

Explaining the reportedly over-massive black holes in early-type galaxies with intermediate-scale discs

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ABSTRACT

The classification “early-type” galaxy includes both elliptically- and lenticular-shaped galaxies. Theoretically, the spheroid-to-disc flux ratio of an early-type galaxy can assume any positive value, but in practice studies often consider only spheroid/disc decompositions in which the disc neatly dominates over the spheroid at large galaxy radii, creating an inner “bulge” as observed in most spiral galaxies. Here we show that decompositions in which the disc remains embedded within the spheroid, labelled by some as “unphysical”, correctly reproduce both the photometric and kinematic properties of early-type galaxies with intermediate-scale discs. Intermediate-scale discs have often been confused with large-scale discs and incorrectly modelled as such; when this happens, the spheroid luminosity is considerably underestimated. This has recently led to some surprising conclusions, such as the claim that a number of galaxies with intermediate-scale discs (Mrk 1216, NGC 1277, NGC 1271, and NGC 1332) host a central black hole whose mass is abnormally large compared to expectations from the (underestimated) spheroid luminosity. We show that when these galaxies are correctly modelled, they no longer appear as extreme outliers in the (black hole mass)-(spheroid mass) diagram. This not only nullifies the need for invoking different evolutionary scenarios for these galaxies but it strengthens the significance of the observed (black hole mass)-(spheroid mass) correlation and confirms its importance as a fundamental ingredient for theoretical and semi-analytic models used to describe the coevolution of spheroids and their central supermassive black holes.

Key words: black hole physics – galaxies: bulges – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: structure – galaxies: individual: Mrk 1216, NGC 1271, NGC 1277, NGC 1332, NGC 4291

1 INTRODUCTION

The awareness that *many* early-type galaxies contain previously over-looked stellar discs dates back half a century (Liller 1966; Michard 1984; Djorgovski 1985; Jedrzejewski 1987b; Bender & Moellenhoff 1987; Carter 1987; Capaccioli 1987; Capaccioli et al. 1988; Strom & Strom 1978; Bender 1988, 1990; Nieto et al. 1988; Rix & White 1990; van den Bergh 1990; Scorsa & Bender 1990, 1995; Simien & Michard 1990). Not surprisingly, it is well known that the identification of a stellar disc in an early-type galaxy, particularly when based on the

galaxy’s photometric properties, is subject to inclination effects. As predicted by Carter (1987), this problem is largely overcome with kinematic analyses (e.g. Franx et al. 1989; Nieto et al. 1991; Rix & White 1992; Cinzano & van der Marel 1993; D’Onofrio et al. 1995; Graham et al. 1998, and the ATLAS^{3D} survey, Cappellari et al. 2011), which allow one to determine the presence of a rotationally-supported component in a way nearly insensitive to projection effects (McElroy 1983; Cappellari et al. 2007; Emsellem et al. 2007). Yet, identifying the radial extent of an early-type galaxy’s disc with respect to the spheroidal component can still be subtle. Studying both the surface brightness profiles and the ellipticity profiles (a concept pioneered by

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Liller 1960)¹ of early-type galaxies in the Virgo cluster – including those with elliptical (E), spindle and lenticular (S0) isophotes – Liller (1966) drew attention to the observation that many of the galaxies displayed “characteristics intermediate between those of type E and type S0”, and she classified them as “ES” galaxies². Building on this and other investigations of ellipticity profiles (e.g. Strom & Strom 1978; di Tullio 1979), Michard (1984) used the classification “S0-like” for these early-type galaxies with humped ellipticity profiles, dominated by a somewhat edge-on disc at intermediate radii. Nieto et al. (1988) identified two dozen such spheroid-dominated early-type galaxies, whose discs do not prevail at large radii, and referred to them as “disk-ellipticals” (or “disky ellipticals”, Simien & Michard 1990) thereby more closely associating them with elliptical galaxies than lenticular galaxies. However, as noted by Nieto et al. (1988), unless the orientation of the disc is favourable (i.e. somewhat edge-on), it can be missed. The same is true when searching for pointy isophotes that are shaped by the combination of the spheroid and a near edge-on disc (e.g. Carter 1978, 1987; Jedrzejewski 1987b; Bender & Moellenhoff 1987). Today, most early-type galaxies are classified as “fast rotators”³ (Emsellem et al. 2011; Scott et al. 2014), that is, they are rapidly rotating within their half-light radius. The exact definition of a fast rotator can be found in Emsellem et al. (2007), although the most recent literature (e.g. Arnold et al. 2011; Romanowsky & Fall 2012; Arnold et al. 2014) prefers the use of the term “central fast rotator” to emphasize the fact that this classification pertains to the kinematic properties of a galaxy only within its half-light radius. Thanks to their more extended kinematic maps, Arnold et al. (2014) revealed that some of the central fast rotators continue to be fast rotating at large radii, whereas other central fast rotators become slow rotating in their outer regions. A specific angular momentum profile that is rapidly increasing beyond 1–2 half-light radii is a signature of a large-scale disc, while a specific angular momentum profile that increases up to 1–2 half-light radii and then declines beyond that point indicates the presence of an intermediate-scale disc that no longer dominates at large radii. Unfortunately, such extended kinematic maps are not yet available for large numbers of galaxies in the local Universe. Nevertheless, the ellipticity profile of a galaxy’s isophotes can help identify the extent of a stellar disc in an early-type galaxy.

Building on the investigation of Rix & White (1990), the toy model shown in Figure 1 illustrates the typ-

ical ellipticity profile ($\epsilon = 1 - b/a$, where b/a is the ratio of minor-to-major axis length) and the specific angular momentum profile ($\lambda = \langle R|V| \rangle / \langle R\sqrt{V^2 + \sigma^2} \rangle$, where R is the semimajor-axis radius, V is the mean velocity and σ is the velocity dispersion, Emsellem et al. 2007) of: (i) a lenticular galaxy, comprised of a large-scale disc which dominates the light at large radii over a relatively smaller encased bulge, i.e. a disc-dominated central fast rotator that continues to be fast rotating beyond one half-light radius; (ii) a “discy elliptical” galaxy (Michard 1984; Nieto et al. 1988) composed of an intermediate-scale disc embedded in a relatively larger spheroid which dominates the light at large radii, i.e. a spheroid-dominated central fast rotator that becomes slow rotating beyond 1–2 half-light radii; and (iii) an elliptical galaxy with an additional nuclear stellar disc, i.e. a (spheroid-dominated) slow rotator. This sequence is analogue to that illustrated in Figure 2 of Cappellari et al. (2011), although here we emphasize the correspondence between the spheroid/disc decomposition of the surface brightness profile and the “shape” of the ellipticity profile (assuming that the disc inclination is not close to face-on) and also the specific angular momentum profiles.

In general, stellar discs are intrinsically flat and close to circular; their apparent ellipticity, dictated by their inclination to our line of sight, is fixed. Spheroids are often rounder than the observed projection on the sky of their associated discs, thus their average ellipticity is often lower than that of their disc. An ellipticity profile that increases with radius can be ascribed to an inclined disc that becomes progressively more important at large radii, whereas a radial decrease of ellipticity signifies the opposite case. This approach can be taken to the next level by inspecting the isophotes for discy structures (e.g. Carter 1978, 1987; Capaccioli 1987; Jedrzejewski 1987b; Bender & Moellenhoff 1987) and checking the velocity line profiles for asymmetry (e.g. Franx & Illingworth 1988; Bender 1990; Rix & White 1992; Scorsa & Bender 1995, and references therein; Scorsa 1998).

While some recent studies have correctly distinguished between large- and intermediate-scale discs, and modelled them accordingly (e.g. Kormendy & Bender 2012; Krajnović et al. 2013), intermediate-scale discs have been missed by many galaxy modellers of late, who have labelled as “unphysical” (Allen et al. 2006) those spheroid/disc decompositions in which the disc does not dominate over the spheroid at large radii as is observed with spiral galaxies. Indeed, Graham et al. (2001, his Figure 7) warned about such erroneous fits to late-type galaxies. However, this has led to the rejection of many early-type galaxy decompositions similar to that illustrated in the top middle panel of Figure 1. Unsurprisingly, studies affected by this bias have not obtained spheroid/disc decompositions with a spheroid-to-total ratio larger than 0.6–0.8 (e.g. Gadotti 2008; Head et al. 2014; Querejeta et al. 2015; Méndez-Abreu & CALIFA Team 2015).

¹ Liller (1960) used ellipticity profiles to help identify elliptical and spiral galaxy type.

² Strom et al. (1977) and Strom & Strom (1978) classified the intermediate “ES” galaxy type as “E/S0”, see also Thompson (1976).

³ The term “fast rotator” is of course not new for describing certain early-type galaxies (e.g. Bertin & Stiavelli 1984; Lake & Dressler 1986).

As mentioned before, an isophotal analysis allows one to identify the presence and the radial extent of a disc in an early-type galaxy only when the disc has a certain level of inclination. On the other hand, a kinematical analysis has the advantage of being virtually insensitive to inclination effects, but cannot help one determine the radial extent of a disc if the kinematical data are limited within one half-light radius. Therefore, the best results are obtained when photometry and kinematics are combined together. In this paper we focus on the increasingly overlooked occurrence of intermediate-scale discs in galaxies with directly measured black hole masses. We report on the photometric and kinematical signatures of these intermediate-sized stellar discs, and the impact they have on the (black hole mass)-to-(spheroid stellar mass) ratio which is used to constrain galaxy evolution models. In Section 2 we present a detailed photometric analysis of three galaxies with intermediate-scale discs (Mrk 1216, NGC 1332, and NGC 3115) and we briefly describe another five galaxies with intermediate-scale discs (NGC 821, NGC 1271, NGC 1277, NGC 3377, and NGC 4697) already modelled by us elsewhere in the literature. We compare our photometric analysis with the kinematical information available from the literature, and explain the differences between our galaxy models and past decompositions. In Section 3 we explore the important implications this has for the (black hole mass)-(spheroid stellar mass) diagram. Finally, in Section 4 we briefly discuss our results in terms of galaxy evolution and we present the location of the ES galaxies relative to other disc galaxies in a common classification scheme of Hubble type versus spheroid-to-disc ratio.

2 INTERMEDIATE-SCALE DISC GALAXIES

Three examples of galaxies with intermediate-scale discs are Mrk 1216, NGC 1332, and NGC 3115. In the following Sections, we present a photometric analysis of these three galaxies, and we compare our results with the kinematical analysis available from the literature for Mrk 1216 and NGC 3115. For the galaxies NGC 1332 and NGC 3115, we used $3.6\ \mu\text{m}$ images obtained with the InfraRed Array Camera (IRAC) onboard the *Spitzer Space Telescope*. For the galaxy Mrk 1216, we used an archived Hubble Space Telescope (*HST*) image taken with the Wide Field Camera 3 (WFC3) and the near-infrared *F160W* filter (*H-band*). Our galaxy decomposition technique is extensively described in Savorgnan & Graham (2015). Briefly, the galaxy images were background-subtracted, and masks for contaminating sources were created. The one-dimensional Point Spread Function (PSF) was characterized using a Gaussian profile for the *HST* observation and a Moffat (1969) profile for the *Spitzer* observations. We performed an isophotal analysis of the galaxies using

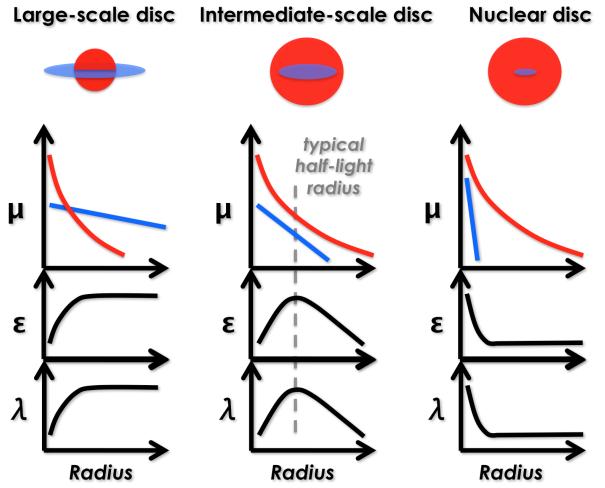


Figure 1. Illustration of the spheroid/disc decomposition of the one-dimensional surface brightness profile, μ , the ellipticity profile, ϵ , and the specific angular momentum profile, λ , for the three prototype early-type galaxy sub-classes. In the flux decompositions, the spheroid (or bulge) and the disc are shown with the red and blue color, respectively. The left panel shows a disc-dominated central fast rotator (lenticular galaxy), composed of a bulge encased in a large-scale disc. The right panel displays a spheroid-dominated slow rotator (elliptical) with (an optional) nuclear stellar disc. The middle panel presents a spheroid-dominated central fast rotator with an intermediate-sized disc embedded in the spheroid.

the IRAF⁴ task `ellipse`⁵ (Jedrzejewski 1987c). The galaxy isophotes were modelled with a series of concentric ellipses, allowing the ellipticity, the position angle and the amplitude of the fourth harmonic to vary with radius. The decomposition of the surface brightness profiles was performed with software written by G. Savorgnan and described in Savorgnan & Graham (2015). We modelled the light profiles with a combination of PSF-convolved analytic functions, using one function per galaxy component.

2.1 NGC 3115

The presence of a disc in the central fast rotator NGC 3115 (e.g. Strom et al. 1977; Nieto et al. 1988; Scorz

⁴ IRAF is the Image Reduction and Analysis Facility, distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

⁵ Our analysis was performed before `isofit` (Ciambur 2015) was conceived or available. After `isofit` was recently developed and implemented in IRAF, we employed it to re-extract the surface brightness profiles of the galaxies NGC 1332 and NGC 3115. We then repeated the analysis and checked that this change does not significantly alter our results. In fact, although `isofit` provides a more accurate description of the isophotes in the presence of an inclined disc, the discs of NGC 1332 and NGC 3115 are relatively faint compared to the spheroidal components, therefore the differences between the light profile obtained with `ellipse` and that obtained with `isofit` are small for these two galaxies.

& Bender 1995) is obvious due to its edge-on orientation (Figure 2). Less obvious is the radial extent of this disc, if one only relies on a visual inspection of the galaxy image. The ellipticity profile (Figure 2) is consistent with the presence of an intermediate-scale disc. Moreover, the kinematics of NGC 3115 (Arnold et al. 2011) also disprove the presence of a large-scale disc, because the galaxy is rapidly rotating only within two galaxy half-light radii ($\sim 2 \times 50$ arcsec), and the rotation significantly drops at larger radii. The unsharp mask of NGC 3115 (Figure 2) betrays the presence of a faint edge-on nuclear ring, which can also be spotted as a small peak in the ellipticity profile (at semi-major axis length $R_{\text{maj}} \sim 15$ arcsec). Such rings are common in early-type galaxies (Michard & Marchal 1993). The spheroidal component of NGC 3115 is well described with a Sérsic (1963) profile. The highly inclined intermediate-scale disc is better fit with an $n < 1$ Sérsic profile (the Sérsic index n regulates the curvature of the Sérsic profile) rather than with an exponential function, as explained by Pastrav et al. (2013). The nuclear ring is modelled with a Gaussian function.

In comparison, Läsker et al. (2014a) fit NGC 3115 with a bulge + disc + envelope, and measured a bulge half-light radius of 3.9 arcsec and a bulge-to-total ratio of 0.12. We describe this galaxy using a spheroid + intermediate-scale disc + nuclear ring, and obtain a spheroid half-light radius of 43.6 arcsec and a spheroid-to-total ratio of 0.85. We have used both kinematical information and ellipticity profiles, together with the surface brightness profile, to obtain a physically consistent and meaningful model.

2.2 NGC 1332

The morphology of NGC 1332 (Figure 3) is very similar to that of NGC 3115, with the ellipticity profile indicating the presence of an intermediate-scale disc, although in this case no nuclear component is evident. We were not able to find any extended kinematic profile or map for this galaxy in the literature. The data within the innermost 6 arcsec were excluded from the fit because, according to our galaxy decomposition, they are possibly affected by the presence of a partially depleted core. The surface brightness profile of NGC 1332 is well described with a Sérsic-spheroid plus an $n < 1$ Sérsic-disc. Our galaxy decomposition suggests that NGC 1332 is a spheroid-dominated galaxy, with a spheroid-to-total ratio of 0.95.

Rusli et al. (2011) did not identify the restricted extent of the intermediate-scale disc, as revealed by the ellipticity profile, and proposed a model featuring a Sérsic-bulge and a large-scale exponential-disc, with a spheroid-to-total ratio of 0.43. Based on their bulge/disc decomposition, they concluded that NGC 1332 is a disc-dominated lenticular galaxy which is displaced from the (black hole mass)-(spheroid luminosity) correlation of Marconi & Hunt (2003) by an order of magnitude along the black hole mass direction. However, in Section 3 we show that, according to our decomposition, NGC 1332 lies within the 1σ scatter about the (black hole mass)-(spheroid stellar mass) correlation for early-type galaxies. We also note that the majority of galaxies with an elevated stellar velocity dispersion ($\sigma > 270$ km s $^{-1}$) are core-Sérsic galaxies (Graham et al. 2003; Ferrarese et al. 2006; Dullo & Graham 2014), i.e. they have a partially de-

pleted core which has been identified from high-resolution photometric data. NGC 1332 has $\sigma = 320$ km s $^{-1}$, but, based on their decomposition of *HST* imaging, Rusli et al. (2011) did not find a core in this galaxy. However, our galaxy decomposition (Figure 3) suggests that NGC 1332 is in fact a core-Sérsic galaxy. Since we did not use high-resolution photometric data, we refrain from a firm conclusion, but we caution that a re-analysis of the *HST* data – by taking into account the correct radial extent of the intermediate-scale disc – may indeed reveal the presence of a depleted core in this galaxy.

2.3 Mrk 1216

Although the disc in the **central fast rotator** Mrk 1216 is not immediately apparent from the image (Figure 4), the velocity map (Yıldırım et al. 2015) reveals the presence of a fast rotating component within three galaxy half-light radii ($\sim 3 \times 5$ arcsec). The ellipticity profile (Figure 4), which extends out to five half-light radii, indicates the presence of an intermediate-scale disc. In addition, a nuclear disc is identified from the change in slope of the ellipticity profile ($R_{\text{maj}} \sim 1 - 2$ arcsec), from the unsharp mask, and from a clear feature in the $B4$ fourth harmonic profile (not shown here). We modelled the surface brightness profile of Mrk 1216 (Figure 4) with a Sérsic-spheroid, an intermediate-sized exponential-disc, and a nuclear exponential-disc.

2.4 Other galaxies

Our models with an intermediate-sized disc embedded within a larger spheroidal component, plus an additional nuclear component when one is present, match the observed light distribution, and explain both the extended kinematic maps (when available, Arnold et al. 2014) and the ellipticity profiles, of five additional galaxies for which a direct measurement of their central supermassive black hole mass is available: NGC 821; NGC 1271; NGC 1277; NGC 3377; and NGC 4697. Our isophotal analysis and galaxy decompositions for NGC 1271 and NGC 1277 will be presented in Graham, Savorgnan & Ciambur (*in prep.*) and Graham et al. (2015), respectively, while the galaxies NGC 821, NGC 3377 and NGC 4697 have been analysed in Savorgnan & Graham (2015).

2.4.1 NGC 1271

Walsh et al. (2015) explored a three-component decomposition for the **central fast rotator** NGC 1271 and identified the galaxy bulge with the innermost of the three components, having a half-light radius of 0.61 arcsec and a bulge-to-total flux ratio of 0.23; our model features a spheroid + intermediate-scale disc, with a spheroid half-light radius of 3.3 arcsec and a spheroid-to-total flux ratio of 0.67.

2.4.2 NGC 1277

van den Bosch et al. (2012) proposed a model for the **central fast rotator** NGC 1277 with a bulge + disc + nuclear source + envelope, which gives a bulge half-light radius of 0.9 arcsec and a bulge-to-total flux ratio of 0.24; our

model consists of a spheroid + intermediate-scale disc + nuclear component, and produces a spheroid half-light radius of 6.0 arcsec and a spheroid-to-total flux ratio of 0.79.

2.4.3 NGC 3377

Läsker et al. (2014a) modelled the **central fast rotator** NGC 3377 (e.g. Jedrzejewski 1987a; Scorza & Bender 1995) with a bulge + nuclear disc + disc + envelope, and obtained a bulge half-light radius of 10.1 arcsec and a bulge-to-total flux ratio of 0.35; our model with a spheroid + intermediate-scale disc + nuclear disc returns a spheroid half-light radius of 61.8 arcsec and a spheroid-to-total flux ratio of 0.94.

2.4.4 NGC 821

Läsker et al. (2014a) decomposed the **central fast rotator** NGC 821 into a bulge + disc + envelope, and measured a bulge half-light radius of 3.8 arcsec and a bulge-to-total flux ratio of 0.19; our decomposition consists of a spheroid + intermediate-scale disc, with a spheroid half-light radius of 36.5 arcsec and a spheroid-to-total flux ratio of 0.79.

2.4.5 NGC 4697

While NGC 4697 (e.g. Carter 1987; Jedrzejewski et al. 1987; Davies 1981) was explicitly referred to as a “fast rotator” by Capaccioli (1987) and Petrou (1981), it is only a central fast rotator and it represents an “extreme” case. Läsker et al. (2014a) fit this galaxy with a bulge + nuclear source + disc + envelope, and obtained a bulge half-light radius of 6.3 arcsec and a bulge-to-total flux ratio of 0.08; we described NGC 4697 using a spheroid + intermediate-scale disc + nuclear disc model, and measured a spheroid half-light radius of 239.3 arcsec and a spheroid-to-total flux ratio of 0.89.

Past models that “forcedly” described intermediate-scale disc galaxies using an inner bulge encased within a large-scale disc commonly required the addition of an extended envelope or halo to account for the outer portion of the spheroid. Such three-component models (bulge + disc + envelope) typically reduce the spheroid luminosity by a factor of 3 – 4, and underestimate the size of the spheroid by a factor of 6 – 10, although more “extreme” cases can be found.

3 THE BLACK HOLE – SPHEROID CORRELATION

Inaccurate measurements of the spheroid-to-total ratio of galaxies can impact galaxy scaling relations. Recently, a handful of galaxies with intermediate-scale discs have been claimed to host *over-massive* black holes, i.e. the mass of their central supermassive black hole has been reported to be significantly larger than what is expected from the galaxy’s spheroid luminosity (or stellar mass). This is the case for the galaxies Mrk 1216 (for which only an upper limit on its black hole mass has been published, Yıldırım et al. 2015), NGC 1271 (Walsh et al. 2015), NGC 1277 (van den Bosch

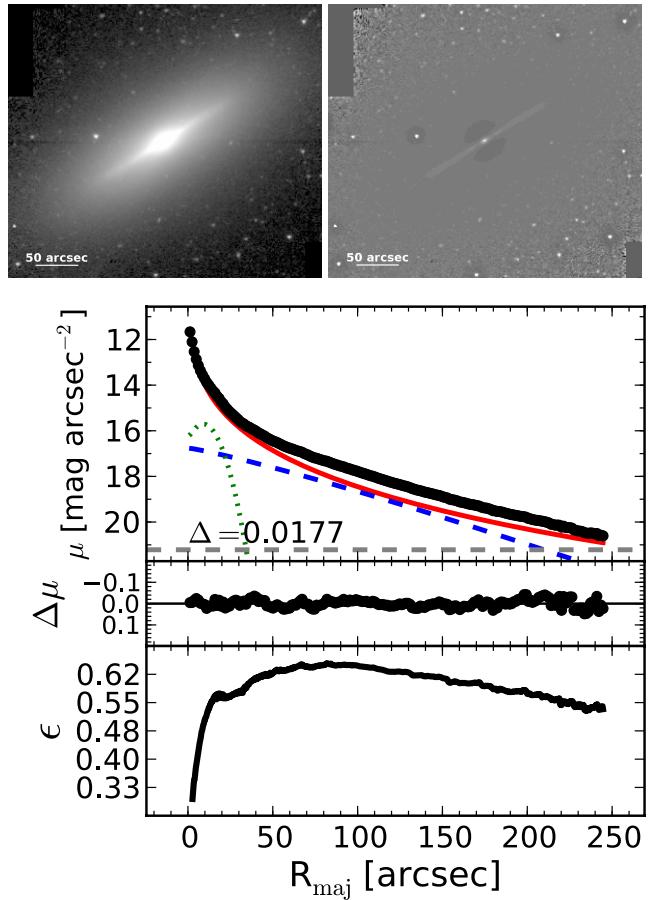


Figure 2. NGC 3115. The top panels are the *Spitzer*/IRAC 3.6 μ m image (left) and its unsharp mask (right), obtained by dividing the image by a Gaussian-smoothed version of itself. The bottom plots display the best-fit model of the surface brightness profile, μ , and the ellipticity profile, ϵ , along the major-axis, R_{maj} . The black points are the observed data, which extend out to five galaxy half-light radii ($\sim 5 \times 50$ arcsec). The color lines represent the individual (PSF-convolved) model components: **red solid** = Sérsic (spheroid), **blue dashed** = Sérsic (disc), **green dotted** = Gaussian ring. The residual profile (data – model) is shown as $\Delta\mu$. The horizontal gray dashed line corresponds to an intensity equal to three times the root mean square of the sky background fluctuations. Δ denotes the root mean square scatter of the fit in units of mag arcsec $^{-2}$.

et al. 2012; Yıldırım et al. 2015) and NGC 1332 (Rusli et al. 2011). In addition to these, the elliptical galaxy NGC 4291 has also been claimed to be a $\sim 3.6\sigma$ outlier above the (black hole mass)-(spheroid mass) scaling relation (Bogdán et al. 2012). Obviously, having both the black hole mass and the spheroid mass correct is important for placing systems in the (black hole mass)-(spheroid mass) diagram.

At present, for early-type galaxies, the spheroid luminosity and the galaxy luminosity can be used to predict the black hole mass with the same level of accuracy⁶ (Savorgnan et

⁶ Note that Läsker et al. (2014b) reported that the spheroid luminosity and the galaxy luminosity are equally good tracers of the

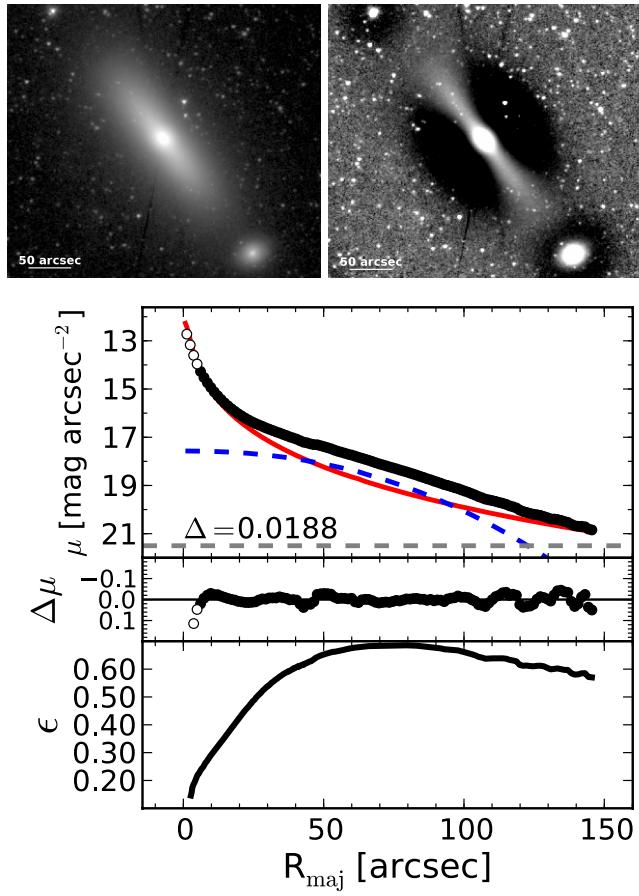


Figure 3. NGC 1332. Similar to Figure 2. The surface brightness profile extends out to seven galaxy half-light radii ($\sim 7 \times 20$ arcsec). The empty points are data excluded from the fit.

al. 2015). If a galaxy hosts a black hole that is over-massive compared to expectations from the spheroid luminosity, but whose mass is normal compared to expectations from the galaxy luminosity, one should wonder whether the spheroid luminosity might have been underestimated due to an inaccurate spheroid/disc decomposition. Indeed, none of the five galaxies just mentioned (Mrk 1216, NGC 1271, NGC 1277, NGC 1332, and NGC 4291) is a noticeable outlier in the (black hole mass)-(galaxy luminosity) diagram. In Figure 5 we show the location of these five galaxies in the updated (black hole mass)-(spheroid stellar mass) diagram for early-type galaxies from Savorgnan et al. (2015). Figure 5 was populated using the galaxy decomposition technique shown here and extensively described in Savorgnan & Graham (2015). Briefly, we obtained Spitzer/IRAC 3.6 μm images for 45 early-type galaxies which already had a dynam-

black hole mass irrespective of the galaxy morphological type, but their sample of 35 galaxies contained only 4 spiral galaxies. However, using a sample of 45 early-type and 17 spiral galaxies, Savorgnan et al. (2015) shows that, when considering all galaxies irrespective of their morphological type, the correlation of the black hole mass with the spheroid luminosity is better than that with the galaxy luminosity.

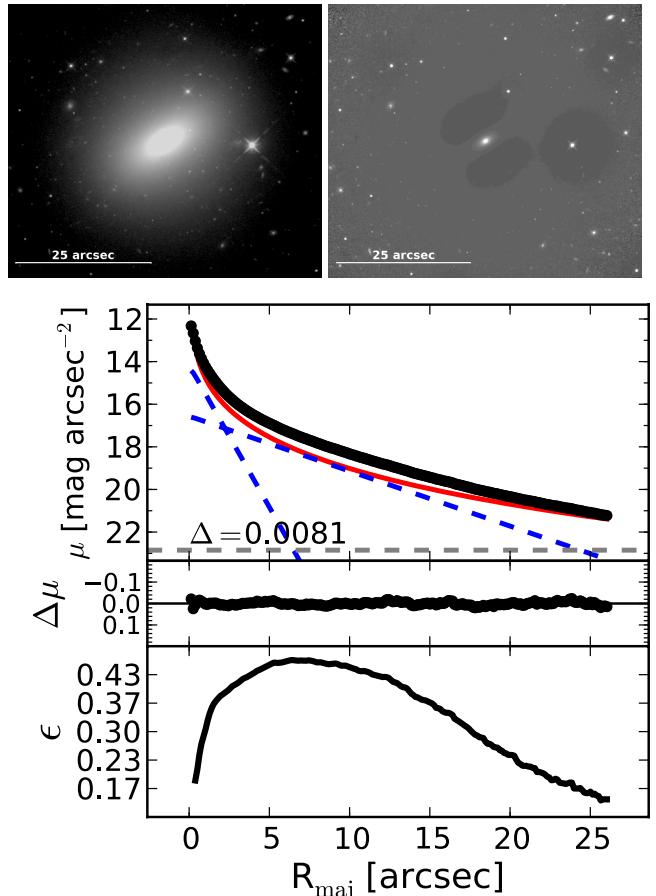


Figure 4. Mrk 1216. Similar to Figure 2. The top panels are the *HST*/WFC3 $F160W$ image (left) and its unsharp mask (right). The surface brightness profile extends out to five galaxy half-light radii ($\sim 5 \times 5$ arcsec). The color lines represent the individual (PSF-convolved) model components: red solid = Sérsic (spheroid), blue dashed = exponential (nuclear and intermediate-scale disc).

ical detection of their black hole mass. We modelled their one-dimensional surface brightness profiles with a combination of analytic functions, using one function per galaxy component. Spheroid luminosities were converted into stellar masses using individual, but almost constant mass-to-light ratios (~ 0.6 , Meidt et al. 2014).

In Figure 5, we show the galaxies Mrk 1216, NGC 1271 and NGC 1277, which were not a part of the original sample of 45 early-type galaxies. For the galaxy NGC 1271, we use the black hole mass measurement and the stellar mass-to-light ratio obtained by Walsh et al. (2015). For the galaxy NGC 1277, we use the black hole mass measurement obtained by van den Bosch et al. (2012) and the stellar mass-to-light ratio obtained by Martín-Navarro et al. (2015). For the galaxy Mrk 1216, we use the upper limit on the black hole mass and the stellar mass-to-light ratio obtained by Yıldırım et al. (2015). For the first time, Figure 5 reveals that when the four intermediate-scale disc galaxies Mrk 1216, NGC 1271, NGC 1277, NGC 1332, and the elliptical galaxy NGC 4291 are properly modelled, they no longer appear as extreme

outliers above the (black hole mass)-(spheroid stellar mass) correlation for early-type galaxies, i.e. they all reside well within a 3σ deviation from the correlation.

4 ORIGIN OF COMPACT MASSIVE GALAXIES

Acknowledging the correct structure of galaxies with intermediate-scale discs is important to properly understand their origin. According to the current paradigm of cosmological structure evolution, the genesis of massive early-type galaxies is characterized by two distinct phases: “in-situ” and “ex-situ”. The first phase takes place in a young Universe (within its first 4 Gyr), when cold gas inflows produced short and intense bursts of star formation that created compact and dense conglomerates of stars with high velocity dispersion (e.g. Prieto et al. 2013). These naked and compact conglomerates, named “red nuggets” (Damjanov et al. 2009), have been observed at high-redshift with half-light sizes of 1–2 kpc (Daddi et al. 2005; Trujillo et al. 2006; van Dokkum et al. 2008). In the second phase (last 10 Gyr), discs and stellar envelopes were accreted around these primordial conglomerates and the external parts of today’s galaxies assembled on scales of 2–20 kpc (e.g. Driver et al. 2013).

Today’s Universe is populated by an abundance of compact, massive spheroids, with the same physical properties – mass and compactness – as the high-redshift red nuggets (Graham 2013; Graham et al. 2015). Some of these local compact massive spheroids are encased within a large-scale disc, that is to say they are the bulges of some lenticular and spiral galaxies. Over the last 10 Gyr their spheroids have evolved by growing a relatively flat disc (e.g. Pichon et al. 2011; Danovich et al. 2012; Stewart et al. 2013) – rather than a three-dimensional envelope – which has increased the galaxy size but preserved the bulge compactness. **Of course some lenticular/ES galaxies may have been built from mergers (e.g. Querejeta et al. 2015, and references therein).** The other compact massive spheroids of today’s Universe belong to some galaxies with intermediate-scale discs. Indeed, Mrk 1216, NGC 1271, NGC 1277, NGC 1332, and NGC 3115 are all local compact intermediate-scale disc galaxies with purely old (> 10 Gyr) stellar populations. These galaxies have undergone the lowest degree of disc growth.

In addition to the observational clues as to the actual physical components in galaxies with intermediate-scale discs, one can reason on other grounds as to why these compact galaxies are not comprised of an inner bulge plus large-scale disc plus outer envelope. If they were such three-component systems, then one would have two possibilities. The first possibility is that these galaxies were already fully assembled 10 Gyr ago; this would explain their old stellar populations, but it would also imply that their discs and envelopes had already formed during the first 4 Gyr of the Universe, in disagreement with the current cosmological picture. The second possibility is that only their inner bulges (with sizes of 0.1–0.2 kpc, according to past decompositions) originated in the first 4 Gyr and they subsequently accreted a substantial disc and envelope. If this was correct, then we would observe high-redshift, star-like, naked bulges with stellar masses within a factor of a few times the currently observed red nuggets but sizes which are 10 times smaller. However,

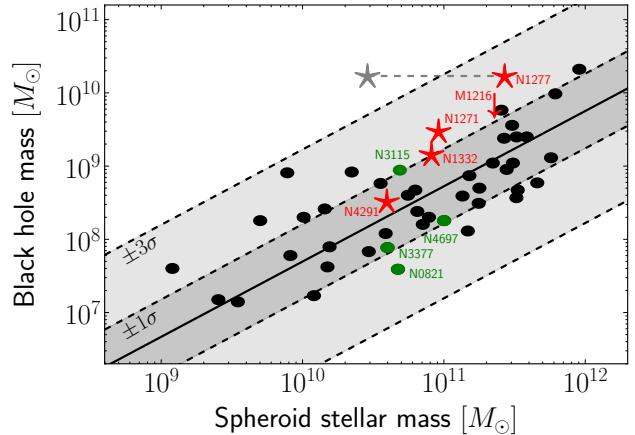


Figure 5. Black hole mass plotted against spheroid stellar mass for 45+3 early-type galaxies (from Savorgnan et al. 2015). The black solid line is the bisector linear regression for all galaxies except Mrk 1216, NGC 1271 and NGC 1277. The dashed lines mark the 1σ and 3σ deviations, where σ (0.51 dex) is the total rms scatter about the correlation in the black hole mass direction. The red symbols mark five galaxies that were claimed to be extreme outliers in this diagram: four intermediate-scale disc galaxies (Mrk 1216, NGC 1271, NGC 1277 and NGC 1332) and one elliptical galaxy (NGC 4291). All five reside well within a 3σ deviation from the correlation when using their correct spheroid stellar mass (van den Bosch et al. 2012) in gray. The green color is used to show the location of four additional intermediate-scale disc galaxies mentioned in Section 2.

a dramatically different expectation is reached if one considers these galaxies today as spheroid-dominated systems with an intermediate-scale disc; in this case, both the galaxy size and the spheroid size are compact (1–2 kpc). This implies that, among the local descendants of the high-redshift red nuggets, the compact intermediate-scale disc galaxies have undergone the lowest degree of disc growth. That is, the bulk of a compact intermediate-scale disc galaxy quickly assembled “in-situ” in a very young Universe and experienced very little evolution over the last 10 Gyr.

4.1 ES galaxies in the Hubble grid

The existence of intermediate-scale discs has led to the suggestion of a likely continuum of disc sizes in early-type galaxies (Simien & de Vaucouleurs 1986; Capaccioli et al. 1988; Bender 1989; Simien & Michard 1990; Scorsa 1993; Scorsa & van den Bosch 1998) as opposed to a dichotomy of say nuclear discs versus large-scale discs. The presence of these intermediate-scale discs blurs the distinction between elliptical (E) and lenticular (S0) galaxies, or central slow-rotators (SR) versus central fast-rotators (FR), see Cappellari et al. (2011, their Figure 1 and 2). There is a need for more than two bins (i.e. nuclear vs. large-scale disc, E vs. S0, SR

vs. FR), and a need for a continuum in the (Hubble-Jeans)-like classification schemes⁷.

It has been argued that the classification scheme for "elliptical" galaxies should not be their apparent axis ratio as seen on the plane of the sky (originally E0–E7, then E0–E4, see Hubble 1936; Sandage 1961; Liller 1966; Cappellari et al. 2011), because this depends on the viewing angle rather than being intrinsic to the galaxy. Obviously when dealing with intermediate-scale discs, the boxy/discy shape of the isophotes is also a function of both radius and disc inclination, making single isophotal shape parameters problematic and particularly inappropriate for the ES class. Section 4 of Kormendy Bender (1996) points out additional complications in regard to this. Instead, early-type galaxies would be better quantified by their spheroid-to-total flux ratio, with a continuum from pure elliptical galaxies to disc-dominated lenticular galaxies (e.g., Capaccioli et al. 1988, and references therein). This spheroid-to-total flux (or better mass) ratio is widely recognised as an important quantity, and its broad range observed in the lenticular galaxies led Cappellari et al. (2011b) to present the "Hubble comb". Building on van den Bergh's (1976) diagram in which both late-type galaxies (i.e., spiral galaxies) and early-type galaxies form separate prongs of an expanded Hubble-Jeans tuning fork, with an additional prong for disc galaxies hosting anaemic spiral patterns, Cappellari et al. (2011b, see also Kormendy Bender 2012) presented a scheme in which the morphological type (a, b, c, etc.) changed if the spheroid-to-total ratio changed. However the primary criteria used to assign the spiral galaxy type over the last half century (Sandage 1961) has been the nature of the spiral arms — the extent to which they are unwound, pitch angle, and the degree of resolution — rather than the spheroid-to-total ratio. Indeed, in the Hubble Atlas of Galaxies, Sandage (1961) notes that Sa type galaxies exist with both small and large bulges.

The grid seen in Figure 6 and discussed in Graham (2014) was used by Freeman (1970, his Figure 9), Borošon (1981), Kent (1985), Kodaira et al. (1986), Simien de Vaucouleurs (1986) and others, and allows for the varying spheroid-to-total ratio among each galaxy type. Rather than using the extended classification scheme for early-type galaxies (E - E⁺ - L⁻ - L^o - L⁺-S0, corresponding to the numerical T-type ranging from -5 to 0, e.g., de Vaucouleurs et al. 1964, Heidmann et al. 1972), we have simply grouped them all together. While, collectively, spiral galaxies typically display a range of spheroid-to-total flux ratios from 0 to 3/4 (e.g. Graham Worley 2008, and references therein), lenticular galaxies commonly display a range from 3/4 to

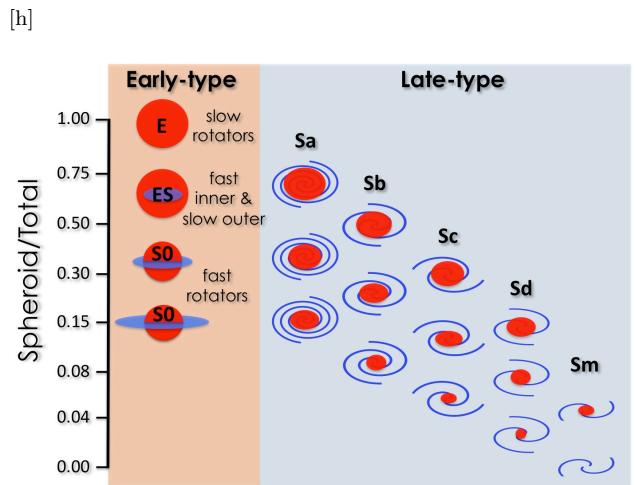


Figure 6. The Hubble grid showing the location of the ES galaxies, intermediate between elliptical (E) and lenticular (S0) galaxies, relative to the spiral galaxies.

0.1 (Laurikainen et al. 2010), and the ES class have larger ratios. The purpose here is not to provide a complete classification scheme, but to simply show where the early-type galaxies with intermediate-scale discs (ES) reside relative to the other Hubble galaxy types in this familiar diagram which has tended not to include the elliptical galaxies to date.

In Figure 6, can you please move the ES galaxy to a spheroid-to-total ratio of 0.75. Common lenticular galaxies with large-scale discs are known to have ratios up to 0.75. Moving the ES galaxy in Figure 6 will therefore better match with the idea that these are intermediate between S0 and E galaxies.

5 SUMMARY AND CONCLUSIONS

Early-type galaxies display a broad distribution of spheroid-to-total flux ratios (e.g. Cappellari et al. 2011), going from disc-less, "pure" elliptical galaxies (slow rotators) to disc-dominated lenticular galaxies (central fast rotators that continue to be fast rotating also beyond one half-light radius). In between these two extremes lie galaxies with intermediate-scale discs (spheroid dominated central fast rotators that become slow rotating in their outer regions), i.e. discs of kiloparsec-size that remain "embedded" within the spheroidal component of the galaxy and do not dominate the galaxy light at large radii as large-scale discs do. While this is likely known to some readers, the surge of papers presenting galaxy decompositions which are not aware of this reality has created a pressing need for this reminder. We have shown that the light distribution of galaxies with intermediate-scale discs can be accurately described with a simple spheroid + disc (+ optional nuclear component) model, without the need for the addition of a bright envelope-component. Our decompositions correctly reproduce both the photometric (surface brightness and ellipticity profiles) and kine-

⁷ As noted by van den Bergh (1997) and Sandage (2005), it was Sir James Jeans (1928) who introduced the (tuning fork)-shaped diagram that encapsulated Hubble's (1926) elliptical-spiral sequence – itself motivated by the earlier work of Jeans (1919).

matic (specific angular momentum profile) properties of nine intermediate-scale disc galaxies. Four of these nine galaxies (Mrk 1216, NGC 1271, NGC 1277, NGC 1332) and one additional elliptical galaxy (NGC 4291) had previously been claimed to be extreme outliers in the (black hole mass)-(spheroid mass) diagram. However, here we have demonstrated that, when correctly modelled, these five galaxies all reside well within the scatter of the correlation, i.e. they do not host over-massive black holes. This serves to strengthen the (black hole mass)-(spheroid mass) relation, and rules out the need for exotic formation scenarios.

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