THE (BLACK HOLE)-BULGE MASS SCALING RELATION AT LOW MASSES

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Received 2014 August 21; accepted 2014 October 27; published 2014 December 19

ABSTRACT

Several recent papers have reported on the occurrence of active galactic nuclei (AGNs) containing undermassive black holes relative to a linear scaling relation between black hole mass ($M_{\text{bh}}$) and host spheroid stellar mass ($M_{\text{sph}}$). However, dramatic revisions to the $M_{\text{bh}}$–$M_{\text{sph}}$ and $M_{\text{bh}}$–$L_{\text{sph}}$ relations, based on samples containing predominantly inactive galaxies, have recently identified a steeper relation at $M_{\text{bh}} \lesssim (2-10)\times10^9M_\odot$, roughly corresponding to $M_{\text{sph}} \lesssim (0.3-1)\times10^{11}M_\odot$. We show that this step, quadratic-like $M_{\text{bh}}$–$M_{\text{sph}}$ relation defined by the Sérsic galaxies, i.e., galaxies without partially depleted cores, roughly tracks the apparent offset of the AGN having $10^8 \lesssim M_{\text{bh}}/M_\odot \lesssim 0.5 \times 10^8$. That is, these AGNs are not randomly offset with low black hole masses, but also follow a steeper (nonlinear) relation. As noted by Busch et al., confirmation or rejection of a possible AGN offset from the steeper $M_{\text{bh}}$–$M_{\text{sph}}$ relation defined by the Sérsic galaxies will benefit from improved stellar mass-to-light ratios for the spheroids hosting these AGNs. Several implications for formation theories are noted. Furthermore, reasons for possible under- and overmassive black holes, the potential existence of intermediate mass black holes ($<10^5M_\odot$), and the new steep (black hole)–(nuclear star cluster) relation, $M_{\text{bh}} \propto M_{\text{nc}}^{2.7\pm0.7}$, are also discussed.

Key words: black hole physics – galaxies: bulges – galaxies: fundamental parameters – galaxies: nuclei

Supporting material: machine-readable table

1. INTRODUCTION

Several years ago, Graham (2007a, 2008a, 2008b) and Hu (2008) reported on galaxies whose black hole masses, $M_{\text{bh}}$, appeared undermassive relative to expectations based on their stellar velocity dispersion, $\sigma$. This apparent sub-structure in the $M_{\text{bh}}$–$\sigma$ diagram (Ferrarese & Merritt 2000; Gebhardt et al. 2000) was due to barred galaxies located, on average, 0.3 dex in the $M_{\text{bh}}$ direction below the $M_{\text{bh}}$–$\sigma$ relation defined by barless galaxies. Graham & Li (2009) subsequently revealed that galaxies with active galactic nuclei (AGNs) also display this same general separation in the $M_{\text{bh}}$–$\sigma$ diagram, supporting the earlier introduction of barred-, barless-, and elliptical-galaxy $M_{\text{bh}}$–$\sigma$ relations (see also Gültekin et al. 2009; Greene et al. 2010). It was noted from the start that either the black hole masses could be low in the barred galaxies or that an elevated velocity dispersion may account for their apparent offset in the $M_{\text{bh}}$–$\sigma$ diagram. Hartmann et al. (2014); see also Brown et al. 2013; Debattista et al. 2013; Monari et al. 2014) have recently used simulations to demonstrate that the observed offset is an expected result from bar dynamics, which inflate the measured velocity dispersion by exactly the amount observed (Graham et al. 2011). Given that this can fully account for the offsets in the $M_{\text{bh}}$–$\sigma$ diagram, it implies that the barred galaxies do not possess undermassive black holes, and thus should not be offset in the black hole mass–spheroid mass ($M_{\text{bh}}$–$M_{\text{sph}}$) diagram.

A few papers (e.g., Jiang et al. 2011a; Jiang et al. 2013; Mathur et al. 2012; Reines et al. 2013), however, have shown that there is an offset at the low-mass end of the $M_{\text{bh}}$–$M_{\text{sph}}$ diagram, such that the black hole mass is lower than predicted by the near-linear $M_{\text{bh}}$–$M_{\text{sph}}$ relation established using galaxies having predominantly higher-mass black holes. These offset galaxies have been labeled by some to contain pseudobulges—spheroidal components thought to be produced by the secular evolution of a disk and associated with bars (Bardeen 1975; Hohl 1975; Hohl & Zang 1979; Combes & Sanders 1981; Kormendy 1982, 1993; Kormendy & Kennicutt 2004). This would agree with one of the scenarios ¹ presented by Hu (2008) and Graham (2008a), and subsequently Kormendy & Bender (2011), but if correct would present a contradiction with the picture presented in the preceding paragraph. However, pseudobulges are particularly difficult to reliably identify (Wyse et al. 1997) because they can possess the same physical properties as low-mass, merger-built bulges, including Sérsic (1968) index, rotation, the presence of embedded disks, and a systematic departure from the bright end of any scaling relation that has used “effective” radii or “effective” surface brightnesses (e.g., Dominguez-Tenorio et al. 1998; Aguerri et al. 2001; Bekki 2010; Sáhà et al. 2012; Querejeta et al. 2014; Graham 2014b, 2013, and references therein).

To address the above contradiction and bypass the issue of pseudobulges, we start by noting that the near-linear scaling relations between $M_{\text{bh}}$ and host spheroid luminosity, $L_{\text{sph}}$, and also host spheroid stellar mass, $M_{\text{sph}}$ (Dressler 1989; Yee 1992; Kormendy & Richstone 1995; Magorrian et al. 1998; Marconi & Hunt 2003; Häring & Rix 2004)² have recently been shown by Graham (2012a) to provide an incomplete description of the (black hole)–spheroid relationship. In essence, the $M_{\text{bh}} \propto \sigma^4$ (Ferrarese & Merritt 2000; Merritt & Ferrarese 2001a; Graham et al. 2011; McConnell et al. 2011; Graham & Scott 2013) and $L_{\text{sph}} \propto \sigma^2$ (Davies et al. 1983; Held et al. 1992; Matković & Guzmán 2005; de Rijcke et al. 2005; Balcells et al. 2007b; Chilingarian et al. 2008; Forbes et al. 2008; Cody et al. 2009; Tortora et al. 2009; Courkchi et al. 2012) scaling relations

¹ Pseudobulges could be offset low in the $M_{\text{bh}}$–$M_{\text{sph}}$ diagram if secular evolution disproportionately increases the central bulge mass relative to the growth of the black hole.

² The linear $M_{\text{sph}}$–$M_{\text{galaxy}}$ relationship proposed by Yee (1992) pertains to the limit in massive spheroids, and it is effectively the relationship for which Magorrian et al. (1998) and Laor (2001) later provided the zero-point.
for “Sérsic spheroids” necessitates a nonlinear $M_{bh}$–$L_{sp}$ and $M_{bh}$–$M_{sp}$ relation. Sérsic spheroids are elliptical galaxies and the bulges of disk galaxies that do not have partially depleted cores; they typically have $B$-band absolute magnitudes $M_B \gtrsim -20.5 \pm 1$ mag, and Sérsic indices $n \lesssim 3–4$. Graham (2012a) pointed out that in these spheroids, one expects to find that $M_{bh} \propto L^{2.5}$ and that the relationship between $M_{bh}$ and $M_{sp}$ should be better described by a near-quadartic relation than a linear relation, as was further shown in Graham & Scott (2013) and Scott et al. (2013). As noted in these works, it is only at high masses ($M_{bh} \gtrsim 10^7 M_\odot$) that a near-linear $M_{bh}$–$M_{sp}$ relation is evident, giving rise to this “broken” scaling relation. Due to the scatter in the $M_{bh}$–$M_{sp}$ diagram, coupled with the location of the brighter Sérsic galaxies at the high-mass end of the near-quadartic $M_{bh}$–$M_{sp}$ relation, surveys that have not sufficiently probed below $M_{bh} \approx 10^4 M_\odot$ can readily miss the bend in the $M_{bh}$–$M_{sp}$ relation (e.g., Sani et al. 2011; Belflori et al. 2012; Vika et al. 2012; van den Bosch et al. 2012; McConnell & Ma 2013; Sanghvi et al. 2014; Feng et al. 2014). A steeper than linear, although not bent, relation was, however, detected early on (Laor 1998, 2001; Wandel 1999) and a number of recent theoretical works have now revealed a steepening relationship at lower masses (Dubois et al. 2012; Khandai et al. 2012; Bonoli et al. 2014; Bellovary et al. 2014), although Khandai et al. (2014, their Figure 22) does not. This would appear to be bringing things more in line with the prediction by Haehnelt et al. (1998) that $M_{bh} \propto M_{halo}^{5/3}$.

These scaling relationships are important for several reasons. Given the broken, or rather bent, $M_{bh}$–$M_{sp}$ relation, it implies that within the Sérsic galaxies, the supermassive black holes grow more rapidly than the stellar spheroids (Graham 2012a). That is, there is no tandem, lockstep growth of black holes and bulges in these galaxies: the $M_{bh}$–$M_{sp}$ relation is not a constant value. Indeed, while this (previously thought to be constant) ratio was doubled in Graham (2012a) for the massive galaxies and then increased further to an average value of 0.49% in the core–Sérsic galaxies (Graham & Scott 2013; see Laor 2001), it can be lower than $\sim 10^{-3}$ in the lower-mass Sérsic galaxies (Graham & Scott 2013; Scott et al. 2013; see also Wandel 1999). Low-mass spheroids therefore offer an even more promising domain than previously thought when assuming a constant $M_{bh}$/$M_{sp}$ mass ratio of 0.14–0.2% (Ho 1999; Merritt & Ferrarese 2001b; Haring & Rix 2004, and references therein), to find new intermediate mass black holes, i.e., those with $10^5 < M_{bh}/M_\odot < 10^8$.

An additional, related, reason pertains to feedback from supermassive black holes (e.g., Page et al. 2012; Wurster & Thacker 2013; Fanidakis et al. 2013) that is commonly thought to regulate star formation in the spheroid and provide a potential solution to the overabundance of massive galaxies predicted by dark matter only simulations. This process has been invoked to produce the turnover in the galaxy luminosity function at high luminosities (e.g., Benson et al. 2003; Bower et al. 2006; Croton et al. 2006). As noted, the near-quadartic $M_{bh}$–$M_{sp}$ relation for Sérsic spheroids flattens into a slope close to unity for the brighter core–Sérsic galaxies (Graham 2012a). The presence of a partially depleted core in these bigger spheroids is thought to indicate that they and their black hole formed through simple, additive, dry major merger events that created the near-linear (one-to-one) $M_{bh}$–$M_{sp}$ relation. The process of “mechanical” or “radio mode” AGN feedback may therefore subsequently maintain, rather than establish, this linear relation.

Here we investigate if galaxies with AGNs hosting low-mass black holes that have been reported in the literature to be offset from the near-linear $M_{bh}$–$M_{sp}$ relation (defined by predominantly massive spheroids) might simply be following the steeper relation of the Sérsic galaxies. If so, then they may not be discrepant galaxies with unusually low $M_{bh}$/$M_{sp}$ mass ratios, but rather abide by the main relation defined by the majority of galaxies today. This will have dramatic implications for cosmological hydrodynamical simulations, such as Illustris (Sijacki et al. 2014), which are tied to the near-linear $M_{bh}$–$M_{sp}$ relation. Our study has been performed using data from many authors, thereby avoiding possible biases in any one study and deriving spheroid stellar masses when not done in the original papers. In Section 2, we introduce the galaxy/black hole samples used, and in Section 3, we present their location in the $M_{bh}$–$M_{sp}$ diagram. Section 4 provides a discussion of related topics such as formation theories, expectations for intermediate mass black holes, coexistence with nuclear star clusters, and potential evolutionary pathways for possible underand overmassive black holes.

2. SAMPLE AND DATA

2.1. Reference Sample

Our initial reference sample consists of 75 galaxies with directly measured supermassive black hole masses and spheroid stellar mass determinations (Scott et al. 2013). The stellar masses were obtained by applying the $(B - K_s)$–(stellar mass-to-light ratio) relation from Bell & de Jong (2001) to the $K_s$-band magnitudes of the 75 spheroids. The initial galaxy magnitudes came from the ARCHANGEL photometry pipeline (Schombert & Smith 2012) applied to Two Micron All-Sky Survey (2MASS) (Skrutskie et al. 2006) images. Inspection of the galaxy images (G. Savorgnan et al., in preparation) has since resulted in three changes of morphological type: NGC 5845 (E → S0, with clear rotation seen by Emsellem et al. 2011); NGC 2974 (E → S0a, with faint spiral arms evident); and NGC 4388 (SB → SBCd, due to a substantial edge-on bar that had inflated past bulge estimates). This resulted in the following revised $B - K_s$ colors and $K_s$-band magnitudes for their bulges: (NGC 5845: 3.85, −21.84 mag); (NGC 2974: 3.66, −22.88 mag); and (NGC 4388: 3.72, −22.14 mag), and thus new spheroid masses following Equation (2) from Scott et al. (2013). These are shown in Table 1. The presence, or otherwise, of a partially depleted stellar core in the full sample was primarily determined from high-resolution Hubble Space Telescope imaging. Here we reclassify NGC 1332 and NGC 3998 as Sérsic galaxies based on their light profiles (Russi et al. 2011; Walsh et al. 2012), whereas in Graham & Scott (2013) and Scott et al. (2013), these galaxies had been tentatively classified as core–Sérsic galaxies based on their central velocity dispersion. In passing, we note that NGC 1332

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8 While this “mechanical” feedback may maintain the (black hole)–spheroid relation, it might not necessarily prevent strong accretion of a planar gas cloud and subsequent disk formation.

9 Some of the spheroid stellar masses used in this work are based on a statistical correction for the bulge-to-disc ratio rather than a direct measurement of the bulge luminosity and mass. For details of the correction and the additional scatter this is expected to introduce, see Graham & Scott (2013).
is a massive ($M = 10^{11} M_\odot$), compact ($R_e = 2 \text{kpc}$) early-type galaxy (G. Savorgnan et al., in preparation), with structural properties similar to NGC 1277.\footnote{We do not include NGC 1277 here because its black hole mass is currently being re-determined by us and is expected to change dramatically from its published value.} Such galaxies with properties similar to some at $z = 2 \pm 0.5$ have been claimed to be very rare in the universe today (e.g., Trujillo et al. 2014).

We also now expand our reference sample through the addition of NGC 1316 (Fornax A, $B - K_s = 3.40$, $M_K = -24.73 \text{mag}$, following Scott et al. 2013). Although we had a measurement of its black hole mass and an estimate of its bulge magnitude in Graham (2012a), we were uncertain as to whether it was a core–Sérsic or a Sérsic galaxy. Unknown to us at the time, however, Beletsky et al. (2011) had revealed the presence of a kinematically cold, nuclear stellar disk with a radius less than 200 pc in this peculiar, barred lenticular galaxy, expanding on the discovery by D’Onofrio (2001). At odds with the initial classification in Faber et al. (1997), NGC 1316 therefore does not possess a partially depleted stellar core.

Finally, Licquia & Newman (2014) have provided a stellar mass estimate for the bulge of the Milky Way, enabling us to also now include our own galaxy. We have taken the associated black hole mass from Chatzopoulos et al. (2014). This gives us a final sample of 77 galaxies with directly measured black hole masses. The changes since Scott et al. (2013) that are mentioned above are captured in Table 1. It is also noted that four of the galaxies listed there have particularly high $M_{bh}/M_{\text{bulge}}$ ratios. Given the small degree of change to the initial sample of 75 galaxies, we do not re-derive the $M_{bh}-M_{\text{bulge}}$ scaling relations given in Scott et al. (2013) for the core–Sérsic and Sérsic galaxies. However, it is noted that the denominator in Equation (4) from Scott et al. (2013) pertaining to the Sérsic galaxies contains a typographical error and should read $2 \times 10^{10}$ rather than $3 \times 10^{10}$.

### 2.2. Undermassive Black Hole Candidates

Our sample of galaxies in Tables 2 and 3 with allegedly undermassive black holes, at least relative to the single, near-linear $M_{bh}-M_{\text{bulge}}$ relation defined by predominantly massive galaxies, has come from the following papers.

Jiang et al. (2013) report that UM 625 falls below the $M_{bh}-M_{\text{bulge}}$ relation. They report a virial black hole mass of $1.6 \times 10^6 M_\odot$, a V-band bulge magnitude of $-19.06 \text{mag}$ (accounting for 60\% of this S0 galaxy’s light), and a V-band stellar mass-to-light ratio of $1.6 M_\odot/L_\odot$, which yields a bulge stellar mass of $5.4 \times 10^8 M_\odot$.

11\footnote{Yuan et al. (2014) include two additional galaxies with million solar mass black holes, but no bulge/disk decomposition is available for them.} Yuan et al. (2014) report on virial masses for two elliptical galaxies,\footnote{SDSS J004042.10110957.6 ($M_{bh} = 1.22 \times 10^6 M_\odot$, $M_{\text{bulge}} = 11.8 \times 10^8 M_\odot$) and J074345.47+480813.5 ($M_{bh} = 0.51-0.66 \times 10^6 M_\odot$, $M_{\text{bulge}} = 20.5 \times 10^9 M_\odot$), assuming here that $M/L_B = 6 \pm 2.5$ (Worthey 1994) and using $M_{\odot}/B = 5.47 \text{mag}$ (Cox 2000).}

Reines et al. (2013, their Tables 1 and 6) present stellar masses along with black hole mass estimates derived using the broad H\alpha line for 10 dwarf galaxies, as done by Yuan et al. (2014). This emission-line method has been calibrated against reverberation mapping techniques that require knowledge of the “virial factor” (Petrosian & Wandel 2000; Onken et al. 2004). Using a common “forward regression” analysis, Graham et al. (2011) derived a virial factor of $3.8^{+0.7}_{-0.6}$ (compare to $5.1^{+1.5}_{-1.1}$ from Park et al. 2012) using a large sample of galaxies. However, Graham et al. (2011) pointed out a sample selection bias (as opposed to a real/natural boundary) that misses low-mass black holes and that is reduced when using an “inverse regression” analysis, resulting in a virial factor of $2.8^{+0.5}_{-0.5}$ (cf. 3.4$^{+1.2}_{-0.6}$ from Park et al. 2012). For several reasons discussed in Graham et al. (2011), this value is an upper limit, but it does (coincidentally?) agree with the isotropic spherical virial coefficient of 3 from Netzer (1990). As noted in footnote 1 of Graham et al. (2011), due to differing notation in the literature, this value is sometimes reduced by a factor of four and given as 0.75. While Jiang et al. (2013) and Yuan et al. (2014) used a “reduced” virial factor of 0.75, Reines et al. (2013) used a value of 1.0. For consistency, we have therefore reduced the black hole mass estimates of Reines et al. (2013) by 1.0/0.75.

For the dwarf Seyfert 1 galaxy POX 52 ($M_{\text{bulge}} = 1.2 \times 10^9$), Thornton et al. (2008) derived a black hole mass estimate using the radius–luminosity relation of Kaspi et al. (2000; giving a broad line region radius from the AGN luminosity) together with the velocity obtained from the broad H\beta line width (enabling an $f'/V^2 R/G$ virial mass estimate). Adjusting the reduced virial factor $f'$ that they used from 1.4 (Onken et al. 2004) to 0.75 (Graham et al. 2011) lowers their virial mass estimate from $(3.1-4.2) \times 10^9 M_\odot$ to $(1.7-2.3) \times 10^9 M_\odot$.

Mathur et al. (2012) have presented 10 black hole masses obtained via the virial relation of Kaspi et al. (2000), who used a reduced virial factor of 0.75, and we include this data set. The absolute $r$-band bulge magnitudes presented in Mathur et al. (2012) were converted into a stellar mass using $M/L_r = 3.5 \pm 1.5$ (Worthey 1994) and $M/L_\odot = 4.50 \text{mag}$ (Vega). While the redshifts (z) of the galaxies from the four previously mentioned studies in this section are all less than 0.05 and $z \lesssim 0.04$ for all but two of them, i.e., most are within 170 Mpc, 8 of the 10 galaxies from Mathur et al. (2012) have $z > 0.06$ and they reach out to $\sim 0.17$. The $K$ correction for this sample is expected to be $\lesssim 0.1$ mag in the $r$ band (Chilingarian et al. 2010) and is therefore not bothered with, especially as we do not have useful color information for much of this sample. While the higher redshift of 0.17 corresponds to $2.5 \log (1+z)^2 = 0.34 \text{mag}$ of cosmological redshift dimming of the observed magnitude, it somewhat cancels with the expected evolutionary correction due to galaxies being brighter when they were younger, which is estimated to be $-1.2z$ mag for elliptical and Sc galaxies, and $-1.75z$ mag for Sa galaxies (Poggianti 1997). Due to this expected cancellation, coupled with our uncertainty as to the morphological type, we have not applied.
these corrections, but instead note that there could be a tenth or a couple of tenths of a magnitude error because of this.

Busch et al. (2014) report on a sample of 11 low-luminosity type 1 quasars whose black hole masses reside below the linear $M_{\text{bh}}-M_{\text{Sph,0}}$ relation. Their Figure 14 reveals that the location of their data in the $M_{\text{bh}}-M_{\text{Sph,0}}$ diagram overlaps with the distribution from the large, predominantly inactive galaxy sample used to define the bent $M_{\text{bh}}-M_{\text{Sph,0}}$ relation in Scott et al. (2013). Here we reduce their black hole masses by $3/3.85$ as they used a virial factor of $3.85$ from Collin et al. (2006). We have derived the spheroid masses from the absolute $K$-band magnitudes (which are minimally affected by dust) listed in their Table 7, by using an average $M/L_K = 0.8$ and $M_{\odot, K} = 3.28$ mag (Vega). Busch et al. (2014) reported a range of $M/L_K$ values from 0.73 to 0.85, slightly greater than the typical value of 0.6 reported by McGaugh & Schombert (2014) for disk galaxies. Given that the galaxy sample from Busch et al. (2014) has $z \lesssim 0.06$, any cosmological corrections would be smaller than the 0.2 mag uncertainty on the magnitudes reported by Busch et al. (2014). However, the dominant uncertainty may well be in the conversion from stellar light to stellar mass.

As noted by Busch et al. (2014), if a significant fraction of young stars is present, then our adopted $M/L$ ratio is too high and we have overestimated the spheroid mass. The same

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**Table 2**

| Galaxy | $M_{\text{bh}}$ ($10^9 M_\odot$) | $M_{\text{Sph}}$ (mag) | $M/L$ | $M_{\text{Sph,0}}$ ($10^9 M_\odot$) |
|--------|-----------------|-----------------|------|-----------------|
| Pox 52 | 2.0 $\pm$ 0.3   | ...             | ...  | 1.2             |
| UM 625 | 16              | $-19.06$ V-mag  | 1.6  | 5.4             |
| SDSS J004021.10-110957.6 | 12.2 | $-17.4$ B-mag | $6 \pm 2.5$ | $8.4^{+3.6}_{-3.5}$ |
| SDSS J074345.47+480813.5 | 5.1 $-6.6$ | $-18.0$ B-mag | $6 \pm 2.5$ | $14.7^{+6.1}_{-5.2}$ |

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**Reines et al. (2013), BPT AGNs**

| Galaxy | $M_{\text{bh}}$ ($10^9 M_\odot$) | $M_{\text{Sph}}$ (mag) | $M/L$ | $M_{\text{Sph,0}}$ ($10^9 M_\odot$) |
|--------|-----------------|-----------------|------|-----------------|
| SDSS J024565.39-003304.8 | 5.0 | ... | ... | 2.57 |
| SDSS J090613.75+561015.5 | 2.5 | ... | ... | 2.29 |
| SDSS J095418.15+471725.1 | 0.8 | ... | ... | 1.32 |
| SDSS J112342.82+581446.4 | 12.6 | ... | ... | 2.95 |
| SDSS J112548.86+333248.7 | 1.0 | ... | ... | 1.26 |
| SDSS J144012.70+024743.5 | 1.6 | ... | ... | 2.88 |

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**Reines et al. (2013), BPT Composites**

| Galaxy | $M_{\text{bh}}$ ($10^9 M_\odot$) | $M_{\text{Sph}}$ (mag) | $M/L$ | $M_{\text{Sph,0}}$ ($10^9 M_\odot$) |
|--------|-----------------|-----------------|------|-----------------|
| SDSS J085125.81+393541.7 | 2.5 | ... | ... | 2.57 |
| SDSS J152637.36+065941.6 | 5.0 | ... | ... | 2.14 |
| SDSS J153425.58+040806.6 | 1.3 | ... | ... | 1.32 |
| SDSS J160531.84+174826.1 | 1.6 | ... | ... | 1.74 |

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**Mathur et al. (2012)**

| Galaxy | $M_{\text{bh}}$ ($10^9 M_\odot$) | $M_{\text{Sph}}$ (mag) | $M/L$ | $M_{\text{Sph,0}}$ ($10^9 M_\odot$) |
|--------|-----------------|-----------------|------|-----------------|
| TON S180 | 71 | $-20.1$ $r$-mag | $3.5 \pm 1.5$ | $24.2^{+10.4}_{-10.4}$ |
| RX J1117.1+6522 | 210 | $-19.7$ $r$-mag | $3.5 \pm 1.5$ | $16.8^{+7.4}_{-7.2}$ |
| RX J1209.8+3217 | 54 | $-19.8$ $r$-mag | $3.5 \pm 1.5$ | $18.4^{+7.0}_{-7.0}$ |
| IRAS F12397+3333 | 45 | $-20.2$ $r$-mag | $3.5 \pm 1.5$ | $26.6^{+11.3}_{-11.3}$ |
| MRK 478 | 269 | $-21.2$ $r$-mag | $3.5 \pm 1.5$ | $66.7^{+28.6}_{-28.6}$ |
| RX J1705.2+3247 | 217 | $-19.8$ $r$-mag | $3.5 \pm 1.5$ | $18.4^{+7.0}_{-7.0}$ |
| RX J2216.8-4451 | 167 | $-21.1$ $r$-mag | $3.5 \pm 1.5$ | $60.8^{+26.1}_{-26.0}$ |
| RX J2217.9-5941 | 124 | $-19.6$ $r$-mag | $3.5 \pm 1.5$ | $15.3^{+6.6}_{-5.4}$ |
| MS 2254.9-3712 | 39 | $-19.1$ $r$-mag | $3.5 \pm 1.5$ | $9.6^{+6.2}_{-5.1}$ |
| MS 23409-1511 | 100 | $-20.7$ $r$-mag | $3.5 \pm 1.5$ | $42.1^{+18.0}_{-18.0}$ |

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**Busch et al. (2014)**

| Galaxy | $M_{\text{bh}}$ ($10^9 M_\odot$) | $M_{\text{Sph}}$ (mag) | $M/L$ | $M_{\text{Sph,0}}$ ($10^9 M_\odot$) |
|--------|-----------------|-----------------|------|-----------------|
| HE0045-2145 | 6.0 | $-22.42$ $K_r$-mag | 0.8 | 15.2 |
| HE0103-5842 | 39.8 | $-23.78$ $K_r$-mag | 0.8 | 53.3 |
| HE0224-2834 | 331 | $-24.48$ $K_r$-mag | 0.8 | 100 |
| HE0253-1641 | 39.8 | $-22.13$ $K_r$-mag | 0.8 | 11.7 |
| HE1310-1051 | 166 | $-23.25$ $K_r$-mag | 0.8 | 32.7 |
| HE1338-1423 | 155 | $-23.97$ $K_r$-mag | 0.8 | 63.5 |
| HE1348-1758 | 15.5 | $-21.99$ $K_r$-mag | 0.8 | 10.3 |
| HE1417-0909 | 135 | $-23.05$ $K_r$-mag | 0.8 | 27.2 |
| HE2128-0221 | 195 | $-23.36$ $K_r$-mag | 0.8 | 36.2 |
| HE2129-3536 | 490 | $-23.23$ $K_r$-mag | 0.8 | 32.1 |
| HE2204-3249 | 1000 | $-25.00$ $K_r$-mag | 0.8 | 164 |
situation may occur with the sample from Yuan et al. (2014) and Mathur et al. (2012; which is also partly why we are not particularly concerned with a possible ∼0.1−0.2 mag error in their bulge magnitudes). Given the coexistence of AGNs and star formation due to the available gas supply, it seems plausible that this could be the case (Alexander & Hickox 2012, his Sections 2 and 3). Although in determining this, one obviously needs to distinguish between star formation contributing toward bulge versus disk growth and be aware that a large fraction of BH accretion and star formation (Straatman et al. 2014) is obscured by dust (Webster et al. 1995; Del Moro et al. 2013; Busch et al. 2014). Obtaining better stellar mass-to-light ratios are, thankfully, a topic already under investigation by G. Busch (2014, private communication). The masses for our sample from Busch et al. (2014), plus all the above masses, are collated in Table 2 to give a total of 35 AGNs.

Finally, we use the large data set from Jiang et al. (2011a, 2011b), providing an additional 147 virial black hole mass estimates (obtained using a “reduced” virial factor $f' = 0.75$) and $i$-band bulge and disk magnitudes. Given that this is our largest data set, we dedicate some space to describing our conversion of their published magnitudes into stellar masses. We have applied the following five corrections to the apparent $F814W$ ($i$-band) bulge magnitudes. (1) They are corrected for foreground Galactic extinction using the recalibrated Galactic extinction maps of Schlafly & Finkbeiner (2011) as given in NED.¹² and (2) further brightened by $2.5 \log(1+z)^2$ due to cosmological redshift $(z)$ dimming. (3) We then correct the Sloan Digital Sky Survey (SDSS) Data Release 6 (DR6; Adelman-McCarthy et al. 2008) $g-i$ color of each galaxy (available through NED) for Galactic dust, enabling us to use the (foreground extinction)-corrected, $(g-i)$-based $K$ corrections from Chilingarian et al. (2010). The corrections obtained apply to the SDSS $i$ band but were assumed to be suitably applicable to the HST $i$ band. These $K$ corrections are small, with all but 3 (29) galaxies requiring an adjustment smaller than 0.2 (0.1) mag. (4) The bulge and disk magnitudes are then separately corrected for internal dust extinction using the generic i-band formula given in Driver et al. (2008) and assuming the reported axis ratios (courtesy of NED) reflect the inclination of each galaxy’s disk. (5) The final correction to the magnitude is to evolve the bulges to $z = 0$. To do this, the bulge-to-disk flux ratio is calculated and used to estimate the morphological type based on the dust-corrected bulge-to-disk flux ratios given in Table 8 of Graham & Worley (2008). Figure 1 shows the results. Although the sample is dominated by early-type (Sb and earlier) disk galaxies, 26 late-type (Sc and later) galaxies are present. We have then roughly applied the (morphological-type)-based $i$-band evolutionary corrections from Poggianti (1997) by using a redshift correction of $-1.6z$ for the Sa ($0.4 < (B/T) < 0.6$) galaxies and $-z$ for the remainder. Given that all but 6 (1) galaxies have a redshift less than 0.2 (0.35), this is also a small overall correction, which is fortunate given the uncertainties associated with this particular correction for disk galaxies. The corrected apparent bulge magnitudes are then converted into absolute magnitudes assuming $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$.

Overlooking the small difference between $i$ and $I$ magnitudes, we use the relation between $M_{i}/L_{i}$ and $g-i$ color in Taylor et al. (2011), such that $\log(M_{i}/L_{i}) = -0.68 + 0.70 (g-i)$, to convert the bulge magnitudes into stellar masses. This relation was calibrated for galaxies with masses down to a few times $10^8 M_{\odot}$, which essentially covers the full range of the Jiang et al. (2011a) sample. Our $g-i$ color was corrected for Galactic extinction, as noted above, and also $K$ corrected. It was not corrected for dust nor evolution. This resulted in $M_{i}/L_{i}$ ratios typically ranging from 0.55 to 1.15. We excluded eight galaxies because two had no $g-i$ color (1033+6353 and 1127+4625),

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¹² NASA/IPAC Extragalactic Database: http://ned.ipac.caltech.edu/
in the sample from Jiang et al. (2011a), of their 139 galaxies that we could use, a bisector regression yields a slope consistent with zero: $0.12 \pm 0.25$. However, we can use this large homogeneous data sample to investigate the scatter in the log $M_{\text{sph},*}$. The median horizontal offset of the Jiang et al. (2011a) data from the near-quadratic $M_{\text{sph},*}$ relation given by Scott et al. (2013) is just 0.19 dex, and an offset of zero is obtained by adjusting the slope of that relation within the 1σ uncertainty quoted by Scott et al. (2013). By contrast, the median horizontal offset about the near-linear $M_{\text{sph},*}$ relation from McConnell & Ma (2013) is 1.63 dex, i.e., a factor in excess of 40.

If the scatter in the $M_{\text{bh}}$–$M_{\text{sph},*}$ diagram remains constant in the horizontal (log $M_{\text{bh}}$) direction, then the scatter in the vertical (log $M_{\text{sph},*}$) direction will naturally increase where the relation steepens. Looking at the Jiang et al. (2011a) data in Figure 2, relative to the Sérsic relation (after accounting for the mean 0.19 dex displacement of the Jiang et al. (2011a) data to higher spheroid masses), 68% of their data (i.e., $\pm 34\%$) is contained within 0.83 dex in the horizontal direction. That is, their galaxy sample has a 1σ scatter of $\sim 0.42$ dex in the horizontal direction about the near-quadratic Sérsic $M_{\text{bh}}$–$M_{\text{sph},*}$ relation. This level of scatter is comparable with the level of scatter commonly reported in the vertical direction around the near-linear segment of the $M_{\text{bh}}$–$M_{\text{sph},*}$ and $M_{\text{sph},*}$ relation defined by the bright spheroids. The scatter in spheroid mass at a given black hole mass therefore appears to be similar at the low- and high-mass end of the $M_{\text{bh}}$–$M_{\text{sph},*}$ diagram. At the low-mass end, for a slope of 2, the 1σ scatter should thus be 0.83 dex in the vertical direction. If, at these low masses, the bulk of the data reside within $\pm 2\sigma$ of the near-quadratic relation, then the observed range in black hole mass at a given spheroid mass should be $3.32$ dex. It is therefore not surprising that studies with a limited range in spheroid mass (as opposed to black hole mass) may also miss detecting the relation.

In spite of the many sources of scatter that our remaining heterogeneous AGN sample (Table 2) may contain, these AGNs appear to follow a sequence whose slope is steeper than 0.97 and less than 2.22. However, given the previously mentioned possibility that we may have overestimated the mass-to-light ratios and thus the bulge masses of some of our AGN hosts, we feel that it would be premature to place too much confidence in a line fit to this data. Our distribution of spheroid stellar masses for the 139 AGNs from Jiang et al. (2011a) does, however, appear broadly consistent with the distribution of dynamical ($5\sigma^2 R_e$) masses reported in Table 2 (obtained using a simple factor of two error for all spheroid and black hole masses). This slope is shallower than 2.22, but it does have overlapping 1σ error bars with the measurement $2.22 \pm 0.58$. In summary, the AGNs are not randomly offset; they follow a steeper relation than the near-linear (i.e., slope close to one) relation defined by the massive systems.
This transition has been associated with the change in slope of the \( L_{\text{sph}} - \sigma \) relation (e.g., Matković & Guzmán 2005; Graham 2013, and references therein). Indeed, the transition across the bend in the \( M_{\text{sph}} - \sigma \) diagram from Cappellari et al. (2013, their Figure 1) matches this same mass range (Graham et al. 2014). It is also interesting to recall that Laor (2000) remarked that only AGNs with black hole masses \( \gtrsim 2 \times 10^8 \, M_\odot \) —which corresponds to the onset of the transition in Figure 2—generate large-scale jets presumably capable of halting star formation and maintaining the near-linear \( M_{\text{bh}} - M_{\text{sph}}^{\ast} \) relation seen at high masses.

This division can be related to galaxy structure in addition to the galaxy dynamics. There is a log-linear relation between the luminosity and the central surface brightness (\( \mu_0 \)) of elliptical galaxies from \( M_B \approx -14 \, \text{mag} \) to \( \approx -20.5 \, \text{mag} \) (Jerjen & Binggeli 1997). There is also a log-linear relation between the luminosity and the Sérsic index of these galaxies (Graham & Guzmán 2003). The lack of a break in the above two log-linear relations at \( M_B \approx -18 \, \text{mag} \) (Sérsic \( n \approx 2 \)) unites the faint and intermediate galaxies. However, galaxies brighter than \( M_B \approx -20.5 \, \pm 0.75 \, \text{mag} \) with partially depleted cores deviate from the \( L - \mu_0 \) relation established by the fainter galaxies (Graham & Guzmán 2003). For an old stellar population with \( M/L_B = 8 \), \( M_B = -20.5 \, \pm 0.75 \, \text{mag} \) corresponds to a mass of \( 2.5 \times 10^{11} \, M_\odot \), which is where the core–Sérsic galaxies start to dominate the \( M_{\text{sph}}^{\ast} - M_{\text{sph}}^{\ast} \) diagram. While these core–Sérsic galaxies can have large-scale disks (e.g., Dullo & Graham 2013), at \( M_{\text{sph}}^{\ast} \gtrsim 4 \times 10^{11} \, M_\odot \), they tend to be slow rotators (Emsellem et al. 2007).

The lower-mass host galaxies of the AGNs with low-mass black holes are, of course, not expected to have partially depleted cores like the giant core–Sérsic galaxies. For this reason, it is not surprising that they follow the same relation as the Sérsic galaxies in the \( M_{\text{bh}} - M_{\text{sph}}^{\ast} \) diagram.

Related to the Sérsic versus core–Sérsic separation, Graham & Scott (2013) flagged two main regimes of black hole growth: gas-dominated processes occurring in Sérsic galaxies and gas-poor (dry) major merging forming the core–Sérsic galaxy sequence in Figure 2. In this scenario, the low-mass spheroids grow their black holes rapidly, relative to the spheroid, through the accretion of gas and stellar material (possibly also merging with other supermassive black holes). Supporting this scenario, Gabor & Bournaud (2013) have recently demonstrated that black holes grow more rapidly, relative to their host spheroids, in lower-mass and gas-rich galaxies. Indeed, a tide of papers (Seymour et al. 2012; Diamond-Stanic & Rieke 2012; Agarwal et al. 2013; LaMassa et al. 2013; Lehmer et al. 2013; Drouart et al. 2014) now reveal changes in the black hole-to-galaxy mass ratio that may support such growth (see also Trakhtenbrot & Netzer 2012 and Alonso-Herrero et al. 2013). For example, LaMassa et al. (2013) report that the star formation growth is related to the black hole growth raised to the power of 0.36. Flipping this implies \( M_{\text{bh}} \propto M_{\text{sph}}^{0.78} \).

In the low-mass regime, the growth of the black hole and spheroid is linked because they both grow from the same source, the galaxy’s cold gas reservoir. This apparently establishes the quadratic or “super-quadratic” relation between the black hole mass and that of the host spheroid during the quasar’s “radiative mode” (Graham & Scott 2013). This continues until a critical point is reached around a spheroid stellar mass of \( 3 \times 10^7 \, M_\odot \). At this mass, radio-mode feedback, also known as “mechanical mode” feedback, from the black hole may become effective enough to expel the majority of the galaxy’s cold gas reservoir and prevent this gas from cooling again (Silk & Rees 1998; Haehnelt et al. 1998), as implemented in many semi-analytical/numerical codes (Kawata & Gibson 2005; Springel et al. 2005; Bower et al. 2006; Merloni & Heinz 2008; Booth & Schaye 2009). However, this latter feedback is not actually responsible for establishing the scaling relation between \( M_{\text{bh}} \) and the host spheroid. With little gas reservoir to accrete from, the supermassive black hole now grows predominantly through dry merging with other massive black holes, leading to the core–Sérsic relation with linear growth of the black hole and host spheroid, maintained by the black hole’s “mechanical/radio mode” feedback (Karouzos et al. 2014) and/or perhaps also from super-stellar winds (Conroy et al. 2014).

The clever, many-merger scenario proposed by Peng (2007) (see also Jahneke & Macciò 2011; Hirschmann et al. 2010) to produce a linear one-to-one scaling via the central limit theorem can be ruled out. Using a sample of galaxies with a range of initial \( M_{\text{bh}}/M_{\text{gal}} \) mass ratios, Peng (2007) noted that after many mergers, it will create an \( M_{\text{bh}} - M_{\text{sph}}^{\ast} \) relation with a slope of 1. This idea was attractive when it was thought that a single linear \( M_{\text{bh}} - M_{\text{sph}}^{\ast} \) relation existed. However, we now know that the primary \( M_{\text{bh}} - M_{\text{sph}}^{\ast} \) relation is not linear but quadratic-like. Moreover, as noted by Anglés-Alcázar et al. (2013), major mergers are not frequent enough to establish a linear relation in this way. The linear branch of the \( M_{\text{bh}} - M_{\text{sph}}^{\ast} \) relation, observed only at the high-mass end of the \( M_{\text{bh}} - M_{\text{sph}}^{\ast} \) diagram, has instead likely arisen from a few dry major mergers of galaxies having roughly the same \( M_{\text{bh}}/M_{\text{sph}}^{\ast} \) ratio (e.g., Dullo & Graham 2014, and references therein).

While hierarchical gas-rich merger models and AGN feedback models are highly valuable (e.g., Fabian 1999; Wyithe & Loeb 2003; Begelman & Nath 2005; Croton et al. 2006; Di Matteo et al. 2008; Natarajan & Volonteri 2012) the prediction (or use) of a linear \( M_{\text{bh}} - M_{\text{sph}}^{\ast} \) relation does not describe the observed distribution for most galaxies. Indeed, any model that has predicted a linear \( M_{\text{bh}} - M_{\text{sph}}^{\ast} \) relation or that the black hole mass and the stellar mass of galactic spheroids should be proportional, or \( \approx 0.001–0.002 \), for galaxies with \( 2 \times 10^6 \lesssim M_{\text{bh}}/M_\odot \lesssim 2 \times 10^6 \) (\( M_{\text{sph}} \approx 3–4 \times 10^{10} \, M_\odot \)) does not appear to match our universe. While black hole feedback (e.g., Binney & Tabor 1995; Ciotti & Ostriker 1997; Silk & Rees 1998) likely regulates the black hole and host spheroid growth, the actual details are still a matter of debate. Promisingly, Lu & Mo (2014) present a nonlinear relation that at stellar masses above \( 10^{10.5} \, M_\odot \) qualitatively matches the galaxy data from Scott et al. (2013).

Evident in Figure 2 is that the 35 galaxies from Table 2 have higher spheroid masses relative to the Sérsic \( M_{\text{sph}} - M_{\text{sph}}^{\ast} \) relation shown there. As noted by Busch et al. (2014), this might be due to an overestimation of the stellar mass-to-light ratios that they and we have used. There is also room for improvement in our \( M_{\text{bh}} - M_{\text{sph}}^{\ast} \) relation for Sérsic galaxies, and G. Savorgnan et al. (in preparation) is working on deriving new spheroid masses from Spitzer data for the Sérsic (and core–Sérsic) galaxies used here. With these advances, we will be in a better position to say if and how the AGNs in Figure 2 are offset. In passing, we note

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13 As a result of these two linear relations, diagrams using “effective” radii and “effective” surface brightnesses are predicted to be (and found to be) curved. They lead to the false impression of a division at \( M_B \approx -18 \, \text{mag} \) (Graham 2013, and references therein).

14 The term “super-quadratic” is used to denote an exponent in a scaling relation that is greater than two but less than three.
two things. First, using a virial factor of six rather than three to determine the black hole masses would (only) shift the AGN black hole masses by a factor of two higher in Figure 2. Second, elliptical galaxies and the bulges of disk galaxies may follow offset sequences in the $M_{bh} - M_{sph,*}$ diagram, associated with the offset sequence in the $L - n$ diagram discussed in Savorgnan et al. (2013). However, better quality data will be needed to test this issue. Building on the Greene & Ho (2007) sample of AGN candidates, Dong et al. (2012) report on 137 (309) AGNs with virial black hole mass estimates—based on the broad He emission line—ranging from $15 \times 10^2 - 1.0 \times 10^6 M_\odot$ to $2 \times 10^2 - 2 \times 10^6 M_\odot$. They were able to refine their sample from galaxies that may have broad He lines due to star formation processes rather than an AGN. They showed that only about one-third of their (typically Sbc galaxy) sample resides in the H ii rather than the Seyfert region of diagnostic diagrams based on narrow-line ratios. Future image decomposition should therefore provide yet more bulge (i.e., spheroid) magnitudes and thus new data for the region of the $M_{bh} - M_{sph,*}$ diagram probed by the Jiang et al. (2011a) data.

4.1. Intermediate Mass ($10^2 - 10^5 M_\odot$) Black Holes

Using the steeper Sérsic relation for galaxies without depleted cores, intermediate mass black holes (IMBHs) have now been predicted to exist in tens of galaxies possessing low-mass spheroids and AGN activity (Graham & Scott 2013). Based on the original linear scaling relation, the majority of these galaxies were thought to host black holes with masses $\gtrsim 10^5 M_\odot$ (Dong & De Robertis 2006). Application of the fundamental plane of black hole activity (Merloni et al. 2003; Falcke et al. 2004) can provide an independent estimate of their black hole mass and we hope to apply this technique to the above-mentioned sample. For example, Graham & Scott (2013) predict $\log(M_{bh}) = 5.3 \pm 0.9$ for NGC 3185, while the black hole fundamental plane predicts $\log(M_{bh}) = 5.2 \pm 1.0$ (N. Webb et al., in preparation). Pushing to yet lower masses is obviously of importance to help determine if and how the $M_{bh} - M_{sph,*}$ relation for Sérsc galaxies continues into the IMBH mass regime. The implications of this near-quadratic relation are many, and while several were highlighted in our 2012–2013 papers, a couple more specific examples are noted here.

First, the velocity dispersion of galaxy ASASSN-14ae suggests an IMBH of mass $3 \times 10^4 M_\odot$ associated with the recent tidal disruption event (Holoien et al. 2014). The galaxy’s young 2.2 Gyr age suggests it is a later-type spiral galaxy, and if we assign a bulge-to-total flux ratio of a tenth (e.g., Graham & Worley 2008), one obtains a bulge magnitude supportive of this black hole mass when using the $M_{bh} - M_{sph,*}$ relation for Sérsc galaxies shown in Figure 2. More than two dozen tidal disruptions of stars by black holes are known (Komossa 2013), typically revealed via luminous X-ray flaring events. We advocate obtaining accurate bulge luminosities and masses for these galaxies because it will enable an additional estimate of the mass of the black holes, possibly supporting the existence of yet more IMBH candidates.

Second, a recent simulation to predict the location of an intermediate-mass black hole from a spaghettified satellite galaxy around M31 may benefit from refined initial conditions. Given the initial satellite mass of $3 \times 10^5 M_\odot$ used by Miki et al. (2014), an $M_{bh}/M_{sph,*}$ mass ratio of $4 \times 10^{-4}$ (derived from the $M_{bh} - M_{sph,*}$ relation for Sérsc galaxies) rather than the (previously assumed constant) value of $10^{-3}$ used by Miki et al. (2014) might be more appropriate. Given the reduced amount of dynamical friction on a black hole that is 2.5 times less massive, it would be interesting to test how this alters their suggested $0.6 \times 0.7$ search box for M31. Observers may also need to brace themselves for weaker observational signatures from such a smaller black hole.

Jiang et al. (2011a) revealed that their low-mass AGN-selected galaxies reside below the near-linear $M_{bh} - M_{sph,*}$ relation (see also Figure 2). If large numbers of galaxies with $10^5 < M_{bh}/M_\odot < 10^6$ had bulges that followed the near-linear $M_{bh} - M_{sph,*}$ relation, then they would have been found; that is, there was no sample selection bias against AGNs in small bulges. However, a small number of “bulgeless”16 galaxies containing AGNs have been reported (Schramm et al. 2013; Simmons et al. 2013; Satyapal et al. 2014), and Jiang et al. (2011b) noted that 5% of their sample had no bulges within the limits of their imaging data. While bulgeless galaxies reside on neither the near-linear nor the near-quadratic $M_{bh} - M_{sph,*}$ relation because they have no bulge, they do serve to highlight that while the $M_{bh} - M_{sph,*}$ diagram has its main tracks, departures can exist. Moreover, if these bulgeless galaxies were to undergo secular evolution of their disks and form a pseudobulge, then at some point, these pseudobulges would evolve rightward in the $M_{bh} - M_{sph,*}$ diagram, possibly crossing and being found close to the near-linear $M_{bh} - M_{sph,*}$ relation before presumably joining the majority of the low-mass bulges that appear to define the near-quadratic $M_{bh} - M_{sph,*}$ relation.

Finally, we note that based on the hypothetical black hole mass estimates from Mieske et al. (2013), they reported that black holes in ultra-compact dwarf galaxies and globular clusters (Lützgendorf et al. 2013, but see Lanzoni 2014) do not appear to follow the near-linear $M_{bh} - L_{sph,*}$ relation defined by galaxies with black holes predominantly more massive than $10^6 M_\odot$. Given the high $M_{bh}/M_{UCD,*}$ ratios for their UCDs and the reported value of 15% for M60-UCD1 (Seth et al. 2014), UCDs are even more at odds with the near-quadratic relation defined by low-mass bulges in the $M_{bh} - M_{sph,*}$ diagram. If UCDs are related to the stripped nuclei of low-mass galaxies, it may therefore be more appropriate to compare them with relations pertaining to black holes in nuclear star clusters, for which $M_{bh}/M_{nc}$ is already observed to reach ~10% (Graham & Spitler 2009).

4.2. Nuclear Star Clusters

There has been much attention on the relationship between black holes and their host galaxies. While large galaxies with depleted cores may be built from dry merging events—explaining their near-linear $M_{bh} - M_{sph,*}$ relation—the Sérsc galaxies and their black holes have formed from more gaseous processes. Most of these Sérsc galaxies also contain a nuclear star cluster (e.g., Baldassare et al. 2014; den Brok et al. 2014, and references therein), which hosts and likely also feeds the central massive black hole to some degree via stellar winds and also stellar capture (e.g., Zhong et al. 2014, and references therein). Knowing the masses of the black holes and also the nuclear star clusters is therefore of interest.

15 One of the black hole mass estimates from Dong et al. (2012) is $0.8 \times 10^5 M_\odot$.

16 Care is required when identifying truly bulgeless galaxies from galaxies that simply have low (i.e., 5%) bulge-to-disk flux ratios.
The high stellar density of nuclear star clusters may result in elevated levels, relative to galaxies without nuclear star clusters, of in-spiraling stellar-mass black holes and neutron stars onto the central massive black hole. The physical size of these orbital decays, and thus the associated orbital period, makes these “extreme mass ratio in-spiral” (EMRI; Hils & Bender 1995; Rubbo et al. 2006; Amaro-Seoane et al. 2014, and references therein) events a likely source of gravitational radiation that could be detected by future space-based gravitational radiation interferometers. Of particular relevance here is that Mapelli et al. (2012) have shown how the reduced \( M_{bh}/M_{\text{sph}} \) ratios—from the near-quadratic rather than near-linear \( M_{bh}-M_{\text{sph}} \) relation—results in an order of magnitude lower number of such EMRI events, with significant implications for the previously proposed Laser Interferometer Space Antenna (LISA; Danzmann & LISA Study 1996), currently replaced by the LISA Pathfinder mission\(^\text{17}\) (LPF; Anza et al. 2005; McNamara 2015) formerly known as SMART-2.

The first attempt to quantify the coexistence of massive black holes (using directly measured black hole masses) and their surrounding nuclear star cluster can be found in Graham & Spitler (2009), with another recent work by Neumayer & Walcher (2012), but see also González Delgado et al. (2008) and Seth et al. (2008). One can gain further insight into their co-evolution by coupling the near-quadratic \( M_{bh}-M_{\text{sph}} \) relation for Sésic galaxies with the \( M_{nc}-M_{\text{sph}} \) relation (Graham & Guzmán 2003; Balcells et al. 2003), where \( M_{nc} \) is the mass of the nuclear cluster of stars at the center of the galaxy. This was first done in Graham (2014a), resulting in the discovery of the very steep \( M_{nc}-M_{bh} \) relationship as follows.

\[
\begin{align*}
M_{nc} & \propto M_{\text{sph}}^{5.5} \pm 0.15. \\
\text{Most recently, a similar exponent of 0.57 \pm 0.05 has been reported by den Brok et al. (2014) based on I-band luminosities rather than masses. Therefore, using the approximation } M_{bh} & \propto M_{\text{sph}}^2 \text{ and } M_{nc} \propto M_{\text{sph}}^{0.6}, \text{ one has } M_{bh} \propto M_{nc}^{3.3}. \text{ If, on the other hand, } M_{nc} \propto M_{\text{sph}}^{0.74} \text{ to } M_{\text{sph}}^{0.0}, \text{ e.g., Graham & Guzmán (2003); Grant et al. (2005); Côté et al. (2006); Balcells et al. (2007a)}, \text{ one still has the rather steep relation } M_{bh} \propto M_{\text{sph}}^{3}. \text{ That is, as one moves along the Sésic galaxy sequence from } n < 1 \text{ in the low-mass spheroids to values of } n \approx 4 \text{ in the higher mass spheroids, the mass of the black hole is expected to grow dramatically faster than that of the nuclear star cluster, which is eventually eroded away in the core–Sésic galaxies (Bekki & Graham 2010).}
\end{align*}
\]

This rapid growth was further checked in Graham (2014a) by combining the relation \( M_{nc}-\sigma^{5.5} \) (Graham et al. 2011) with the \( M_{nc}-\sigma^{3} \) relation. Recent studies have reported values of \( X \) equal to 1.57 \( \pm \) 0.24 (Graham 2012b), 2.73 \( \pm \) 0.29 (Leigh et al. 2012) and 2.11 \( \pm \) 0.31 (Scott & Graham 2013). Adopting a rough exponent of \( X = 2 \), one has that \( M_{bh} \propto M_{\text{sph}}^{2.7} \). It therefore seems apparent that the growth of black hole outstrips that of nuclear star clusters, with a relation something like \( M_{bh} \propto M_{\text{sph}}^{2.7} \). (given the current ranges presented above).

4.3. Impact on Next-generation Telescopes

Do et al. (2014) have predicted that the planned Thirty Meter Telescope (TMT; Sanders 2013) will be able to observe, i.e., resolve, the sphere of influence of black holes in 100,000 galaxies. They did so by estimating the black hole masses using the \( M_{bh}-L_{\text{bulge}} \) relation. However, as first noted by Graham (2012a) and seen in Figure 2, this relation dramatically overestimates the black hole masses of low-luminosity bulges, and will thus overestimate the sphere of influence of the black holes in such bulges. This in turn results in an overestimate to the numbers of black holes whose spheres of influence will be resolved by the TMT. It is beyond the scope of this paper to re-derive the expected number, but this reduced number should be of value to those developing the science objectives and instrumentation for the billion dollar TMT (Wright et al. 2014; Moore et al. 2014), the European Extremely Large Telescope (E-ELT; Liske et al. 2012; Evans et al. 2014) and the Giant Magellan Telescope (GMT; Johns et al. 2012; McGregor et al. 2014).

4.4. Continued Black Hole Growth in Sésic Galaxies as a Formation Mechanism for Overmassive Black Holes

If a galaxy’s gas reservoir is not expelled by feedback from its supermassive black hole (perhaps due to accretion from a disk rather than isotropically) or is replenished in a way that the supermassive black hole cannot prevent (perhaps through a wet merger bringing in a significant amount of gas or through cold accretion), then the supermassive black hole and its host spheroid will presumably continue to follow the Sésic galaxy relation as gaseous processes will still be dominant. Above spheroid stellar masses of \( 10^{11} M_\odot \), the Sésic relation is not well populated, therefore this type of growth must be rare in massive galaxies; however, there are now several potential examples of this mechanism.

If the reported black hole mass in NGC 1277 is confirmed, this galaxy may be a candidate for continued growth via gas-dominated processes beyond the typical spheroid mass marked by the bend in the scaling relations. Other potential examples of this process include the ultra-massive black holes hosted by brightest cluster galaxies (BCGs) identified by Hlavacek-Larrondo et al. (2012). These black holes potentially became overmassive relative to their host spheroids due to the widespread availability of gas from the strong cooling flows found in the host clusters of the BCGs. Given that the growth of these black holes is likely dominated by gaseous processes, one might expect them to grow off and above the linear \( M_{bh}-M_{\text{sph}} \) relation for core–Sésic galaxies.

4.5. Other Explanations for Outlying Galaxies

A number of other physical processes can be responsible for changing the location of a galaxy in the \( M_{bh}-M_{\text{sph}} \) diagram. These mechanisms either inhibit (or reverse) the growth of the stellar spheroid or somehow grow the black hole more rapidly than expected. Perhaps the most commonly invoked mechanism for a galaxy appearing as an outlier in the left of the \( M_{bh}-M_{\text{sph}} \) diagram is tidal stripping of the host galaxy. In this scenario, a galaxy originally follows the black hole scaling relations, but due to a tidal interaction with a nearby more-massive neighbor, it loses a significant fraction of its stellar mass, causing it to move to the left in the \( M_{bh}-M_{\text{sph}} \) diagram. This scenario is discussed in more detail in Blom et al. (2014). The so-called compact elliptical (cE) galaxy M32 is a well-known example of a galaxy thought to be tidally stripped (Dressler 1989; Bekki et al. 2001; Graham 2002; Chilingarian et al. 2009) (but see Dierickx et al. 2014), and its position in the \( M_{bh}-M_{\text{sph}} \) diagram is consistent with this argument. This type of galaxy is very rare compared to the number of normal galaxies, and their inclusion in the \( M_{bh}-M_{\text{sph}} \) diagram can therefore severely bias one’s

\[\text{http://sci.esa.int/lisa-pathfinder/}\]
impression of what is happening at low masses (e.g., Graham 2007b; Sesana et al. 2014, their Figure 8).

In contrast, tidal stripping is unlikely to be responsible for NGC 1277’s position in the $M_{bh} - M_{\text{sph}*}$ diagram because (1) it shows no signs of tidal disturbance (van den Bosch et al. 2012); (2) given its large mass, tidal stripping by a companion would not be efficient in stripping away stars; and (3) to have once been on the $M_{bh} - M_{\text{sph}*}$, it would need to have been stripped of an extreme $\sim 2 \times 10^{12} M_\odot$ of stars, or $\sim 98\%$ of its spheroid mass. NGC 4486B is a less clear-cut object, with a massive companion (M87) that could be responsible for the tidal stripping of some of its stars. It is possible that both tidal stripping and continuing Sérsic-mode growth played a role in NGC 4486B, with its black hole growing unusually large through continued Sérsic-mode growth and then being stripped of its stars through a tidal interaction. Of course, the reported black masses in NGC 1277 and NGC 4486B may simply be in error. This could happen due to velocity shear from an unresolved rotating disk that elevates the central velocity dispersion, as noted in Graham et al. (2011).

Other possible pathways for producing outliers in the $M_{bh} - M_{\text{sph}*}$ diagram are less well explored. Mechanisms for feeding gas onto a central black hole, while avoiding significant star formation include: accretion from a dense, flat, gaseous disk or bar (Nayakshin et al. 2012); ultra-fast outflows (Tombesi et al. 2010) from AGNs with sub-Eddington accretion rates leading to velocity shear from an unresolved rotating disk that elevates the central velocity dispersion. However, they do reside on the high $M_{\text{sph}*}$ edge of this cloud, possibly indicating that their spheroid masses have been overestimated due to use of an overly large mass-to-light ratio conversion factor. The spheroids hosting AGNs with $10^7 \lesssim M_{bh}/M_\odot \lesssim 10^9$ closely track this relation to lower masses. They also reveal that the (horizontal) scatter in the log($M_{\text{sph}*}$) direction is comparable at low and high masses. As such, the recent identification of separate scaling relations for Sérsic and core–Sérsic galaxies appears to explain many of the black holes in AGNs once thought to be undermassive.

Through improvements in the quality of the $M_{bh}$ and $M_{\text{sph}*}$ data, which are expected to be achievable in the near future via refined virial factors, bulge/disk/bar decompositions of galaxy light, and stellar mass-to-light ratios, we hope to further study the coevolution of black holes with their host galaxy. This will include determining if AGNs may be offset from the $M_{\text{sph}*}$ relation for Sérsic galaxies defined by largely inactive galaxies and exploration into the realm of intermediate mass black holes.

This research was supported by Australian Research Council funding through grants DP110103509 and FT110010263. This research made use of the “K-corrections calculator” service available at http://kcor.sai.msu.ru/ and the NASA/IPAC Extragalactic Database (NED: http://ned.ipac.caltech.edu).

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