

M-M PAPER, MORPHOLOGICAL BIAS

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ABSTRACT

abstract

Subject headings: keywords

1. INTRODUCTION

More than two and a half decades ago, Dressler (1989) foresaw a “rough scaling of black hole mass with the mass of the spheroidal component”, as suggested by the sequence of five galaxies (M87, M104, M31, M32 and the Milky Way). His “rough scaling” was a premature version of the nowadays popular correlation between black hole mass, M_{BH} , and host spheroid luminosity, L_{sph} , and also host spheroid mass, M_{sph} (Yee 1992; Kormendy & Richstone 1995; Magorrian et al. 1998; Marconi & Hunt 2003; Häring & Rix 2004). These early studies were dominated by high-mass, early-type galaxies, for which they reported a quasi-linear $M_{\text{BH}} - M_{\text{sph}}$ relation, consistent with a dry-merging formation scenario. Subsequent studies of the $M_{\text{BH}} - L_{\text{sph}}$ and $M_{\text{BH}} - M_{\text{sph}}$ diagrams (Ferrarese & Ford 2005; Lauer et al. 2007a; Graham 2007, 2008; Gültekin et al. 2009; Sani et al. 2011; Beifiori et al. 2012; Erwin & Gadotti 2012; Vika et al. 2012; van den Bosch et al. 2012; McConnell & Ma 2013; Kormendy & Ho 2013; Rusli et al. 2013; see Graham 2015 for an extensive review about the early discovery and successive improvements of these correlations) used similar galaxy samples, which remained dominated by high-mass, early-type objects having $M_{\text{BH}} \gtrsim 0.5 \times 10^8 M_{\odot}$, and recovered a near-linear relation. However, the consensus about a linear $M_{\text{BH}} - M_{\text{sph}}$ correlation was not unanimous. Some studies reported a slope steeper than one, or noticed that low-mass spheroids were downwards offset from the relation traced by their high-mass counterparts (Laor 1998; Wandel 1999; Laor 2001; Ryan et al. 2007). Recently, Läsker et al. (2014a,b) derived $2.2 \mu\text{m}$ bulge luminosities for 35 galaxies (among which only 4 were classified as spiral galaxies), and reported a slope below unity for their $M_{\text{BH}} - M_{\text{sph}}$ relation. They also claimed that the black hole mass correlates equally well with the total galaxy luminosity as it does with the bulge luminosity.

The $M_{\text{BH}} - L_{\text{sph}}$ relation can be predicted from other two correlations involving the bulge velocity dispersion, σ . The first of these two is the $M_{\text{BH}} - \sigma$ relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000), which can be described by a single power-law ($M_{\text{BH}} \propto \sigma^5$) over the range in velocity dispersion $70 - 350 \text{ km s}^{-1}$ (e.g. Graham et al. 2011; McConnell et al. 2011; Graham & Scott 2013). The second is the $L_{\text{sph}} - \sigma$ relation, which has long been known to be a “double power-law”, being $L_{\text{sph}} \propto \sigma^5$ at the luminous end (Schechter 1980; Malumuth & Kirshner 1981; von der Linden et al.

2007; Liu et al. 2008), and $L_{\text{sph}} \propto \sigma^2$ at intermediate and faint luminosities (Davies et al. 1983; Held et al. 1992; Matković & Guzmán 2005; de Rijcke et al. 2005; Balcells et al. 2007; Chilingarian et al. 2008; Forbes et al. 2008; Cody et al. 2009; Tortora et al. 2009; Kourkchi et al. 2012). The change in slope of the $L_{\text{sph}} - \sigma$ relation occurs at $M_B \approx -20.5 \text{ mag}$, corresponding to $\sigma \approx 200 \text{ km s}^{-1}$. That is, the $M_{\text{BH}} - L_{\text{sph}}$ relation should be better described by a “broken”, rather than a single, power-law, having $M_{\text{BH}} \propto L_{\text{sph}}^{2.5}$ at the low-luminosity end, and $M_{\text{BH}} \propto L_{\text{sph}}^1$ at the high-luminosity end. Due to the scatter in the $M_{\text{BH}} - L_{\text{sph}}$ (or $M_{\text{BH}} - M_{\text{sph}}$) diagram, studies that have not sufficiently probed below $M_{\text{BH}} \approx 10^7 M_{\odot}$ can easily miss the change in slope occurring at $M_{\text{BH}} \approx 10^{(8 \pm 1)} M_{\odot}$, and erroneously recover a single log-linear relation.

When Graham (2012) pointed out this overlooked inconsistency, he identified two different populations of galaxies, namely the core-Sérsic (Graham et al. 2003; Trujillo et al. 2004) and Sérsic spheroids¹, and attributed the change in slope (from log-quadratic to log-linear) to their different formation mechanisms. In this scenario, core-Sérsic spheroids are built in additive dry merger events, where the black hole and the bulge grow at the same pace, increasing their mass in lock steps ($M_{\text{BH}} \propto L_{\text{sph}}^1$), whereas Sérsic spheroids originate from gas-rich processes, in which the mass of the black hole increases more rapidly than the mass of its host spheroid ($M_{\text{BH}} \propto L_{\text{sph}}^{2.5}$). Graham & Scott (2013) and Scott et al. (2013) presented double power-law linear regressions for Sérsic/core-Sérsic spheroids in the $M_{\text{BH}} - L_{\text{sph}}$ and $M_{\text{BH}} - M_{*,\text{sph}}$ (spheroid stellar mass) diagrams, respectively, probing down to $M_{\text{BH}} \approx 10^6 M_{\odot}$. To obtain their dust-corrected *bulge* magnitudes, they did not perform bulge/disc decompositions, but instead they converted B -band and K_S -band observed, total *galaxy* magnitudes using a mean statistical correction based on each object’s morphological type and disc inclination². It should be noted that $\sim 80\%$

¹ Core-Sérsic spheroids have partially depleted cores relative to their outer Sérsic light profile, whereas Sérsic spheroids have no central deficit of stars. While core-Sérsic spheroids are also “core galaxies”, as given by the Nuker definition (Lauer et al. 2007b), it should be noted that $\sim 20\%$ of “core galaxies” are not core-Sérsic spheroids (Dullo & Graham 2014, their Appendix A.2), i.e. do not have depleted cores. The change in slope of the $L_{\text{sph}} - \sigma$ relation corresponds to the division between core-Sérsic and Sérsic spheroids (e.g. Graham & Guzmán 2003).

² While this resulted in individual bulge magnitudes not being exactly correct, their large sample size allowed them to obtain a reasonably ensemble average correction.

of their core-Sérsic spheroids were morphologically classified as elliptical galaxies, and $\sim 80\%$ of their Sérsic spheroids were morphologically classified as bulges of disk galaxies (lenticulars and spirals).

Several recent papers (Jiang et al. 2011, 2013; Mathur et al. 2012; Reines et al. 2013) claimed 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 expected from the near-linear correlation traced by the high-mass, early-type spheroids. However, Graham & Scott (2015) showed that the low-mass spheroids ($10^{8.5} \lesssim M_{*,\text{sph}}/M_{\odot} \lesssim 10^{10.5}$) are not randomly offset from the high-mass, near-linear correlation, but lie on the two times steeper relation traced by the Sérsic spheroids.

Here we investigate substructure in the $M_{\text{BH}} - L_{\text{sph}}$ and $M_{\text{BH}} - M_{*,\text{sph}}$ diagrams using state-of-the-art galaxy decompositions (Savorgnan & Graham *in preparation*, hereafter *Paper I*) for the largest sample of galaxies with directly measured black hole masses. Our decompositions were obtained from $3.6 \mu\text{m}$ *Spitzer* satellite imagery, which is an excellent proxy for the stellar mass, superior to the K -band (Sheth et al. 2010 and references therein). Nine of our galaxies have $M_{\text{BH}} \lesssim 10^7 M_{\odot}$, which allows us to accurately constrain the slope of the correlation at the low-mass end. In addition to this, our galaxy sample includes 17 spiral galaxies, representing a notable improvement over the past studies dominated by early-type systems.

2. DATA

Our galaxy sample consists of 66 objects for which a dynamical measurement of the black hole mass had been reported in the literature at the time we started this project, and for which we were able to obtain useful bulge parameters from $3.6 \mu\text{m}$ *Spitzer* satellite imagery. Bulge luminosities were derived from our state-of-the-art galaxy decompositions, which take into account bulges, disks, spiral arms, bars, rings, haloes, extended or unresolved nuclear sources and partially depleted cores. Kinematical information (Emsellem et al. 2011; Scott et al. 2014; Arnold et al. 2014) was used to confirm the presence of rotationally supported components in most early-type galaxies, and to identify their extent (intermediate-scale, embedded disks or large-scale disks). *Paper I* will present the dataset used here to investigate the $M_{\text{BH}} - L_{\text{sph}}$ and $M_{\text{BH}} - M_{*,\text{sph}}$ diagrams, give details about the data reduction process and the sophisticated galaxy modelling technique that we developed, and illustrate the individual 66 galaxy decompositions.

3. ANALYSIS

4. ANALYSIS

5. RESULTS

6. CONCLUSIONS

This research was supported by Australian Research Council funding through grants DP110103509 and FT110100263. 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. This research has made

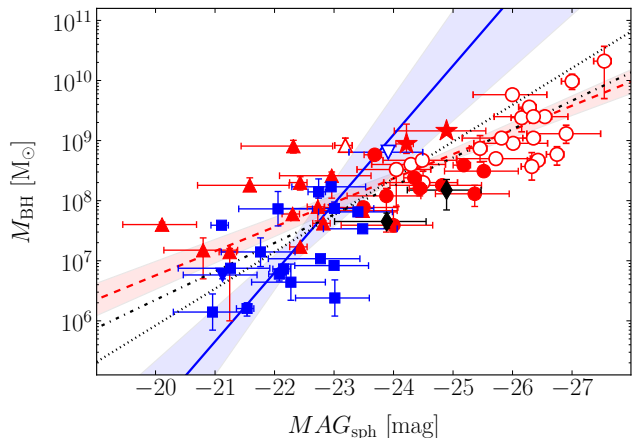


FIG. 1.—

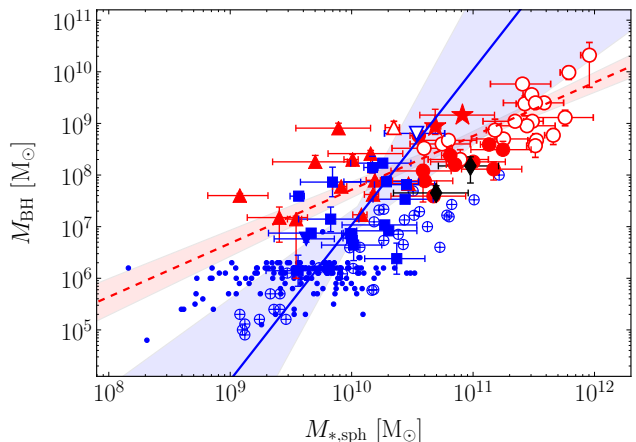


FIG. 2.—

use of the GOLDMine database (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.

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