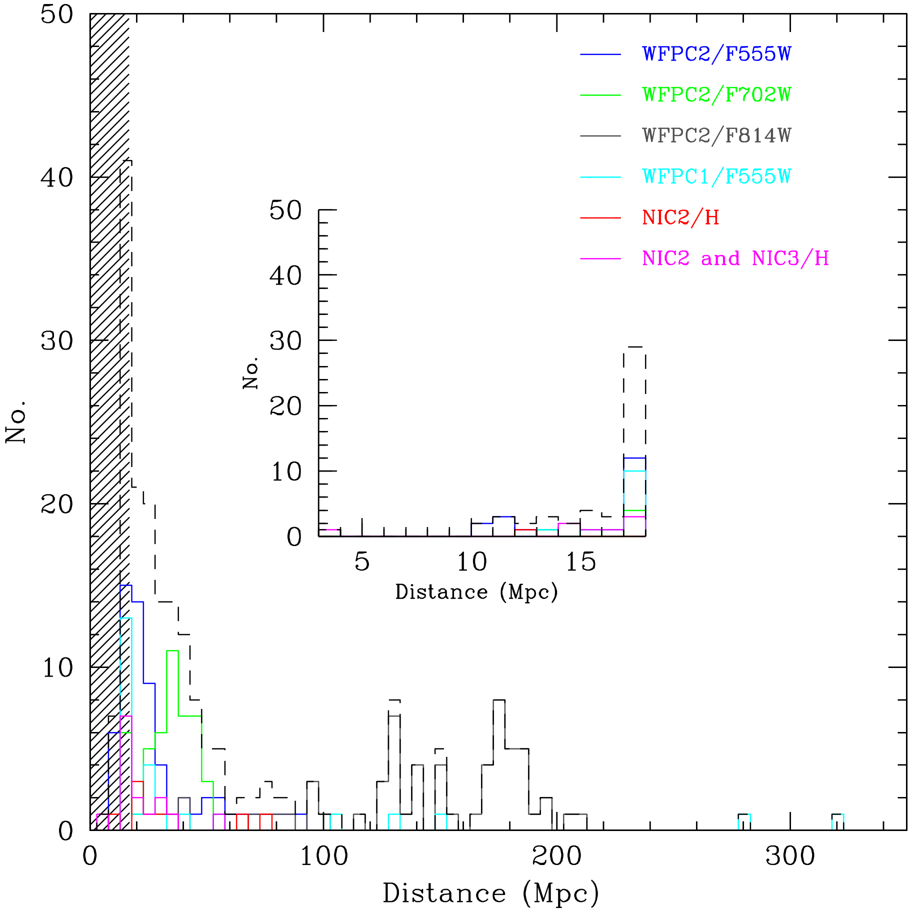

Figure 2. The distribution of distances for the galaxies included in the Lauer et al. posting. The dashed region identifies galaxies at the same distance as, or closer than, the ACSVCS galaxies (accounting for the fact that Lauer et al. place the mean distance of Virgo at 17.9 Mpc) - the same region is expanded in the inset. The dashed black curve shows the cumulative distribution.

ously observed with an indentical instrument/filter configuration; (2) has superior mean spatial resolution; (3) is by far the most homogeneous in terms of environment/distance (all galaxies being located in a single cluster and at approximatively at the same distance); (4) is the only sample containing a large number of low- and intermediate-luminosity galaxies (≈ 60 galaxies with $M_B \gtrsim -18$); and (5) is the only sample for which color information is available for all galaxies.

Remarkably, Lauer et al. claim that the ACSVCS sample offers no resolution advantage compared to existing HST samples and, in several instances, assert that the data used in their analysis has better angular and comparable spatial resolution as the ACS data used by F06: e.g., (1) “While the VCS ACS/WFC images have lower angular resolution than the WFPC2/PC F555W images used for much of [our] sample....”†; and (2) “A

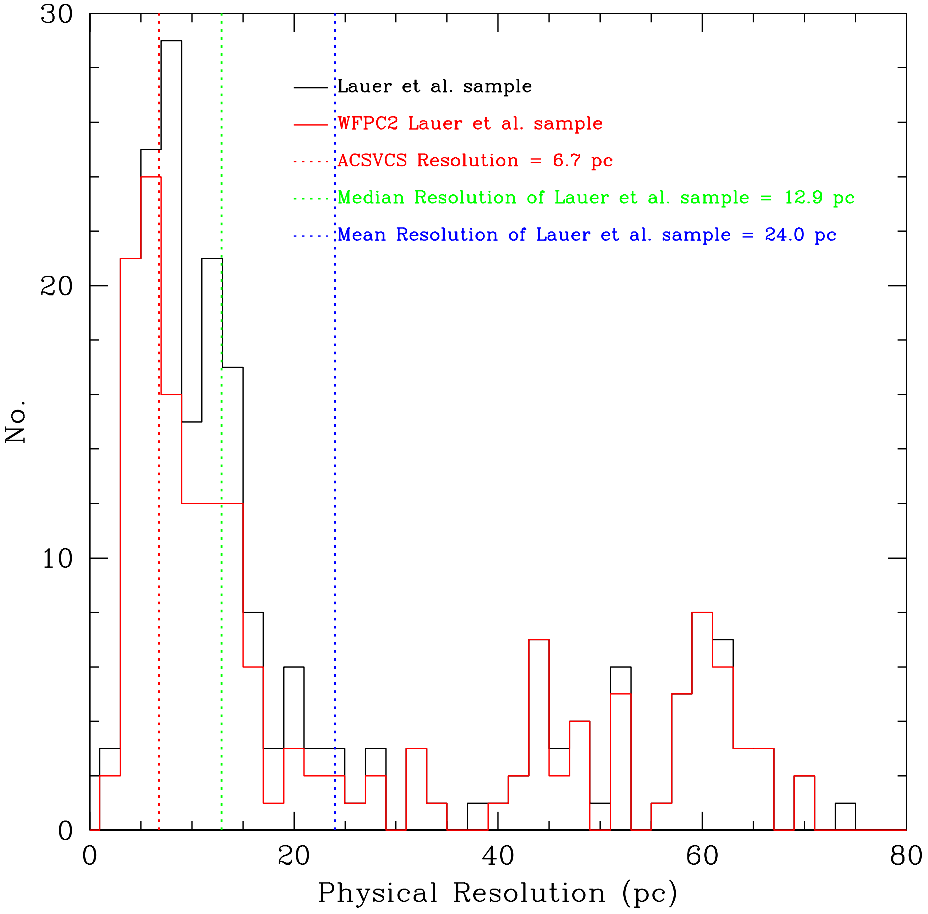

Figure 3. The distribution of physical resolution (calculated based on the FWHM of the PSF) for the 219 galaxies that comprise the Lauer et al. sample. The ACSVCS resolution, 6.7 pc, is significantly higher than the mean or median resolution of the Lauer et al. sample. If only data observed with WFPC2 are considered (for a total of 169 galaxies), the mean resolution is 23.6 pc and the median resolution is 11.9 pc, in both cases lower than that of the ACSVCS sample, as stated in F06. Two additional Lauer et al. galaxies (not shown) have resolutions of 135 pc (A1020) and 155 pc (A1831)

comparison of WFPC2/PC1 and ACS/WFC PSFs shows that WFPC2 actually provides significantly better angular resolution.... The present sample has 49 galaxies at Virgo distance or closer, and a substantial number that are no more than 50% more distant; both the present and [ACS]VCS samples are probing the same physical scales in the galaxies."

These statements are misleading. While it is true that 49 galaxies in the Lauer et

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† In fact, slightly more than a quarter of the galaxies in the Lauer et al. compilation was observed with HST/WFPC2/F555W.

al. sample[‡] are at the distance of Virgo (28 galaxies) or closer (21 galaxies), only 27 of these were observed with WFPC2, and of these six were observed with F702W, which provides a lower resolution than F555W. Thirteen of the 49 galaxies were observed with WFPC1, and 9 with NICMOS, instruments that both have significantly lower resolution than ACS/WFC. Figure 3 shows the distribution in physical resolution (FWHM) for the complete sample used by Lauer et al. (in black) and the subset of WFPC2 data (in red). The resolution of the ACSVCS data is 6.7 pc (for all galaxies). The mean resolution of the Lauer et al. complete sample is 24.0 pc, and the median resolution is 12.9 pc; the same numbers for the subset of the Lauer et al. sample that used WFPC2 data are 23.6 pc and 11.9 pc. The ACSVCS spatial resolution is therefore between 2 and 3.5 times better, as already stated in F06. There is no question that on the whole it is the ACSVCS data, not the Lauer et al. sample, that provides a sharper (and more homogeneous) view of the innermost regions of early-type galaxies.

3. Nuker vs. Sérsic Models

3.1. *Data Presentation in Lauer et al.*

In their Figures 11 and 12, Lauer et al. show surface brightness profiles from deconvolved WFPC2/F555W or WFPC1/F555W data (with the exception of NGC4464 = VCC1178, for which ACS data are shown). The blue curves in their figures show the Nuker model that was designed to best fit the WFPC1/WFPC2 surface brightness profile given as a function of semi-major axis length. The red line shows the intrinsic (prior to PSF convolution) ACSVCS model, with parameters given in F06. Note that the ACSVCS models were fitted (after PSF convolution) to ACS F475W data in the observational plane and cast as a function of mean geometric radius. To "account" for the filter and x-axis mismatch between the ACSVCS models and the WFPC1/WFPC2 data against which Lauer et al. plot those models, Lauer et al. scale the data vertically by a constant factor and multiply the semi-major axis length by a factor involving ellipticity (presumably also derived from the WFPC1/WFPC2 F555W data, although this is not stated explicitly) to convert it to mean geometric radius. No measures were taken to match the ACSVCS models to the PSF of the deconvolved WFPC1/WFPC2 images.

Lauer et al. argue that such a comparison is legitimate on the basis of the fact that profiles from deconvolved WFPC1, WFPC2 and ACS data agree. But this point is irrelevant: even neglecting differences in the filter and radial definition between the ACSVCS models and the data against which they are plotted, the PSF of a deconvolved image is not a δ-function, and does not match the PSF of the ACSVCS model prior to convolution. A correct analysis must compare the performance of each model against the data used to fit those models.

3.2. *A Fair Comparison*

Figures 4a to 9a correspond to Figures 11, 12 and 13 of Lauer et al. In our Figures, however, each model is shown against the data used to fit that model: the Nuker models used by Lauer et al. are plotted in blue against the deconvolved WFPC1 or WFPC2 data used to perform the fit (shown as a function of semi-major axis length), while the red curves represent the PSF-convolved ACSVCS core-Sérsic or Sérsic models overplotted on the ACS/WFC F475W data in the observational plane (shown as a function of mean

For simplicity, we will henceforth refer to the WFPC1/WFPC2/NICMOS data that were used to fit the Nuker model parameters compiled by Lauer et al. (Table 1) as the "Lauer et al. data" although much of these data were taken by teams unrelated to Lauer and collaborators.

geometric radius). The first crucial point to note is the much larger spatial coverage of the ACSVCS compared to the WFPC2 or WFPC1 data: thanks to the larger FOV of the ACS, the curvature of the profile on kiloparsec scales can now be appreciated. It is also immediately apparent that such curvature cannot be reproduced by the power-law behavior of the Nuker model on large scales. Unlike the Nuker models, the ACSVCS models do a remarkably good job at fitting the entire profile of the galaxies, in many cases over more than three decades in radius. The systematic failure of the Nuker model on large scales was not evident in the figures shows in the Lauer et al. posting, where profiles are not plotted on scales larger than 1-10″.

We now turn our attention to the quality of the model fits at small radii ($r \lesssim 1''$): i.e., the region of interest when measuring the inner profile slope, γ. In Figures 4b to 9b, we show residuals (model–data) in the innermost 1″, from which the quality of the Nuker (in blue) and ACSVCS core-Sérsic or Sérsic (in red) fits can be judged. In all cases, the data and residuals are plotted only up to the radius which was deemed reliable based on the images ($0\farcs05$ in the case of the ACSVCS data).

Let us compare the fits on a galaxy by galaxy basis. Figures 4a and 4b (corresponding to the first four panels of Figure 11 of Lauer et al.) show that, in the case of NGC4365 (VCC731), the ACSVCS core-Sérsic model used by F06 provides a better representation of the data at small radii than the Nuker model. For NGC4382 (VCC798) and NGC4406 (VCC881), the quality of the Nuker and core-Sérsic model fits is comparable on small scales; on larger scales, the Nuker model *always* fares worse than the Sérsic model. NGC4458 (VCC1146) is classified by F06 as a nucleated galaxy, and will be discussed in detail in §4.

Figures 5a to 5b (corresponding to the second page of Figure 11 of Lauer et al.) show that the ACSVCS core-Sérsic model is a better representation of the data for NGC4472 (VCC1226), while the Nuker model works better than the ACSVCS core-Sérsic model for NGC4473 (VCC1231). At first glance, the Nuker model is also a significantly better representation of the data for NGC4478 (VCC1279), however, this galaxy deserves a closer inspection. As discussed by F06, NGC4478 hosts an edge-on, 1″ blue stellar disk at its center. The presence of the disk is clear from the images themselves as well as from the isophotal analysis, but it really jumps out from the F475W-F850LP color image (see Figure 13 and notes in the Appendix of F06). We will not speculate as to the reasons why the disk was missed in the WFPC2 images analyzed by Lauer et al., but, in hindsight, the irregularity in the deconvolved WFPC2 profile (lower left panel of the second page of Figure 11 of Lauer et al.) should have been a giveaway (Lauer et al. note that NGC4478 has a "small nucleus"). The ACSVCS Sérsic model for this galaxy was not fitted within the inner 1″ to avoid contamination by the disk, thereby explaining the large residuals in this region. It can, of course, be debated whether extrapolating the ACSVCS model (which fits the profile between 1″ and 50″) inward gives a faithful estimate of the intrinsic profile slope at $0\farcs1$ (the radius at which γ was measured by F06). What is certain is that the slope derived from the Nuker model favored by Lauer et al. *does not.* The Nuker model was fitted between $0\farcs1$ and $\sim 10''$: by being forced to follow the disk's profile for the first decade of this radial range, it is not fitting the main body of the galaxy, but rather a component that is clearly distinct in both morphology and stellar population. The slope estimated by Lauer et al. is therefore certainly not a good estimate of the γ of the underlying galaxy. We note that, even in the case of NGC4473 (for which, as noted above, the Nuker model provides a better description of the data than the ACSVCS Sérsic model), F06 pointed out the presence of a small, blue boxy feature in the $(g-z)$ color images, although in this case the evidence of a separate component at the center is not as strong as for NGC4478.

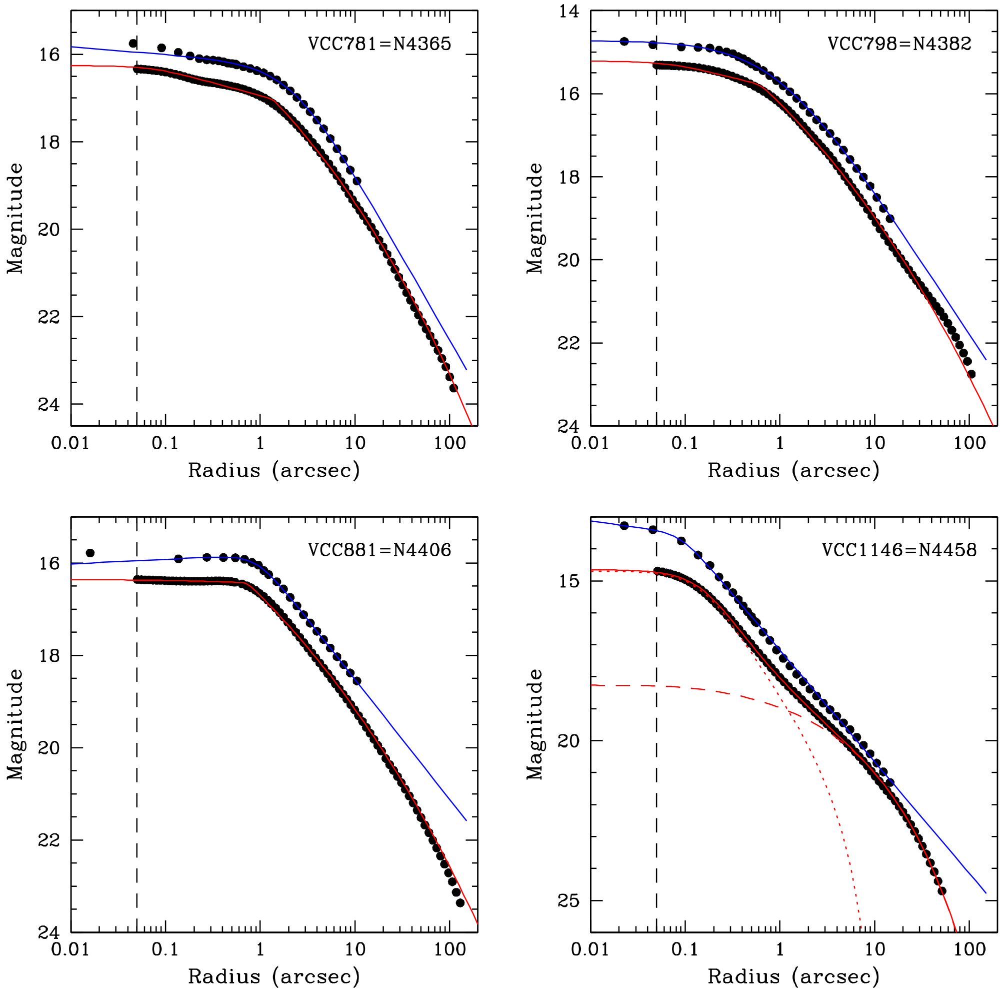

Figure 4a. The equivalent of the first page of Figure 11 of Lauer et al. The blue line is the best-fit Nuker model, superimposed on the (deconvolved) Nuker surface brightness profile (as shown in Figure 11 of Lauer et al.). The red curve shows the best-fit, PSF-convolved ACSVCS model superimposed on the ACSVCS data. If a nucleus was fitted to the data (as in the case of NGC4458 = VCC1146), the corresponding PSF-convolved King profile is shown as a dotted line, while the Sérsic model for the galaxy is shown by the dashed line. The radius represents the major axis radius for the Nuker data, and the geometric mean radius for the ACSVCS data. Surface brightnesses refer to the V-band for the Nuker data, and the g-band for the ACSVCS data. The vertical line is drawn at $0''.05$ (the size of an ACS/WFC pixel. The WFPC2/PC and WFPC1/PC pixel scales are $0''.045$ and $0''.043$ respectively).

Finally, the galaxy in the bottom right panel of Figure 5a is NGC4486 (VCC1316 = M87). The data used by Lauer et al. to fit this galaxy are WFPC1/F785LP (tranformed to Johnson I) data from which the contribution of the bright AGN and optical synchrotron jet has been subtracted prior to deconvolution (from Lauer et al. 1992). In the aberrated WFPC1 images, the AGN dominates the inner $1''$ (see Figure 3 of Lauer et al. 1992). Using such heavily processed data to fit a model down to 0.1 arcsec is risky to say the

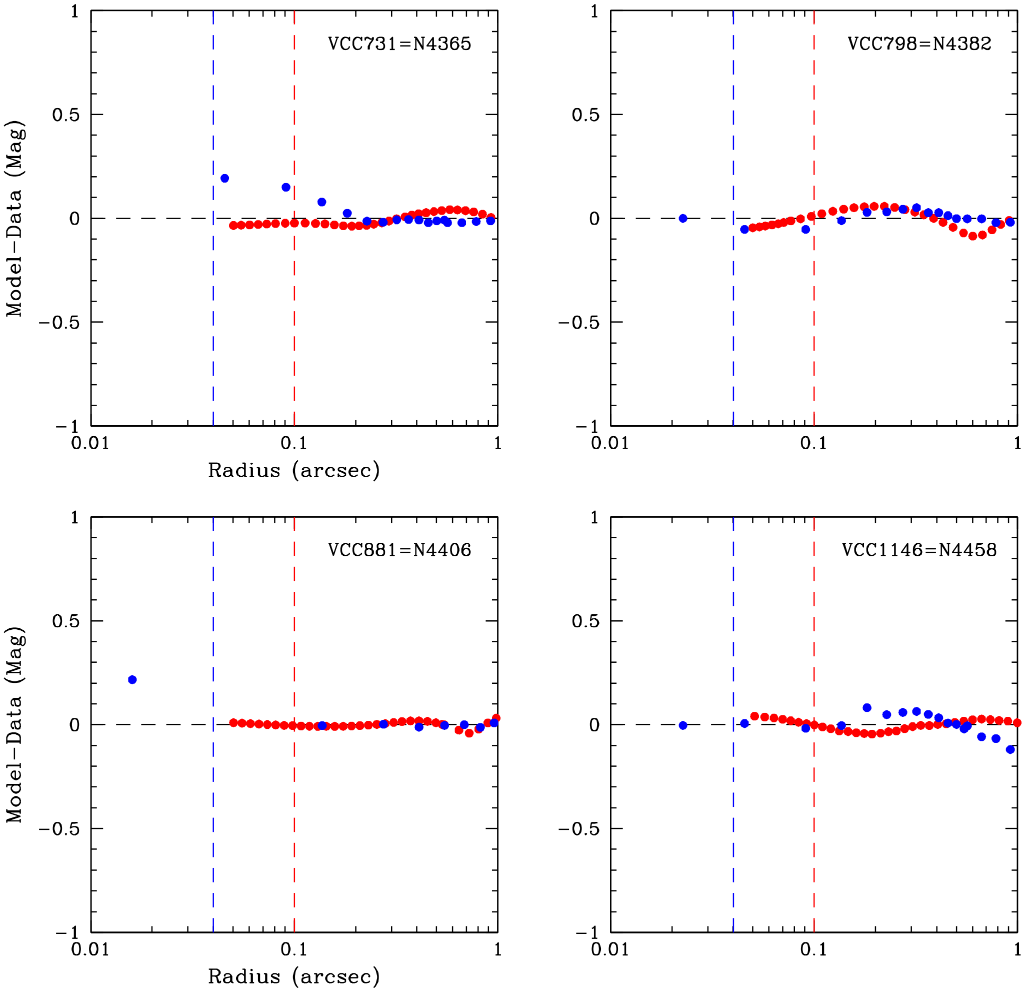

Figure 4b. Surface brightness residuals (model – data) for the Nuker model fits (blue) and the ACSVCS fits (red) for the galaxies shown in Figure 4a. The red vertical line is drawn at 0″.1 (i.e., the radius at which the ACSVCS slope was measured), while the vertical blue line shows the resolution limit claimed by Lauer et al. for the deconvolved WFPC1/WFPC2 data, where the slope was calculated.

least; using such data to argue for the superiority of the Nuker fit over the core-Sérsic fit from the ACSVCS is insupportable. Our Figure 5a demonstrates that the ACSVCS model provides a good representation of the surface brightness profile between 0″.3 and over 100″. Inside 0″.3, the profile is dominated by emission from the central AGN, and this region was excluded in the ACSVCS fit for precisely this reason.

Moving on to Figures 6a, 6b, 7a and 7b, the ACSVCS and Nuker fits are of comparable quality for NGC4486B (VCC1297)†, NG4649 (VCC1978), NGC4621 (VCC1903) and NGC4434 (VCC1025), while the Nuker model fits are somewhat better (on small scales) for NGC4552 (although the Nuker model fit is not a good match to the profile

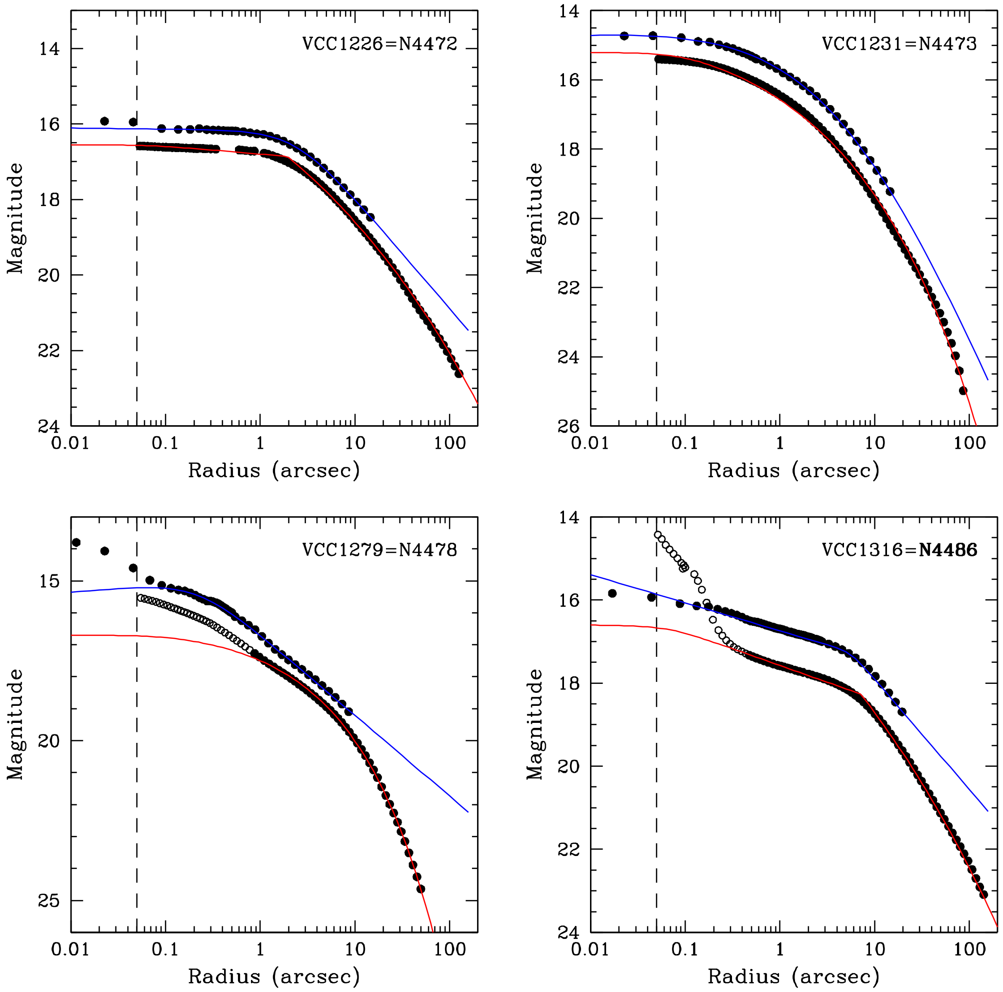

Figure 5a. The equivalent of the second page of Figure 11 of Lauer et al.. The data used for the Nuker fit of NGC 4486 (M87, upper line) is WFPC1/F785LP data from which the contribution of the bright AGN was removed before deconvolution (Lauer et al. 1992 – the data needed to be shifted downwards by 1.35 mag to match the model parameters tabulated in the Lauer et al. posting) – in the original images, the AGN component dominates the galaxy profile within the inner 1″. The core-Sérsic model (red line) was not fitted to the ACS data (lower curve) within 0″.45 (open symbols) to avoid contamination of the AGN (the synchtron jet was masked while fitting the isophotes). In the case of NGC 4478, the Sérsic model (red line) was not fitted to the ACS data within 0″.8 (open symbols) to avoid contamination from the blue stellar disk detected in the nuclear region of this galaxy (see discussion in the text and F06).

at 0″.4, where the Nuker model slope is measured), NGC4464 (VCC1178) and NGC4660 (VCC2000).

In summary, there is no evidence from the fits shown in these figures that, on small radial scales ($r \lesssim 1''$), the Nuker models perform consistently better than the ACSVCS

† Note that in Figure 11 of Lauer et al., the galaxy at the top left is labeled as NGC4486 when in fact it is NGC4486B.

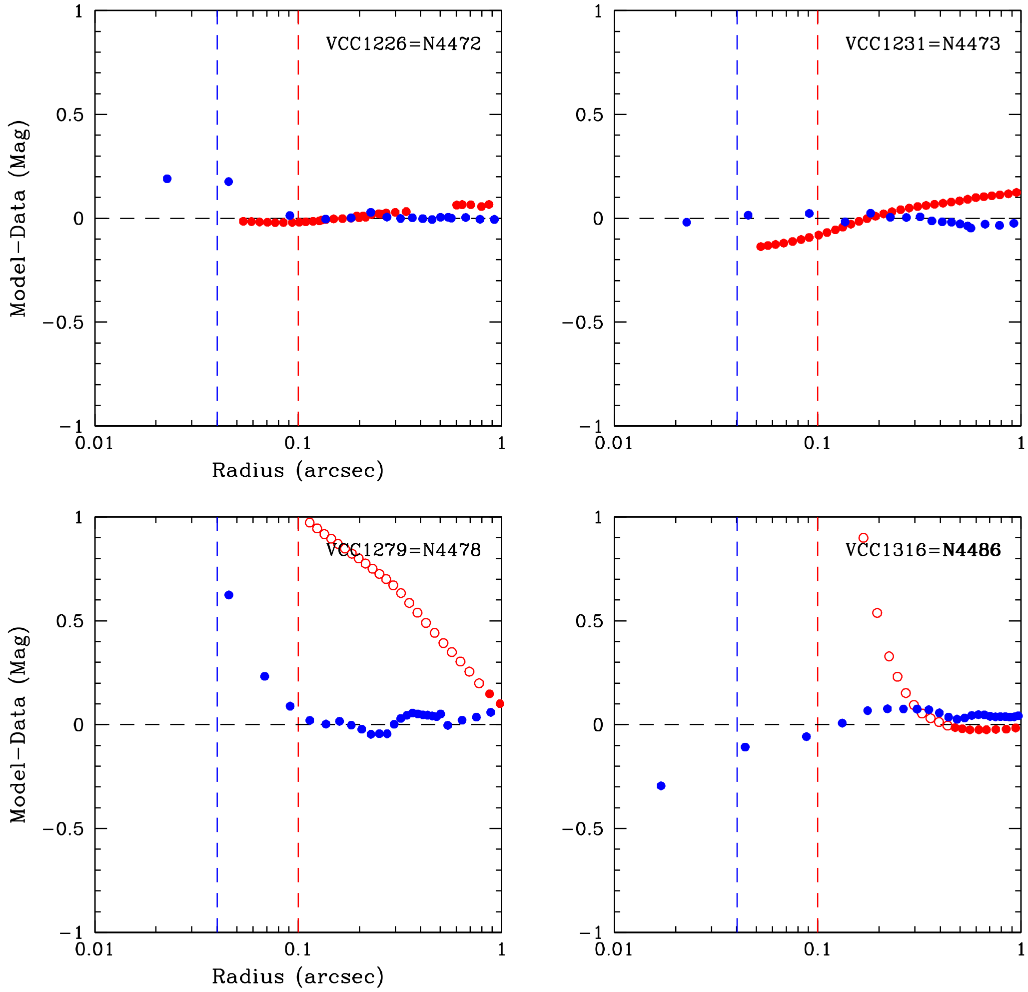

Figure 5b. Surface brightness residuals (model – data) for the Nuker model fits (blue) and the ACSVCS fits (red) for the galaxies shown in Figure 5a. The ACSVCS models were not fitted to the data within the radial range where residuals are shown as open circles.

models. The Lauer et al. claim to the contrary is driven by a misleading comparison of the ACSVCS models to data taken with a different filter, instrument, and described by a different PSF. In at least one case (NGC4478), Lauer et al. failed to recognize and properly account for the existence of a morphologically separate nuclear component; in this case, the Nuker model fit adopted by Lauer et al. is certainly in error. On larger scales ($r \gtrsim 10''$), the ACSVCS models are *always* a better description of the data than the Nuker models.

4. Identification of Stellar Nuclei

The second criticism advanced by Lauer et al. concerns the definition of stellar nuclei. F06 and C06 identified nuclei from a variety of diagnostics, including sudden upturns in

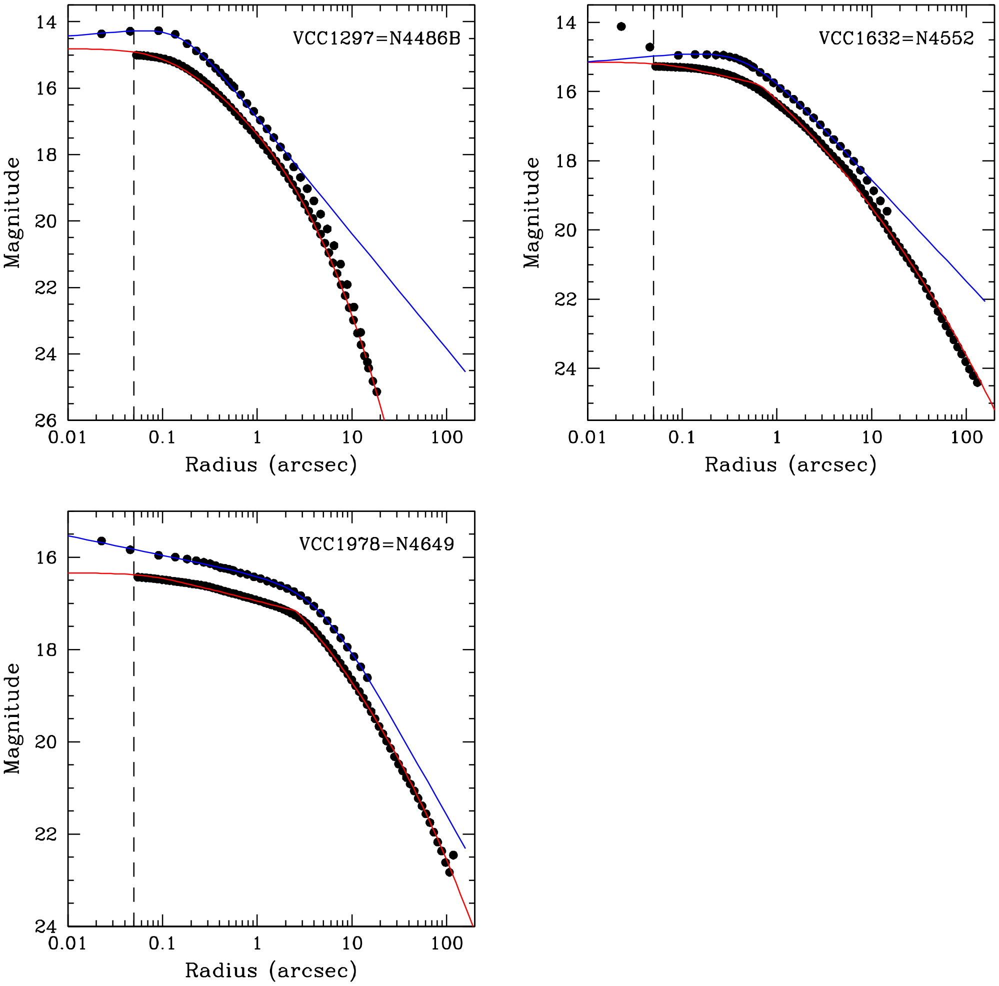

Figure 6a. The equivalent of the third page of Figure 11 of Lauer et al.

the surface brightness profiles and color changes in the $(g-z)$ color images. In clearly nucleated galaxies, nuclei were fitted by King models added to the Sérsic model representing the main body of the galaxy. Lauer et al. argue that the nuclei identified by F06 and C06, in most of the ACSVCS galaxies, are spuriously introduced to fill in the gap left over by the fact that the fitted Sérsic models underestimate the profile in the inner region: i.e., they state "... excursions of the data above the Sérsic model are declared to be separate nuclear components, rather than as a simple failure of the model. The VCS nuclei effectively absorb the central flux left over from the Sérsic fits". Referring to the galaxies shown in their Figure 13 (classified as nucleated by F06 and C06), Lauer et al. comment that "there are no strong upward breaks in any of the galaxies discussed in this section [shown in Figure 13] that would make detection of a nucleus unambiguous". Yet this statement is in plain contradiction with a statement made only a few paragraphs earlier: "Lauer et al. (1995) identified nuclei in all of these galaxies as well [i.e. the galax-

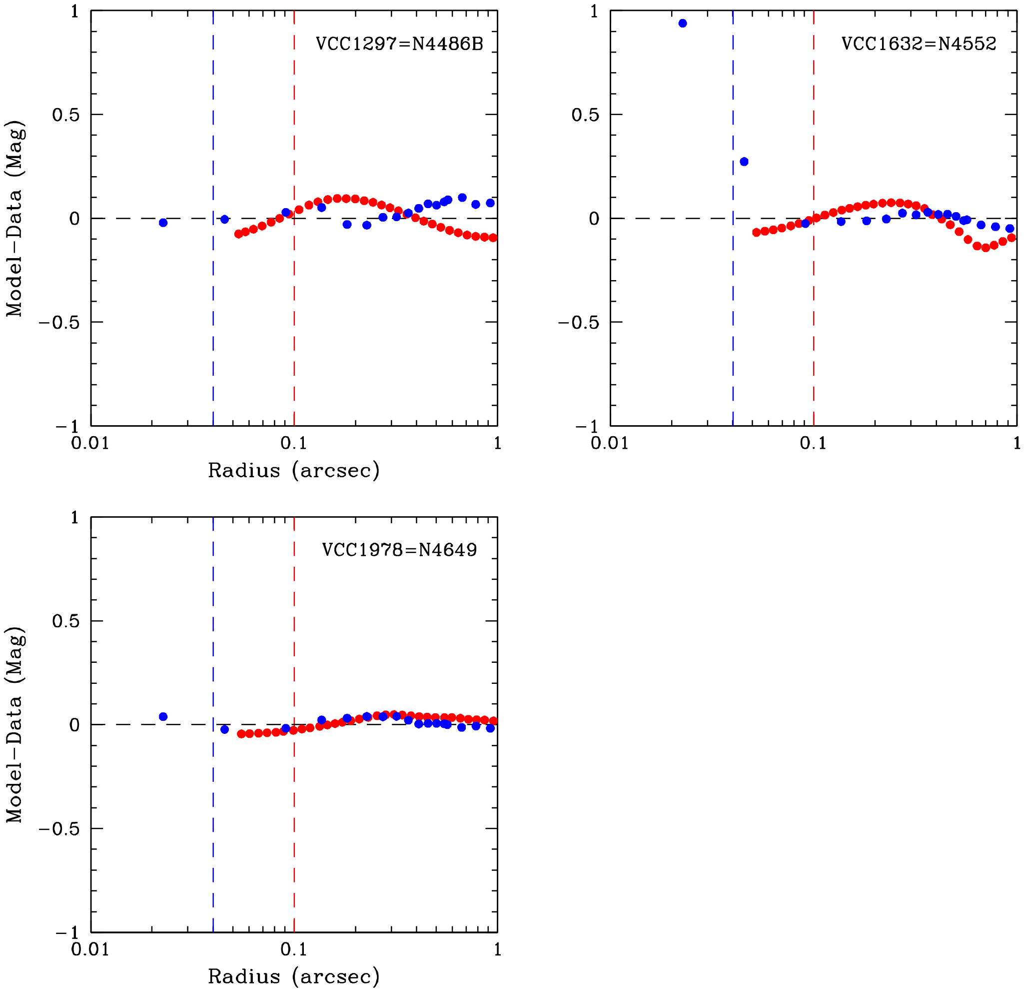

Figure 6b. Surface brightness residuals (model – data) for the Nuker model fits (blue) and the ACSVCS fits (red) for the galaxies shown in Figure 6a.

ies shown in Figure 13], albeit ones of markedly lower luminosity and extent than those presented by Côté et al. (2006).”

Therefore, despite their claim to the contrary, it is not the *existence* of a nucleus that is called into question, but the *definition*. F06 and C06 define nuclei as excesses with respect to Sérsic models, while Lauer et al. “identify nuclei by looking for upturns above a power-law cusp as $r \to 0$”. Thus, both Lauer et al. and F06 and C06 define nuclei as upturns relative to the inward extrapolation of the model that best fits the outer parts of the profile. In view of this, it is difficult to understand the Lauer et al. dismissal of the ACSVCS approach (“takes it as an a priori assumption rather than as a hypothesis that the envelopes of galaxies, which is where the Sérsic models are fitted, can be used to deduce the structure of the central profile at small radii.”) given that Lauer et al. choose a Nuker model to make precisely this same decision. The Lauer et al. criticism is even more puzzling when one realizes that the “outer envelope” used by F06 and C06

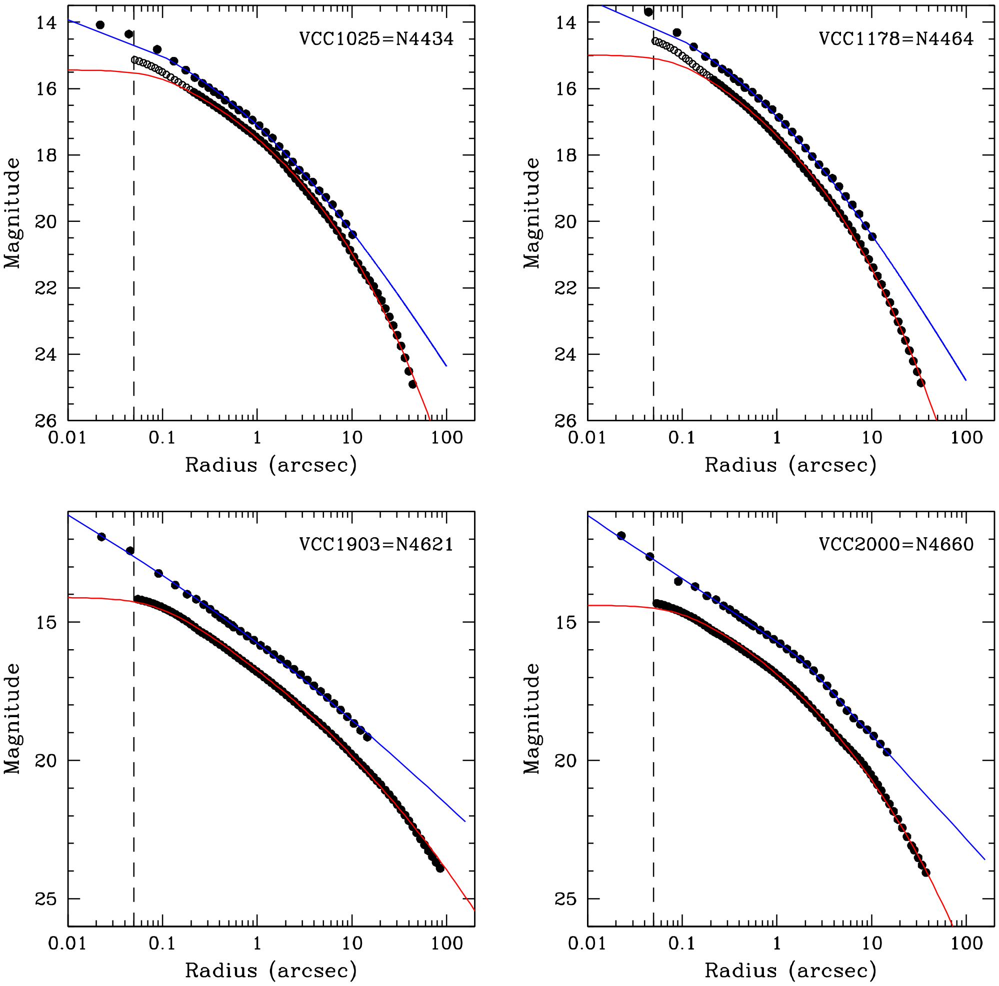

Figure 7a. The equivalent of Figure 12 of Lauer et al.. The ACSVCS models (shown in red) were not fitted within the inner 0″.2 of NGC 4434 and NGC 4464 (shown as open symbols). A compact stellar nucleus was identified within this region, although the small contrast between the nucleus and the underlying galaxy prevented from deriving an accurate King model fit. Note that the Nuker model favored by Lauer et al. (blue line) does not provide a good fit to the profile within this region. In the case of NGC 4621 and NGC 4660, we show the F850LP, rather than F475W ACS profiles – the latter were saturated within the inner 0″.25, a region that was therefore omitted in fitting the F475W profiles. The F850LP profiles and models have been shifted downwards by 2 mag for clarity.

to fit Sérsic models is, in fact, nearly the full extent of the galaxy (i.e., a region between a few 0″.1 to 20″−100″). The Lauer et al. Nuker fits, on the other hand, are typically shown between 0″.1 and a few arcsec (see their Figure 13). In short, Lauer et al. appear to argue that having surface brightness data with the maximum possible radial coverage, and using it to find the models that best fit the global profile, is a detriment rather than an advantage.

At this point, the only relevant question is which of a Sérsic or a Nuker model does a

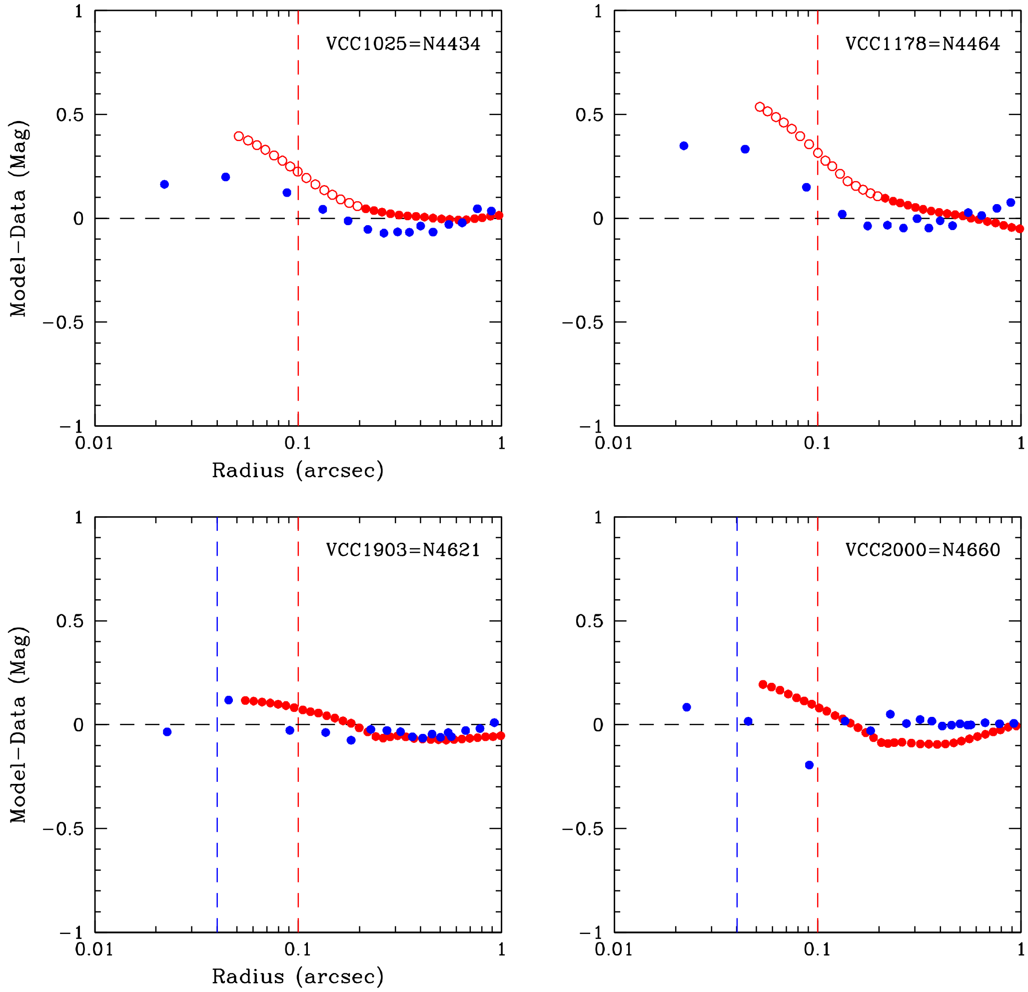

Figure 7b. Surface brightness residuals (model – data) for the Nuker model fits (blue) and the ACSVCS fits (red) for the galaxies shown in Figure 7a. The ACSVCS models were not fitted to data within the radial range in which residuals are plotted as open symbols.

better job at fitting the profiles in the region beyond the nucleus. Lauer et al. claim that a Nuker model does: "It is evident from examining the profiles fits in Figure 12 [typo: should be Figure 13] that the Nuker laws can accurately describe the ACS profiles of these galaxies into small radii." The veracity of this claim is tested in Figures 8a, 8b, 9a and 9b, where we show the Nuker model against the data to which it was originally fit, and the Sérsic and King (both combined and separate) models against the ACSVCS data (F06, C06). As was the case for Figures 4−6, it is worth noticing once again the wider radial coverage of the ACSVCS data, but also the fact that the data used by Lauer et al. are considerably noisier than the ACSVCS data. The Lauer et al. Nuker model fits to these galaxies use deconvolved, pre-refurbishment WFPC1 data and the intrinsically low S/N of the data is further amplified in their deconvolution process. At any rate, the inescapable conclusion from the residuals shown in these figures is that, in every case,

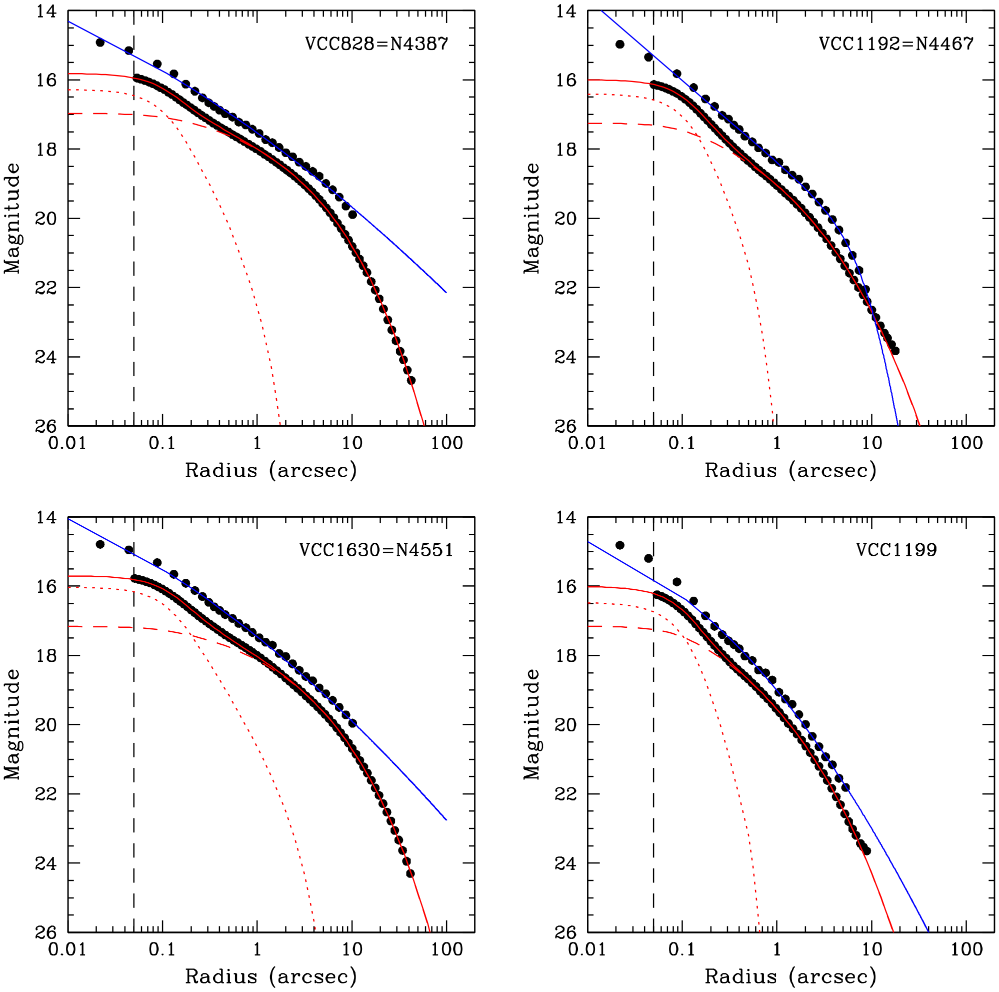

Figure 8a. The equivalent of the first page of Figure 13 of Lauer et al. For all galaxies shown in this figure, deconvolved WFPC1 data were used by Lauer et al. to fit Nuker models.

and in stark contrast to the claim of Lauer et al., the Nuker model of Lauer et al. *does not* provide a good description of the data at *any* radius; in the innermost region in particular, the residuals always show a characteristic S-shaped signature.

The ACSVCS Sérsic+King model, on the other hand, provides an excellent description of the data. The reader might wonder why this is not the impression one is left with when looking at Figure 13 of the Lauer et al. posting. There are three reasons. First, Lauer et al. misrepresent the ACSVCS analysis by showing only the Sérsic models, and omitting the contribution of the nucleus that is essential in the ACSVCS description of these galaxies. Second, they plot pre-convolved Sérsic models against deconvolved data, an inappropriate comparison as argued earlier. Finally, for both Sérsic and Nuker models, they plot a very limited radial extent (typically the inner 3-5″, but as little as 2″ for VCC 1199) and show no residuals, making it impossible for the reader to appreciate the global trends in the surface brightness profiles and the overall quality of the fits. Within

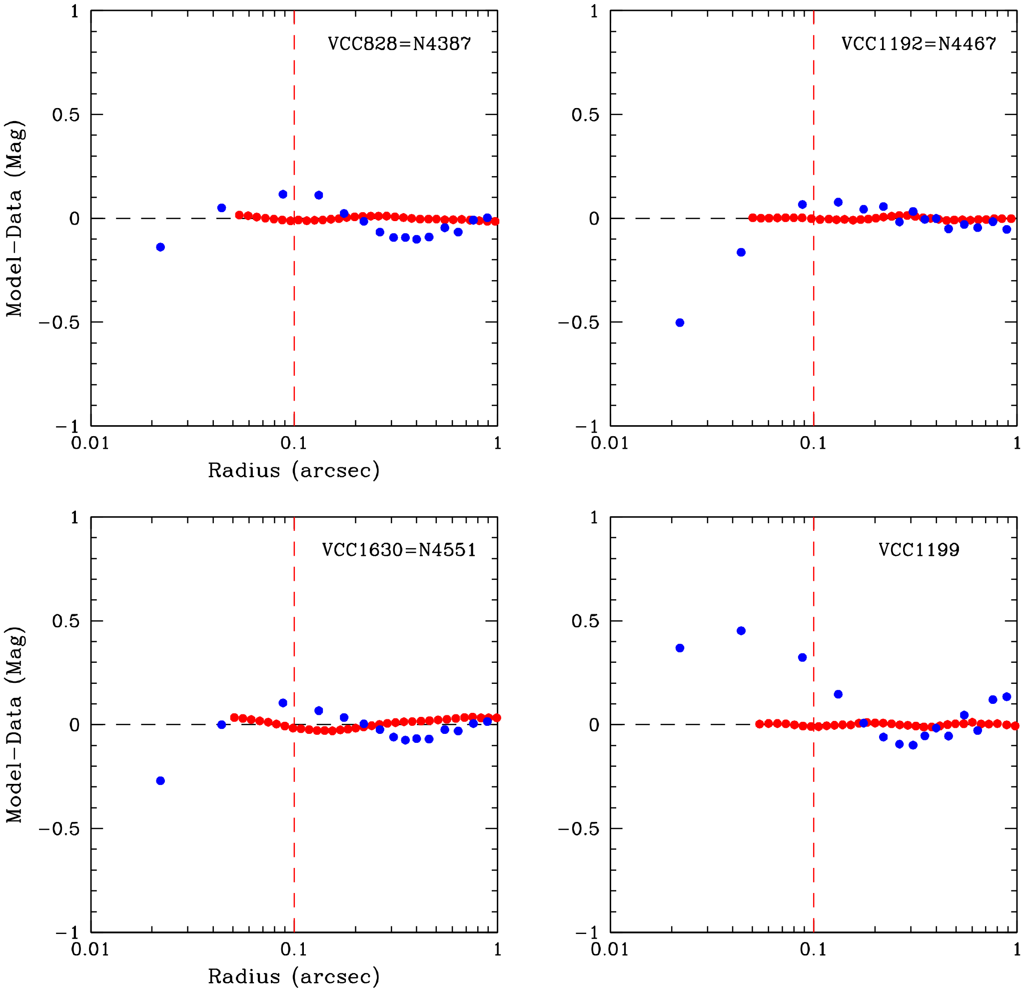

Figure 8b. Surface brightness residuals (model – data) for the Nuker model fits (blue) and the ACSVCS fits (red) for the galaxies shown in Figure 8a.

the restricted radial range plotted by Lauer et al. it is indeed true that an upturn in the surface brightness profile is not "unambiguous". But when the full extent of the profile is plotted, as shown in our Figures 8 and 9, the upturns are unmistakable. Indeed, because of the limited radial extent of the data to which the Nuker model was fitted, Lauer et al. failed to properly characterize the nuclei, and missed the existence of the nuclear scaling relations discussed in C06, Ferrarese et al. (2006b) and Wehner & Harris (2006). Contemporaneous work in spiral galaxies suggests that similar scaling relations are followed by the nuclei in these environments as well (e.g., Böker et al. 2002, 2004; Rossa et al. 2006; Seth et al. 2006).

Finally, we make one last comment regarding NGC4458 = VCC1146 (bottom right panel of Figures 4a and 4b). This galaxy also shows a central upturn, which F06 and C06 take as indication that a central component is present. Figure 14 of Lauer et al., by plotting only the Sérsic ACSVCS model and not the fitted nuclear component, and

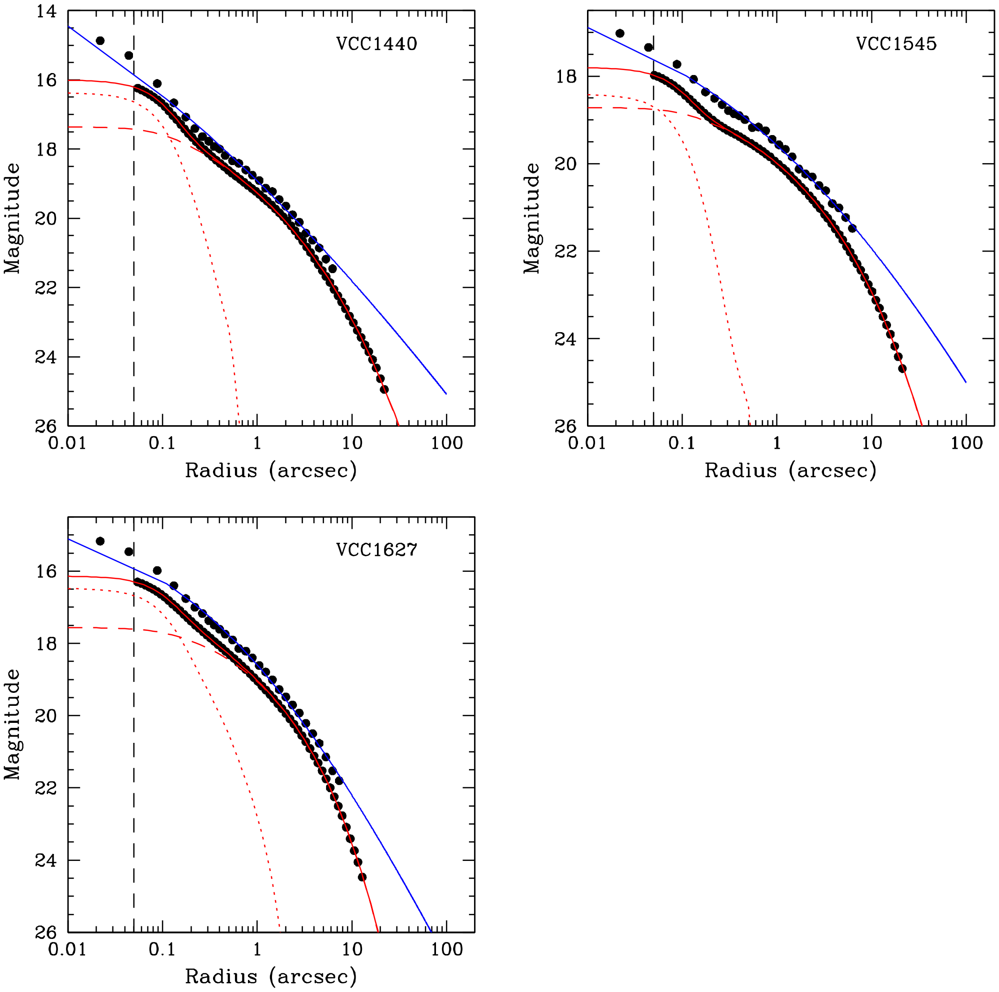

Figure 9a. The equivalent of the second page of Figure 13 of Lauer et al. For all galaxies shown in this figure, deconvolved WFPC1 data were used by Lauer et al. to fit Nuker models.

by showing only the WFPC2 data (not the ACSVCS data), is misleading. However, it is interesting to note that, while the Nuker fit to this galaxy does an excellent job in the inner 0″.1, the fit at larger radii shows the typical "S-shaped" residuals that are generally seen when a nucleus is present. Lauer et al., in their attempt to fit the innermost region of this galaxy, are in fact fitting a Nuker model to this nuclear component, and in the process producing a very poor fit to the main body of the galaxy — the very component their model is intended to represent.

The question remains, of course, whether any model fitted to the data beyond the central nucleus and extrapolated inwards, can give a truthful estimate of the slope of the profile of the galaxy underlying the nucleus at that radius. This is indeed an interesting question, and one to which there can be no secure answer. We will point out, however, that a Sérsic model does a remarkably good job at fitting the profiles of faint non-nucleated galaxies up to the innermost radius corresponding to the resolution element of

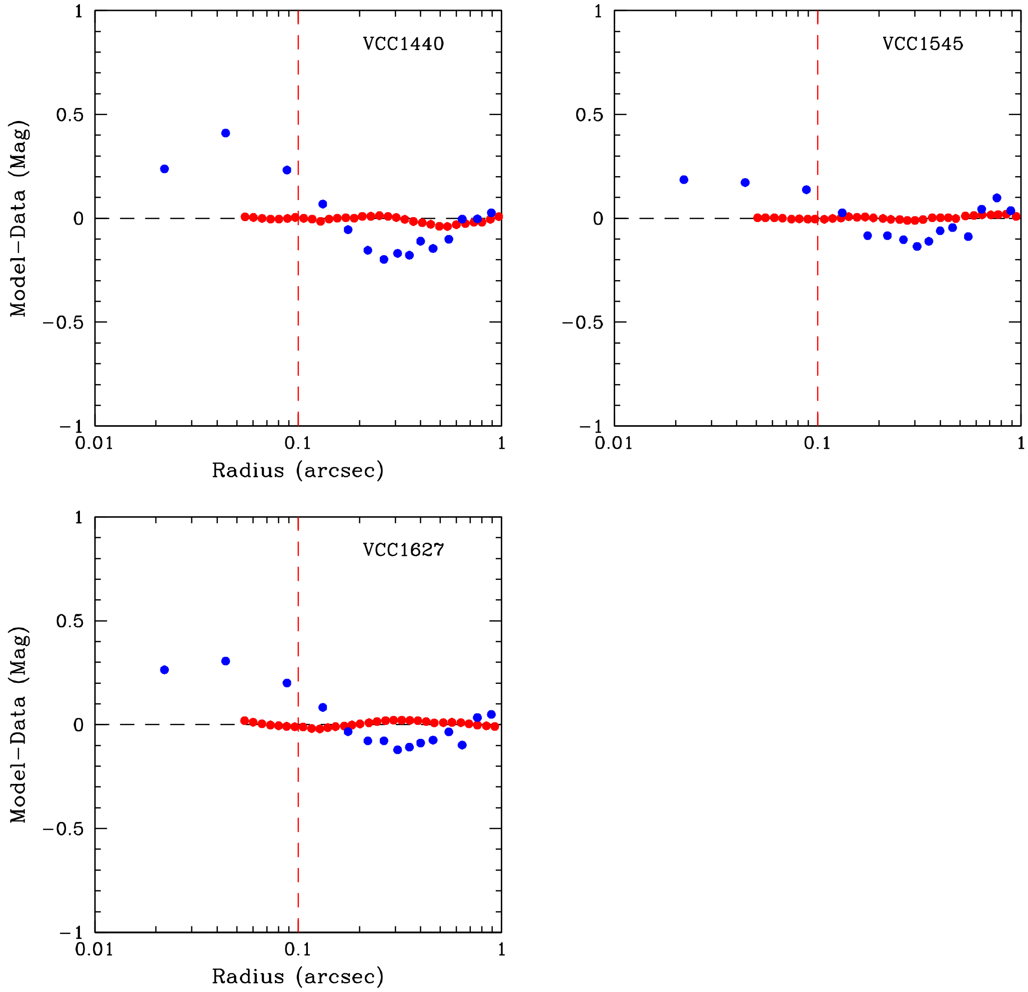

Figure 9b. Surface brightness residuals (model – data) for the Nuker model fits (blue) and the ACSVCS fits (red) for the galaxies shown in Figure 9a.

the ACS (e.g. VCC1049, VCC1833, VCC9, VCC1499, VCC1857, VCC1948, see Figure 103 of F06). In nucleated galaxies, it fits the profiles between a few 0″.1 and several tens of arcsec. Based on this, the assumption that it might also describe the surface brightness profile underlying the nucleus ($r \lesssim$ a few 0″.1) does not appear outlandish. Lauer et al. Nuker models, on the other hand, are often a compromise fit between the main body of the galaxy and the nucleus, which is not properly recognized and accounted for because of the generally low S/N of the data (compounded by the deconvolution procedure), the limited radial extent of the surface brightness profiles, and the lack of color information for many of their galaxies, from which the presence or absence of a separate nuclear component could be ascertained.

5. Discussion and Conclusions

The parameterization of the surface brightness profiles of early-type galaxies has been long used to characterize scaling relations and differences/commonalities between these systems. In Ferrarese et al. (2006, F06), and Côté et al. (2006, C06), the surface brightness profiles of 100 early-type galaxies in the Virgo cluster, each observed with the ACS/WFC on board HST, were fitted using core-Sérsic, Sérsic, or Sérsic+King models. In the previous sections, we have compared the quality of such fits with that provided by "Nuker" models, used in a recent astro-ph posting by Lauer et al. to describe WFPC1 or WFPC2 data for a sample of galaxies in common with the F06 and C06 sample. We argue that the Nuker model, while being inadequate at describing the surface brightness profiles of early-type galaxies on kiloparsec scales, even on small scales does not provide a characterization of the profiles that is superior to that provided by the models used in the ACSVCS analysis. Indeed, we have shown that the limited radial extent and low S/N for much of the Virgo data used by Lauer et al., was responsible for the fact that these authors failed to properly identify and characterize stellar nuclei and that, as a consequence, their Nuker models are forced to partially fit the profile of the nucleus, rather than that of the underlying galaxy. For the rest of this contribution, we point out a few other issues of concern with the analysis presented in the Lauer et al. astro-ph posting.

We start by examining the working definition of γ used Lauer et al., as the logarithmic slope measured at the resolution limit of the instrument. Given that the Lauer et al. compilation was observed with a variety of instrument/filter combinations, the angular scale at which γ is measured is different for each sample. Furthermore, given the enormous range in distance (a factor 100) spanned by their galaxies, γ is measured at *very* different physical scales in each galaxy.

According to Lauer et al., the instrument resolution limit is $0\farcs04$ for WFPC2 (except for some unspecified galaxies for which drizzled images exist, and for which the limit is taken to be $0\farcs02$) and $0\farcs1$ for WFPC1, NIC2 and NIC3.† This lack of uniformity is an obvious concern: Lauer et al. themselves note that when γ is recalculated at $0\farcs04$ using the Nuker model parameters of Rest et al. (2001) — who themselves judged $0\farcs1$ to be a more appropriate choice based on the analysis of their own data — in 12 cases (25% of the sample) γ changes by a sufficiently large amount to move the galaxy classification within the "core – intermediate – power-law" scheme favored by Rest et al. (2001) – with galaxies preferentially been moved out of the "intermediate" class into the "core" class‡ . One is therefore left to wonder how the bimodal distribution of γ values found by Lauer et al. would be affected if the galaxies observed with WFPC1, NIC2 and NIC3 had instead been observed with WPFC2, in which case γ would have been measured at a radius smaller by a factor of ~ 2.5–5.

This critical issue is further clouded by the fact that the Lauer et al. slope is *not always* measured at the resolution limit of the instrument. As Lauer et al. state, "the limits shown are those we have adopted to avoid central nuclei, and so on, and when larger than the general resolution limits presented in §2 are always the scale at which we measured γ".

† Note that the pixel scales of the instruments are $0\farcs043$ (WFPC1/PC), $0\farcs045$ (WFPC2/PC), $0\farcs075$ (NIC2) and $0\farcs2$ (NIC3). The resolution limits adopted by Lauer et al. appear rather optimistic, given that they are a factor 2.25 smaller than a pixel for the drizzled WFPC2 images, that the FWHM of the NIC2 and NIC3 PSFs are $0\farcs14$ and $0\farcs22$ respectively, and that the NICMOS images of Ravindranath et al. were not deconvolved.

‡ Seven galaxies, classified by Rest et al. as intermediate cases are reclassified by Lauer et al. as core galaxies, while four galaxies classified by Rest et al. as power-law, are reclassified by Lauer et al. as intermediate. One galaxy, classified by Rest et al. as power-law, is reclassified by Lauer et al. as core.

Therefore, for galaxies that are believed to be nucleated, the slope is *measured at the innermost radius that is believed not to be affected by the nuclear component.* Lauer et al. do not actually tabulate the radius at which γ is measured in each individual galaxy, but for NGC4365, for instance, their Figure 11 shows that γ is measured at a radius that is a factor 10 larger than the instrumental resolution limit. Therefore, even if one could find a good justification as to why γ should be measured at the resolution limit of the instrument (which we cannot, and certainly not for for a sample of galaxies lying at different distances and observed with instruments for which this limit varies by a factor five), Lauer et al. violate their own rule in their analysis.

Indeed, casting the radius at which γ is measured in terms of an angular scale has very little sense when dealing with a sample of galaxies which span a factor 100 in distance (as already pointed out by Graham et al. 2003). If the core/power-law bimodality has a physical origin, it would seem more appropriate to measure the slope at either the same physical, rather than angular radius, or at least at a radius corresponding to a constant fraction of some characteristic scale radius in every galaxy (such as the effective radius of the galaxy). The only condition here is that such radius must be chosen to be smaller than the break radius observed for the brightest galaxies.

To summarize, the main points from the preceding sections are:

- The ACSVCS sample is superior to the sample compiled by Lauer et al. in terms of:
  (*a*) Spatial resolution (better by an average factor of $\sim$ three);
  (*b*) Homogeneity. All ACSVCS galaxies are observed with the same instrument/filter combination, while the Lauer et al. is an inhomogeneous compilation of samples observed with four different instruments and in four different bandpasses;
  (*c*) Sample selection. All ACSVCS galaxies belong to the Virgo Cluster and uniformly cover the luminosity function of early-type galaxies. The Lauer et al. sample includes objects observed as part of five different projects so its biases and completeness are not easily characterizable;
  (*d*) Availability of two bands for all galaxies. The color information is an important factor in assessing the presence of stellar nuclei and separate morphological components; these cannot be easily recognized from single-band data such as those used by Lauer et al.;
  (*e*) Spatial coverage. The radial extent of the brightness profiles in common between the two studies is typically greater by an order of magnitude for the ACSVCS sample.
- In non-nucleated galaxies, Lauer et al. claim that the core-Sérsic and Sérsic models used to fit the ACSVCS data do not provide a good characterization of the profile. This claim is based on a comparison of the ACSVCS models to deconvolved WFPC2 or WFPC1 data taken with a different filter (i.e., the data used to fit Nuker models). This comparison is fundamentally inappropriate since it does not account for the PSF mismatch between the ACSVCS models and the deconvolved images. When the ACSVCS models are compared to the ACSVCS data, their ability to reproduce the profiles at small radii is comparable to that of the Nuker model fitted to deconvolved WFPC1 or WFPC2 data. At the same time, the ACSVCS models provide good fits at large radii, whereas the Nuker models fail dramatically on such scales.
- In nucleated galaxies, Nuker models are poor fits to the inner profiles despite the claim of Lauer et al. to the contrary. ACSVCS models for these galaxies, including a King component that describes the nuclei, do an excellent job of matching the profile. The low S/N and limited radial extent of the WFPC1 data used by Lauer et al. to fit Nuker models to these galaxies prevented them from identifying the global trends in the profiles, which are essential when judging the extent of contamination by central components. As a result, the fitted Nuker profiles are a compromise between the nucleus

and the underlying galaxy, fitting neither particularly well, as is shown by the clear S-shaped signature imprinted in the Nuker model residuals.

In short, on small scales, a Nuker model does not provide a better description of the data than a Sérsic or core-Sérsic model. On kiloparsec scales, a Nuker model is unable to follow the continuous curvature that characterizes galaxy profiles. Indeed, Graham et al. (2003) argued that the curvature of the profiles on large scales undermines the use of a Nuker model by making the fits sensitive to the radial extent covered by the data, to the point that the physical interpretation of the model parameters is compromised.

Core-Sérsic, Sérsic, or Sérsic+King models appear better suited to describe the surface brightness profiles of early-type galaxies from parsec to kiloparsec scales. The fitted parameters do not appear to suffer from significant biases, and the models use a relatively small number of free parameters (three for non-nucleated galaxies, and six when a nucleus is present). As more and better surface brightness data become available, it is possible — and indeed, likely — that shortcomings of these models will also begin to emerge, and that a newer and better parameterization will be required. Until then, a Sérsic/core-Sérsic parametrization should be preferred to that offered by a Nuker model.

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