Formation and Evolution of Galaxy Bulges
Proceedings IAU Symposium No. 245, 2007
M. Bureau, E. Athanassoula & B. Barbuy, eds.

doi:10.1017/S1743921308017651

The structure of early-type galaxies from the ACS Virgo and Fornax cluster surveys: cores, nuclei and supermassive black holes

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Abstract. The core structure of early-type galaxies is revisited in light of recent results from the ACS Virgo and Fornax Cluster Surveys. These surveys are comprised of HST/ACS g, z band images for a representative sample of 143 early-type galaxies, spanning a factor 720 in $B-$band luminosity. The data indicates a clear transition in the core structure going from the brightest to the faintest galaxies. In contrast to previous claims, however, this transition is found to be a continuous function of galaxy magnitude. We characterize the core structure in terms of deviations of the observed surface brightness profile – measured within $\sim 2\%$ of the galaxy effective radius – relative to the inner extrapolation of the Sérsic law that best fits the profiles on larger scales. Virtually all galaxies fainter than $M_B \sim -20$ mag contain distinct stellar nuclei, and are described by surface brightness profiles that lie above the Sérsic extrapolation, while the reverse is true for brighter galaxies. The latter are also known to host supermassive black holes. A relation between SBHs and stellar nuclei is suggested by the fact that both types of "central massive objects" contain the same fraction, 0.2% of the total mass of the host galaxy.

Keywords. galaxies: elliptical and lenticular, cD – galaxies: fundamental parameters – galaxies: nuclei – galaxies: photometry – galaxies: structure

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 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).

Early Hubble Space Telescope (HST) studies of early-type galaxies found that cores fall in two distinct classes: in bright galaxies (which, somewhat unfortunately, came to be known as "core" galaxies) the cores exhibit a shallow surface brightness profile, while in fainter, "power-law" galaxies, cores have surface brightness which keeps 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). Although the division between "core" and "power-law" galaxies became less clear in later studies (Ravindranath *et al.* 1996; Rest *et al.* 2001), the two classes are generally believed to reflect different formation/evolutionary histories. Dissipation is thought to play an important role in the evolution of power-law galaxies, while core galaxies are believed to be the result of the dissipationless merging of fainter galaxies, and of their central SBHs. Indeed, dynamical detections of SBHs exist for approximatively three dozen galaxies (see Ferrarese & Ford 2005 for a review), and it is generally believed that all local galaxies brighter than a few $0.1L_*$ 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 the dynamical centers of galaxies. Stellar nuclei – or nuclear star clusters – have been detected in a large fraction (70% to 90%) of galaxies of all Hubble types and luminosities (Carollo *et al.* 1998; Böker *et al.* 2002; Lotz *et al.* 2004; Grant *et al.* 2005; Côté et al. 2006). 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, with luminosity-weighted ages ranging from 10 Myr to 10 Gyr.

This contribution explores the connection between cores, nuclei and supermassive black holes as emerged based on the ACS Virgo and Fornax Cluster Surveys (ACSVCS/FCS, Côté *et al.* 2004; Jordán *et al.* 2007), the largest homogeneous HST imaging surveys designed to provide an unbiased characterization of the core structure of early-type galaxies. A short description of the surveys can be found in Côté *et al.* (these proceedings)

2. Cores, Power-Laws, and Everything in Between

The distribution of logarithmic slopes of the surface brightness profile, γ, calculated at $0''.1$ (=8pc at the distance of Virgo) for the 100 ACSVCS galaxies forms a continuous sequence from dwarf to giant ellipticals, across a factor of 460 in $B-$band luminosity (Ferrarese *et al.* 2006a). In particular, the ACSVCS data does not show any evidence of a bimodal behaviour that would point to a separation between “core” and “power-law” galaxies. Furthermore, the *shallowest* surface brightness profiles ($\gamma \sim 0$) are not found in the *brightest* giant ellipticals, but rather in the *fainter* dwarf galaxies ($M_B \gtrsim -18$ mag).

In contrast to these studies, Lauer *et al.* (2007) report a bimodal separation of galaxies into core and power-law classes based on γ values compiled from several independent studies for a sample of 219 galaxies. Of the several reasons which contribute to the disagreement between the two studies (see Ferrarese *et al.* 2006c), the most critical is sample selection. The only criterion used by Lauer *et al.* to include a galaxy in their sample is the availability of parameters from a Nuker law (Lauer *et al.* 1995) fitted to the surface brigthness profile measured from HST data; the ACSVCS/FCS galaxies, for instance, are not included, since Ferrarese *et al.* did not use Nuker laws to fit the profiles. The luminosity function of the resulting sample is strongly bimodal (Lauer *et al.* 2007; see also Figure 4 of Côté *et al.* 2007) and unrepresentative of the Schecter function form that provides a reasonable match to the early-type galaxy population in both field and cluster environments (e.g. Schecter 1976; Loveday *et al.* 1992; Marzke *et al.* 1994; Blanton *et al.* 2003). In particular, galaxies with $M_B \sim -20.5$ mag are under-represented in the Lauer *et al.* (2007) sample; interestingly, this is exactly the magnitude “valley” that marks the alleged separation between core and power-law galaxies.

The ACSVCS/FCS samples, on the other hand, are well described by the Schechter function representing the early-type galaxy population in the Virgo Cluster (Sandage, Binggeli & Tammann 1985, Figure 4 of Côté *et al.* 2007). As mentioned, the distribution of slopes for the ACSVCS/FCS samples is a continuous function of M_B. Côté *et al.* (2007) demonstrates that, if γ values from such continuous distribution are assigned to galaxies drawn from a bimodal luminosity function such as the one describing the sample of Lauer *et al.*, the resulting distribution of γ will be, not surprisingly, also bimodal. This will lead to a distinct, but unphysical, separation between “core” and “power-law” galaxies.

One may ask: is γ the best parameter to be used in characterizing the structure of cores? Ferrarese *et al.* (2006c) note that, by being a differential measurement, γ is very sensitive to the spatial resolution of the data, and conclusions based on compilations of γ values for galaxies at differing distances and/or observed with different instruments (such as is the case for the Lauer *et al.* sample), should be viewed with caution. This was demonstrated by Côté *et al.* (2007), who also proposed a more physical characterization of galaxy cores. 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/FCS images), the surface brightness profiles of the ACSVCS/FCS 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. In the brightest galaxies ($M_B \gtrsim -20.3$ mag) the measured inner profiles (typically within $0\farcs5$ to $2\farcs5$, corresponding to 40 to 200pc) are shallower than expected based on an inward extrapolation of the Sérsic model constrained by the region beyond. The opposite is seen in fainter galaxies, $\sim 80\%$ of which show a clear upturn, or inflection, in the surface brightness profile within (typically) the innermost few tens of parsec region (see Côté *et al.*, these proceedings). The upturn signals the presence a stellar nucleus that is most likely structurally distinct from the main body of the underlying galaxy. The ensuing picture is one in which, in moving down the luminosity function from giant to dwarf early-type galaxies, the innermost $\sim$100 parsec region undergoes a systematic and smooth transition from light (mass) deficit (relative to the overall best fitting Sersic model) to light excess. Remarkably, such deviations seem to occur within a constant fraction, $\sim 2\%$ of the galaxy effective radius ($\pm 1\sigma$ range $0.010 - 0.045$ R_e).

Côté *et al.* (2007) define a parameter, $\Delta_{0.02}$, as the log of the ratio between the observed profile and the extrapolation of the best fitting Sérsic model, both integrated within $0.02R_e$. By being an integrated parameter, measured within a physical scale which appears to be independent, on average, of galaxy magnitude, $\Delta_{0.02}$ is less sensitive than γ to the resolution of the data and the details of the analysis. Furthermore, its definition is related to a *physical* criterion (i.e., the presence of a nucleus or a central light deficit), while γ *per se* is not. For instance, as mentioned, both very bright and very faint galaxies have shallow, almost constant density cores with $\gamma \sim 0$, in spite of their overall very different surface brightness profiles. On the contrary, essentially no galaxies fainter than $M_B \sim -20.5$ mag have light deficits, while most have stellar nuclei. The distribution of $\Delta_{0.02}$ is continuous as a function of M_B over the ~ 720 luminosity range spanned by the ACSVCS/FCS galaxies, again suggesting that the core structure of early-type galaxies varies in a continuous fashion as a function of galaxy luminosity.

3. Stellar Nuclei and Supermassive Black Holes

Because both SBHs and stellar nuclei are often found in galactic centers, the obvious question to ask is whether a relationship might exist between them. The masses of SBHs are known to correlate with the stellar velocity dispersion of the host bulge (Ferrarese & Merritt 2000; Gebhardt *et al.* 2000). The ACSVCS stellar nuclei obey an $M_\bullet$-σ relation with the same slope, although different normalization, as the one defined by SBHs (Ferrarese *et al.* 2006b). Furthermore, when the galaxy's virial mass, $\mathcal{M}_{gal} \propto \sigma^2 r_e/G$, is calculated, SBHs and stellar nuclei are found to obey the same $M_\bullet$-$\mathcal{M}_{gal}$ relation. Interestingly, the same relation is also found to hold in spiral galaxies (Rossa *et al.* 2006) and to extend to dEs as faint as $M_B \sim -11.7$ mag (Wehner & Harris 2006).

These findings can be summarized as follows: a constant fraction, $\mathcal{M}_{\rm CMO}/\mathcal{M}_{gal} \sim 0.2\%$, of a galaxy total mass is often used in the formation of a nuclear structure, or

https://doi.org/10.1017/S1743921308017651 Published online by Cambridge University Press

central massive object (CMO). This holds true for galaxies spanning a factor 10^4 $M_\odot$ in mass, all Hubble types, luminosities and environments. Despite their different natures, SBHs and stellar nuclei are complementary incarnations of CMOs — they likely share a common formation mechanism and follow a similar evolutionary path throughout their host galaxys history (McLaughlin *et al.* 2006).

Perhaps the most intriguing question at this point 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. At the other extreme of the luminosity range spanned by the ACSVCS galaxies we find NGC205 and M33: two galaxies for which there is no evidence of a SBH, and yet host stellar nuclei that follow the same scaling relations as the nuclei detected in the ACSVCS galaxies. It is possible that nuclei form in every galaxy, but are subsequently destroyed in the brighest systems 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.

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