Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **457,** 320–327 (2016) doi:10.1093/mnras/stv2713

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

Giulia A. D. Savorgnan* and Alister W. Graham
Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia

Accepted 2015 November 17. Received 2015 November 10; in original form 2015 September 22

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: individual: Mrk 1216, NGC 1271, NGC 1277, NGC 1332, NGC 4291 – galaxies: structure.

1 INTRODUCTION

The awareness that *many* early-type galaxies contain previously overlooked stellar discs dates back half a century (Liller 1966; Strom & Strom 1978; Michard 1984; Djorgovski 1985; Bender & Moellenhoff 1987; Jedrzejewski 1987a; Capaccioli 1987; Carter 1987; Capaccioli, Piotto & Rampazzo 1988). 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, Illingworth & Heckman 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. 2011a), 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 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' galaxies. 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, Capaccioli & Held (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). However, as noted by Nieto et al. (1988), unless the

---

* E-mail: gsavorgn@astro.swin.edu.au

Published by Oxford University Press on behalf of the Royal Astronomical Society

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; Bender & Moellenhoff 1987; Ebneter et al. 1987; Jedrzejewski 1987a; Bender 1988; Bijaoui, Marchal & Michard 1989).

Today, most early-type galaxies are classified as 'fast rotators' (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.[1] 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.

In general, stellar discs are intrinsically flat and close to circular (e.g. Andersen et al. 2001; Andersen & Bershady 2002); 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; Bender & Moellenhoff 1987; Capaccioli 1987; Jedrzejewski 1987a) and checking the velocity line profiles for asymmetry (e.g. Franx & Illingworth 1988; Bender 1990; Rix & White 1992; Scorza & Bender 1995, and references therein; Scorza 1998).

Building on the investigations in works such as Liller (1966), Jedrzejewski (1987a) and Rix & White (1990), the toy model shown in Fig. 1 illustrates the typical 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: (1) 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; (2) 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 (3) an elliptical galaxy with an additional nuclear stellar disc, i.e. a (spheroid-dominated) slow rotator. This sequence is analogue to that illustrated in fig. 2 of Cappellari et al. (2011b), 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.

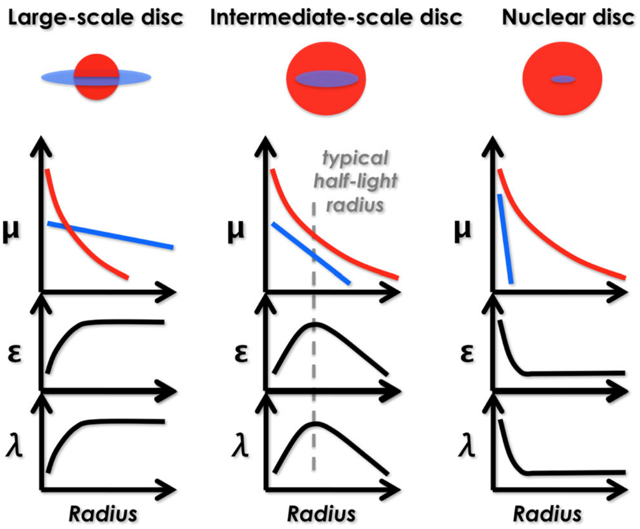

Figure 1. Illustration of the spheroid/disc decomposition of the one-dimensional surface brightness profile, μ, the ellipticity profile, ϵ, and the specific angular momentum profile, λ, for the three prototype early-type galaxy sub-classes. In the flux decompositions, the spheroid (or bulge) and the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

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. This has led to the rejection of many early-type galaxy decompositions similar to that illustrated in the top middle panel of Fig. 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; Méndez-Abreu & CALIFA Team 2015; Querejeta et al. 2015).

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 kinematic analysis has the advantage of being virtually insensitive to inclination effects, but cannot help one determine the radial extent of a disc if the kinematic 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)

---

[1] As pointed out by Cappellari et al. (2011a), while all of the disky ellipticals from Bender, Saglia & Gerhard (1994) are fast rotators, the complement is not true because weak discs only impact the isophotal shape if the discs have orientations close to edge-on, whereas their rotational signature can still be detected when they have a near face-on orientation. Of course if a disc is face-on, then the galaxy will not be classified as a fast rotator.

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.

2 INTERMEDIATE-SCALE DISC GALAXIES

Three examples of galaxies with intermediate-scale discs are Mrk 1216, NGC 1332, and NGC 3115. In the following section, 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 μm 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 the IRAF[2] task `ellipse`[3] (Jedrzejewski 1987b). 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; Scorza & Bender 1995) is obvious due to its edge-on orientation (Fig. 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 (Fig. 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 (∼2 arcsec × 50 arcsec), and the rotation significantly drops at larger radii. The unsharp mask of NGC 3115 (Fig. 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 semimajor-axis length $R_{\rm maj} \sim 15$ arcsec). Such rings are common in early-type galaxies (e.g. 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 fitted 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.

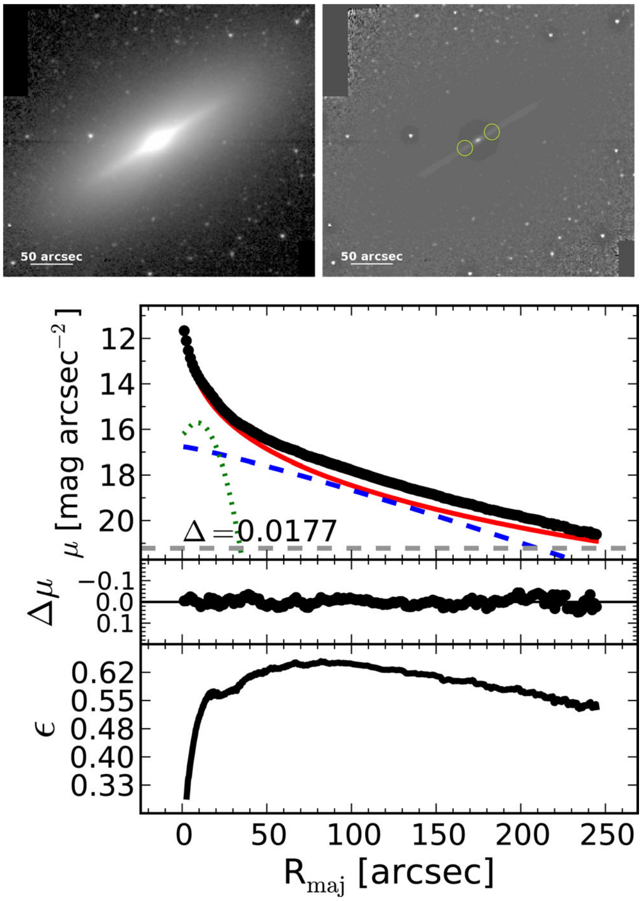

Figure 2. NGC 3115. The top panels are the *Spitzer*/IRAC 3.6 μm image (left) and its unsharp mask (right), obtained by dividing the image by a Gaussian-smoothed version of itself. In the unsharp mask, the green circles indicate the position of the two brighter spots associated with the edge-on nuclear ring. The bottom plots display the best-fitting model of the surface brightness profile, μ, and the ellipticity profile, ϵ, along the major axis, $R_{\rm maj}$. The black points are the observed data, which extend out to five galaxy half-light radii (∼5 arcsec × 50 arcsec). The colour 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 grey 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}.

In comparison, Läsker, Ferrarese & van de Ven (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

---

[2] 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 under cooperative agreement with the National Science Foundation.

[3] 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.

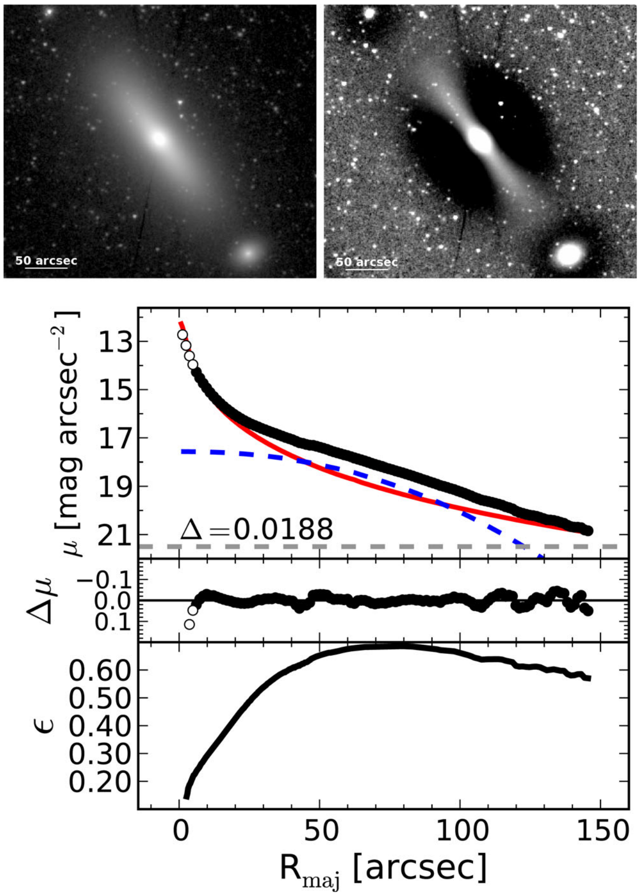

Figure 3. NGC 1332. Similar to Fig. 2. The surface brightness profile extends out to seven galaxy half-light radii (∼7 arcsec × 20 arcsec). The empty points are data excluded from the fit.

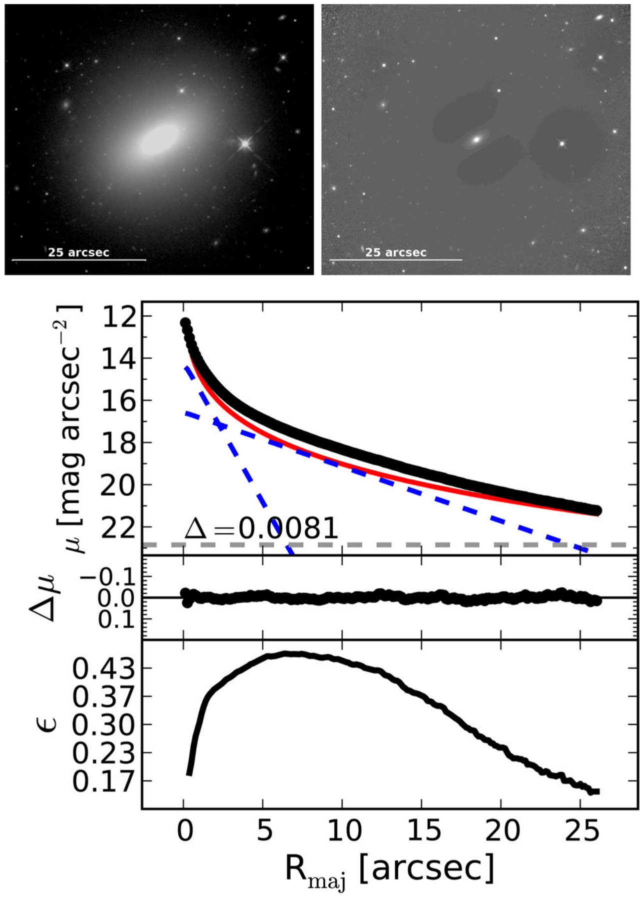

Figure 4. Mrk 1216. Similar to Fig. 2. The top panels are the *HST*/WFC3 *F160W* image (left) and its unsharp mask (right). The surface brightness profile extends out to five galaxy half-light radii (∼5 arcsec × 5 arcsec). The colour lines represent the individual (PSF-convolved) model components: red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

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 (Fig. 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 depleted 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 (Fig. 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 (Fig. 4), the velocity map (Yıldırım et al. 2015) reveals the presence of a fast rotating component within three galaxy half-light radii (∼3 arcsec × 5 arcsec). The ellipticity profile (Fig. 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 ($R_{\rm maj} \sim 1-2$ 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 (Fig. 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 preparation) and Graham et al. (2015a), 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. (2015b) 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. Davies 1981; Carter 1987; Jedrzejewski, Davies & Illingworth 1987) 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 overmassive 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. 2015b), NGC 1277 (van den Bosch et al. 2012; Walsh et al. 2015a; 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 an $\sim 3.6\sigma$ 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 accuracy[4] (Savorgnan et al. 2015). If a galaxy hosts a black hole that is overmassive 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,

---

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

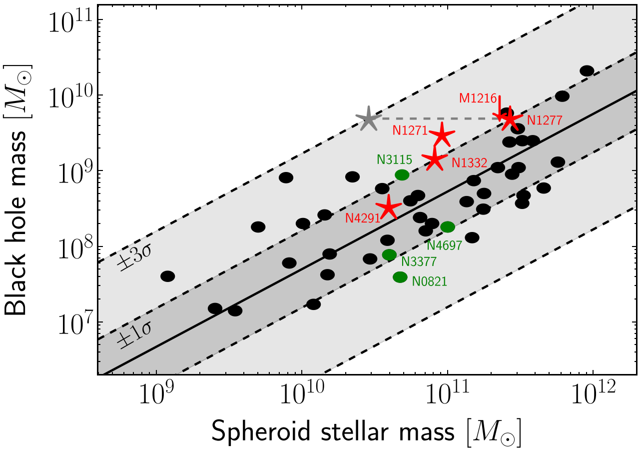

Figure 5. Black hole mass plotted against spheroid stellar mass for 45 + 3 early-type galaxies (from Savorgnan et al. 2015). The black solid line is the bisector linear regression for all galaxies except Mrk 1216, NGC 1271, and NGC 1277. The dashed lines mark the 1σ and 3σ deviations, where σ (0.51 dex) 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 mass. For NGC 1277, we show the previously reported spheroid stellar mass (van den Bosch et al. 2012) in grey. The green colour is used to show the location of four additional intermediate-scale disc galaxies mentioned in Section 2.

NGC 1332, and NGC 4291) is a noticeable outlier in the (black hole mass)–(galaxy luminosity) diagram. In Fig. 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). Fig. 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 dynamical 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 Fig. 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. (2015b). For the galaxy NGC 1277, we use the black hole mass measurement obtained by Walsh et al. (2015a) and the stellar mass-to-light ratio obtained by Martín-Navarro et al. (2015). Note that for NGC 1277, we recover a spheroid stellar mass of 2.7×10^{11} $M_\odot$, in agreement with the value of $\approx$1-2 $\times 10^{11}$ $M_\odot$ obtained by Emsellem (2013) from his multi-Gaussian expansion models.[5] 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, Fig. 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, Jimenez & Haiman 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, Dullo & Savorgnan 2015b). 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, 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

---

[5] In Emsellem (2013), readers will find a clever discussion of the problematics associated with the definition and the identification of the 'bulge' component in a galaxy.

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.

5 SUMMARY AND CONCLUSIONS

Early-type galaxies display a broad distribution of spheroid-to-total flux ratios (e.g. Cappellari et al. 2011b), 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 kinematic (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 overmassive black holes. This serves to strengthen the (black hole mass)–(spheroid mass) relation, and rules out the need for exotic formation scenarios.

ACKNOWLEDGEMENTS

This research was supported by Australian Research Council funding through grant FT110100263. GS is grateful to Matteo Fossati, Luca Cortese and Giuseppe Gavazzi for useful comments and discussion. The publication of this paper would not have been possible without the invaluable support of Chris Blake and Duncan Forbes. We warmly thank our anonymous referee for their very careful review of our paper, and for the comments, corrections and suggestions that ensued. This work is based on observations made with the IRAC instrument (Fazio et al. 2004) on-board the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA, and also on observations made with the NASA/ESA *HST*, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSA). This research has made use of the GOLDMine data base (Gavazzi et al. 2003) and the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Allen P. D., Driver S. P., Graham A. W., Cameron E., Liske J., de Propris R., 2006, MNRAS, 371, 2
Andersen D., Bershady M. A., 2002, in Athanassoula E., Bosma A., Mujica R., eds, ASP Conf. Ser. Vol. 275, Disks of Galaxies: Kinematics, Dynamics and Peturbations. Astron. Soc. Pac., San Francisco, p. 39
Andersen D. R., Bershady M. A., Sparke L. S., Gallagher J. S., III, Wilcots E. M., 2001, ApJ, 551, L131
Arnold J. A., Romanowsky A. J., Brodie J. P., Chomiuk L., Spitler L. R., Strader J., Benson A. J., Forbes D. A., 2011, ApJ, 736, L26
Arnold J. A. et al., 2014, ApJ, 791, 80
Bender R., 1988, A&A, 193, L7
Bender R., 1990, A&A, 229, 441
Bender R., Moellenhoff C., 1987, A&A, 177, 71
Bender R., Saglia R. P., Gerhard O. E., 1994, MNRAS, 269, 785
Bijaoui A., Marchal J., Michard R., 1989, in Corwin H. G., Jr, Bottinelli L., eds, World of Galaxies (Le Monde des Galaxies), p. 250
Bogdán Á. et al., 2012, ApJ, 753, 140
Capaccioli M., 1987, in de Zeeuw P. T., ed., Proc. IAU Symp. 127, Structure and Dynamics of Elliptical Galaxies. Reidel, Dordrecht, p. 47
Capaccioli M., Piotto G., Rampazzo R., 1988, AJ, 96, 487
Cappellari M. et al., 2007, MNRAS, 379, 418
Cappellari M. et al., 2011a, MNRAS, 413, 813
Cappellari M. et al., 2011b, MNRAS, 416, 1680
Carter D., 1978, MNRAS, 182, 797
Carter D., 1987, ApJ, 312, 514
Ciambur B. C., 2015, ApJ, 810, 120
Cinzano P., van der Marel R. P., 1993, in Danziger I. J., Zeilinger W. W., Kjär K., eds, Eur. South. Obs. Conf. Workshop Proc. Vol. 45. Structure, Dynamics and Chemical Evolution of Elliptical Galaxies, p. 105
D'Onofrio M., Zaggia S. R., Longo G., Caon N., Capaccioli M., 1995, A&A, 296, 319
Daddi E. et al., 2005, ApJ, 626, 680
Damjanov I. et al., 2009, ApJ, 695, 101
Danovich M., Dekel A., Hahn O., Teyssier R., 2012, MNRAS, 422, 1732
Davies R. L., 1981, MNRAS, 194, 879
di Tullio G. A., 1979, A&AS, 37, 591
Djorgovski S. B., 1985, PhD thesis, California Univ.
Driver S. P., Robotham A. S. G., Bland-Hawthorn J., Brown M., Hopkins A., Liske J., Phillipps S., Wilkins S., 2013, MNRAS, 430, 2622
Dullo B. T., Graham A. W., 2014, MNRAS, 444, 2700
Ebneter K., Davis M., Jeske N., Stevens M., 1987, BAAS, 19, 681
Emsellem E., 2013, MNRAS, 433, 1862
Emsellem E. et al., 2007, MNRAS, 379, 401
Emsellem E. et al., 2011, MNRAS, 414, 888
Fazio G. G. et al., 2004, ApJS, 154, 10
Ferrarese L. et al., 2006, ApJS, 164, 334
Franx M., Illingworth G. D., 1988, ApJ, 327, L55
Franx M., Illingworth G., Heckman T., 1989, ApJ, 344, 613
Gadotti D. A., 2008, MNRAS, 384, 420
Gavazzi G., Boselli A., Donati A., Franzetti P., Scodeggio M., 2003, A&A, 400, 451
Graham A. W., Colless M. M., Busarello G., Zaggia S., Longo G., 1998, A&AS, 133, 325
Graham A. W., Erwin P., Trujillo I., Asensio Ramos A., 2003, AJ, 125, 2951
Graham A. W., Durré M., Savorgnan G. A. D., Batcheldor D., Watson B., Medling A., Scott N., Marconi A., 2015a, ApJ, Submitted
Graham A. W., Dullo B. T., Savorgnan G. A. D., 2015b, ApJ, 804, 32
Head J. T. C. G., Lucey J. R., Hudson M. J., Smith R. J., 2014, MNRAS, 440, 1690
Jedrzejewski R. I., 1987a, in de Zeeuw P. T., ed., Proc. IAU Symp. 127, Structure and Dynamics of Elliptical Galaxies. Reidel, Dordrecht, p. 37
Jedrzejewski R. I., 1987b, MNRAS, 226, 747
Jedrzejewski R. I., Davies R. L., Illingworth G. D., 1987, AJ, 94, 1508
Kormendy J., Bender R., 2012, ApJS, 198, 2
Krajnović D. et al., 2013, MNRAS, 432, 1768
Läsker R., Ferrarese L., van de Ven G., 2014a, ApJ

Läsker R., Ferrarese L., van de Ven G., Shankar F., 2014b, ApJ
Liller M. H., 1966, ApJ, 146, 28
McElroy D. B., 1983, ApJ, 270, 485
Marconi A., Hunt L. K., 2003, ApJ, 589, L21
Martín-Navarro I., La Barbera F., Vazdekis A., Ferré-Mateu A., Trujillo I., Beasley M. A., 2015, MNRAS, 451, 1081
Meidt S. E. et al., 2014, ApJ, 788, 144
Méndez-Abreu J., CALIFA Team 2015, in Cenarro A. J., Figueras F., Hernández-Monteagudo C., Trujillo Bueno J., Valdivielso L., eds, Proceedings of the XI Scientific Meeting of the Spanish Astronomical Society, Highlights of Spanish Astrophysics VIII. Teruel, p. 268
Michard R., 1984, A&A, 140, L39
Michard R., Marchal J., 1993, A&AS, 98, 29
Moffat A. F. J., 1969, A&A, 3, 455
Nieto J.-L., Capaccioli M., Held E. V., 1988, A&A, 195, L1
Nieto J.-L., Bender R., Arnaud J., Surma P., 1991, A&A, 244, L25
Pastrav B. A., Popescu C. C., Tuffs R. J., Sansom A. E., 2013, A&A, 553, A80
Petrou M., 1981, MNRAS, 196, 933
Pichon C., Pogosyan D., Kimm T., Slyz A., Devriendt J., Dubois Y., 2011, MNRAS, 418, 2493
Prieto J., Jimenez R., Haiman Z., 2013, MNRAS, 436, 2301
Querejeta M., Eliche-Moral M. C., Tapia T., Borlaff A., Rodríguez-Pérez C., Zamorano J., Gallego J., 2015, A&A, 573, A78
Rix H.-W., White S. D. M., 1990, ApJ, 362, 52
Rix H.-W., White S. D. M., 1992, MNRAS, 254, 389
Romanowsky A. J., Fall S. M., 2012, ApJS, 203, 17
Rusli S. P., Thomas J., Erwin P., Saglia R. P., Nowak N., Bender R., 2011, MNRAS, 410, 1223
Savorgnan G. A. D., Graham A. W., 2015, ApJ, preprint (arXiv:1511.07446S)
Savorgnan G. A. D., Graham A. W., Marconi A., Sani E., 2015, ApJ, preprint (arXiv:1511.07437)
Scorza C., 1998, in Aguilar A., Carraminana A., eds, IX Latin American Regional IAU Meeting, Focal Points in Latin American Astronomy. p. 117
Scorza C., Bender R., 1995, A&A, 293, 20
Scott N., Davies R. L., Houghton R. C. W., Cappellari M., Graham A. W., Pimbblet K. A., 2014, MNRAS, 441, 274
Sérsic J. L., 1963, Bull. Argentina Assoc. Astron., 6, 41
Simien F., Michard R., 1990, A&A, 227, 11
Stewart K. R., Brooks A. M., Bullock J. S., Maller A. H., Diemand J., Wadsley J., Moustakas L. A., 2013, ApJ, 769, 74
Strom S. E., Strom K. M., 1978, AJ, 83, 732
Strom K. M., Strom S. E., Jensen E. B., Moller J., Thompson L. A., Thuan T. X., 1977, ApJ, 212, 335
Trujillo I. et al., 2006, MNRAS, 373, L36
van den Bosch R. C. E., Gebhardt K., Gültekin K., van de Ven G., van der Wel A., Walsh J. L., 2012, Nature, 491, 729
van Dokkum P. G. et al., 2008, ApJ, 677, L5
Walsh J. L., van den Bosch R. C. E., Gebhardt K., Yıldırım A., Richstone D. O., Gültekin K., Husemann B., 2015a, preprint (arXiv:1511.04455)
Walsh J. L., van den Bosch R. C. E., Gebhardt K., Yildirim A., Gültekin K., Husemann B., Richstone D. O., 2015b, ApJ, 808, 183
Yıldırım A., van den Bosch R. C. E., van de Ven G., Husemann B., Lyubenova M., Walsh J. L., Gebhardt K., Gültekin K., 2015, MNRAS, 452, 1792

This paper has been typeset from a TEX/LATEX file prepared by the author.