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The Black Hole Mass - Spheroid Luminosity relation

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ABSTRACT

The differing $M_{\rm bh}$-L relations presented in McLure & Dunlop, Marconi & Hunt and Erwin et al. have been investigated. A number of issues have been identified and addressed in each of these studies, including but not limited to: the removal of a dependency on the Hubble constant; a correction for dust attenuation in the bulges of disc galaxies; the identification of lenticular galaxies previously treated as elliptical galaxies; and application of the same $(Y|X)$ regression analysis. These adjustments result in relations which now predict similar black hole masses. The optimal K-band relation is $\log(M_{\rm bh}/M_{\odot}) = -0.37(\pm 0.04)[M_K + 24] + 8.29(\pm 0.08)$, with a total (not intrinsic) scatter in $\log M_{\rm bh}$ equal to 0.33 dex. This level of scatter is similar to the value of 0.34 dex from the $M_{\rm bh}$-σ relation of Tremaine et al. and compares favourably with the value of 0.31 dex from the $M_{\rm bh}$-n relation of Graham & Driver. Using different photometric data, consistent relations in the B- and R-band are also provided, although we do note that the small $(N = 13)$ R-band sample used by Erwin et al. is found here to have a slope of -0.30 ± 0.06 and a total scatter of 0.31 dex. Performing a symmetrical regression on the larger K-band sample gives a slope of ~ -0.40, implying $M_{\rm bh} \propto L^{1.00}$. Implications for galaxy-black hole coevolution, in terms of dry mergers, are briefly discussed, as are the predictions for intermediate mass black holes. Finally, as previously noted by Tundo et al., a potential bias in the galaxy sample used to define the $M_{\rm bh}$-L relations is shown and a corrective formula provided.

Key words: black hole physics — galaxies: bulges — galaxies: photometry —

1 INTRODUCTION

The mass of a spheroid's supermassive black hole (SMBH), denoted by $M_{\rm bh}$, is known to correlate with several physical properties of the spheroid, by which we mean either an elliptical galaxy or the bulge of a disc galaxy. At first it was thought that the velocity dispersion, σ, of the bulge was the primary driving mechanism (Ferrarese & Merritt 2000; Gebhardt et al. 2000). However, in the following year the radial concentration of stars in the spheroids was observed to correlate just as well with the SMBH mass and yielded a relation with the same small degree of scatter (Graham et al. 2001). While the luminosity of the stars initially appeared to provide a weaker relation, it is now known that this was predominantly due to rough estimates of the spheroid's luminosity. Performing a Sérsic (1963) $R^{1/n}$-bulge plus exponential disc decomposition of the galaxy light, Marconi & Hunt (2003) and Erwin et al. (2004) revealed that the total scatter about the near-infrared and optical $M_{\rm bh}$-L relations was similarly small at ∼0.35 dex. Most recently, Graham & Driver (2007a, their Section 6) have predicted that the central stellar density, prior to core-depletion of the host spheroid, may also be intimately connected with the SMBH mass.

These relationships are important for two main reasons. First, they provide an easy means to predict SMBH masses in thousands of galaxies for which direct measurements of the SMBH mass is not possible (e.g., Yu & Tremaine 2002; Marconi et al. 2004; Shankar et al. 2004; Graham et al. 2007 and references therein). The other reason is that they are a clue to the driving physical processes at work in galaxies.

However, as with the controversy over the slope of the $M_{\rm bh}$-σ relation (Merritt & Ferrarese 2001a; Tremaine et al. 2002; Novak et al. 2006), the slope of the $M_{\rm bh}$-L relation is not yet agreed upon. While McLure & Dunlop report a value of -0.50 ± 0.05, the data in Erwin et al. (2004) has a slope of -0.25 ± 0.05. Moreover, the differing relations from different studies tend not to predict the same SMBH mass. For example, when $L_K = 10^{10} L_{K,\odot}$ $(10^{11} L_{K,\odot})$, the K-band expression in McLure & Dunlop (2004, their equation 1) predicts SMBH masses which are three (two) times less than those predicted by the K-band $M_{\rm bh}$-L relation in Marconi & Hunt (2003).

In this paper we re-investigate the past $M_{\rm bh}$-L rela-

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tions and address a number of ways in which they can be updated. In Section 2 we present an early data set used to construct an $M_{\rm bh}$-L relation. We use this data to illustrate how we define the regression analysis that we shall adopt in this paper. Section 3 starts with studies which avoided the bulge/disc separation issue by excluding disc galaxies. while Section 4 explores those studies which used elliptical, lenticular and spiral galaxies. We obtain new B-, R- and K-band relations which are consistent with each other and suitable for predicting black hole masses in other galaxies. In Section 5 we discuss how intermediate mass black holes factor in, and briefly mention some of the implications of these new relations for the coevolution of spheroids and SMBHs,

Finally, in an appendix we provide a re-derivation of the $M_{\rm bh}$-L relation taking into allowance a potential bias in the galaxy sample.

2 CONSTRUCTION OF THE $M_{\rm BH}$-L RELATION

2.1 Kormendy & Gebhardt (2001)

As noted by Kormendy & Gebhardt (2001, see their section 5) SMBHs seem to be associated with the dynamically hot, spheroidal component of a galaxy. Those authors therefore presented a B-band relation based on the bulge, rather than total, magnitudes from Faber et al. (1997). Using $M_{B,\odot} = 5.47$ mag, their $M_{\rm bh}$-L relation can be written as

$$\log(M_{\rm bh}/M_\odot) = -0.43[M_B + 19.5] + 7.88. \quad (1)$$

Given our objective is to construct the optimal relation ($y = a + bx$) for estimating the SMBH mass (y) from the magnitude (x) of a galaxy, we adopt the method of regression analysis given in Tremaine et al. (2002)[1] We allow for intrinsic scatter (in the y-direction), which we denote by the term ϵ, and also for measurement errors on the N pairs of observables x_i and y_i, which we denote δx_i and δy_i. Tremaine et al.'s (2002) modified version of the routine FITEXY (Press et al. 1992, their Section 15.3) minimises the quantity

$$\chi^2 = \sum_{i=1}^{N} \frac{(y_i - a - bx_i)^2}{\delta {y_i}^2 + b^2 \delta {x_i}^2 + \epsilon^2}. \quad (2)$$

The intrinsic scatter ϵ is solved for by repeating the fit until $\chi^2/(N-2)$ equals 1. The uncertainty on ϵ is obtained when the reduced chi-squared value, $\chi^2/(N-2)$, equals $1 \pm \sqrt{2/N}$. To achieve a minimisation in the x-direction, one simply replaces the ϵ^2 term in the denominator of equation 2 with $b^2\epsilon^2$. A symmetrical regression is therefore some kind of average of these two regressions (Novak et al. 2006).

Application of equation 2 to the data from Kormendy & Gebhardt yields the relation

$$\log(M_{\rm bh}/M_\odot) = -0.38(\pm 0.06)[M_B + 19.5] + 8.00(\pm 0.09), \quad (3)$$

which has a total rms scatter of 0.56 dex in the $\log M_{\rm bh}$ direction and an intrinsic scatter (assuming a magnitude error of 0.3 mag) of $0.46^{+0.08}_{-0.06}$ dex.

This level of scatter is unpleasantly high and resulted in the $M_{\rm bh}$-L relation taking second place to the $M_{\rm bh}$-σ (and $M_{\rm bh}$-n) relation. However, it has since been realised/shown that this level of scatter was a consequence of a poor bulge/disc separation (Marconi & Hunt 2003; Erwin et al. 2004) and the use of systems in which the SMBH's sphere of influence was not well resolved (e.g. Merritt & Ferrarese 2001c; Ferrarese & Ford 2005). The following Section avoids the issue of the bulge/disc separation by dealing with a study that used elliptical galaxies. Section 4 effectively tackles this issue by using studies in which a Sérsic-bulge[2] plus exponential-disc decomposition of the galaxy's stellar light has been performed.

3 ELLIPTICAL GALAXIES

3.1 McLure & Dunlop (2002)

Given that the mass of a SMBH is known to correlate with the properties of the host spheroid, rather than the host galaxy, McLure & Dunlop (2002) presented the $M_{\rm bh}$-L relation after excluding (the bulk of the) disc galaxies[3]. Their expression (for a predominantly elliptical galaxy sample) is

$$\log(M_{\rm bh}/M_\odot) = -0.50(\pm 0.05)M_R - 2.91(\pm 1.23). \quad (4)$$

Here we re-derive this expression after implementing the following alterations.

- Measurements of black hole mass depend linearly on the distance to each galaxy. Distances for 16 of the 18 galaxies used by McLure & Dunlop have been obtained using surface brightness fluctuations (Tonry et al. 2001) and so their SMBH masses are independent of the Hubble constant. However, in converting the apparent magnitude of these 18 galaxies into absolute magnitudes, McLure & Dunlop used the galaxy redshift and a Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1}. This was done because of their comparison with a sample of AGN for which $H_0 = 50$ km s^{-1} Mpc^{-1} had been used. A more consistent approach would involve the use of the H_0-independent distances for the non-AGN galaxies to determine their absolute magnitudes, and a Hubble constant of 73 km s^{-1} Mpc^{-1} (Blakeslee et al. 2002) for the AGN sample. Here we use these H_0-independent distances for *both* the SMBH masses and the spheroid magnitudes of our (local non-AGN) galaxies.
- Nine of the 18 R-band magnitudes which McLure & Dunlop used were ($B - R_c = 1.57$)-adjusted B-band magnitudes from Faber et al. (1997) — which themselves came from the "Seven Samurai" data (Faber et al. 1989) and/or the third reference galaxy catalogue (RC3, de Vaucouleurs et al. 1991). The other nine R-band magnitudes are reported to be ($V - R = 0.61$)-adjusted V-band magnitudes from Merritt & Ferrarese (2001b). Although this paper has no V-band

[1] This is not a symmetrical method of regression, but rather one which minimises the scatter in the y-direction (see Novak et al. 2006 and Graham & Driver 2007a). The criticism in Tundo et al. (2007, their Section 2.2) of the Tremaine et al. (2002) method is therefore misplaced.

[2] A modern review of the Sérsic model can be found in Graham & Driver (2005).

[3] Bettoni et al. (2003) performed the same task, obtaining a consistent relation.

magnitudes, Merritt & Ferrarese (2001a) has V-band magnitudes from Faber et al. (1989) for 4 of these 9 galaxies. We therefore use the Faber et al. (1989) B-band apparent magnitudes (and the related absolute magnitudes in Tremaine et al. 2002). The Faber et al. (1989) magnitudes are derived from photoelectric aperture growth curves. While the magnitude quality indicators from that paper suggest an error of < 0.15 or 0.30 mag, depending on the galaxy, we have adopted the upper value for all galaxies in our regression analysis.

- We have removed NGC 4564 and NGC 2778 which are not elliptical galaxies but S0 galaxies[4] (see Graham & Driver 2007b) whose total galaxy luminosities would have biased the previous relation. We have also excluded the peculiar elliptical galaxy IC 1459 due to uncertainty on its SMBH mass. While the stellar dynamics of its core suggest a SMBH mass of $2.6\times10^9 M_\odot$, the gas dynamics reveal the mass could be as low as $3.5\times10^8 M_\odot$ (Cappellari et al. 2002). We have treated NGC 221 as an S0 galaxy according to the B/T flux ratio in Graham (2002).
- We have included NGC 1399 and NGC 5845 for which accurate SMBH masses have since become available, giving a total of 17 galaxies.
- Due to our desire to obtain a relation for predicting accurate SMBH masses using the magnitudes of other galaxies, we perform a non-symmetrical regression which results in the smallest degree of scatter in the $\log M_{\rm bh}$ direction. That is, we apply equation 2.

Table 1 provides distances, updated SMBH masses (based on these distances) and absolute magnitudes (again based on these distances) for this set of galaxies. Using the distances and apparent bulge magnitudes from Table 1, and applying equation 2, we obtain the relation

$$\log(M_{\rm bh}/M_\odot) = -0.42(\pm0.06)[M_B+20] + 8.32(\pm0.10), (5)$$

with an absolute scatter in $\log M_{\rm bh}$ of 0.36 dex. This relation can be seen in Figure 1. Using the absolute magnitudes given in Table 1, rather than the apparent magnitudes, one obtains

$$\log(M_{\rm bh}/M_\odot) = (-0.36\pm0.06)[M_B+20] + (8.33\pm0.10). (6)$$

These equations have an order of magnitude less uncertainty on the intercept term than the uncertainty given in equation 4. They also have a shallower slope.

3.1.1 Independence of H_0

As can be seen in Table 1, two of the galaxies used to construct the above $M_{\rm bh}$-L relation have magnitudes and black hole masses that depend on the Hubble constant. We have explored whether or not equation 5 and 6 would be significantly different if (i) these two galaxies were excluded and (ii) if we had used a Hubble constant of 50 or 100, rather than 73 km s^{-1} Mpc^{-1} for these two galaxies (NGC 6251 and NGC 7052). In all cases the slope and intercept varied by no more than 0.02 and 0.03, respectively. What this means is that the $M_{\rm bh}$-L relations given above, and in the rest of this Section, are effectively independent of the Hubble constant.

Table 1. Revised (see Section 3.1) sample of elliptical galaxies from McLure & Dunlop (2002). Distances are taken from Tonry et al. (2001, their table 1), except for NGC 6251 ($v_{\rm CMB}$=7382 km s^{-1}, Wegner et al. 2003) and NGC 7052 ($v_{\rm CMB}$=4411 km s^{-1}, Wegner et al. 2003). These two galaxies are not listed in Tonry et al. (2001) and a Hubble constant of $H_0 = 73$ km s^{-1} Mpc^{-1} (Blakeslee et al. 2002; Spergel et al. 2006) has been used. Unless noted otherwise, the apparent B-band magnitudes, m_B, are the B_T^0 magnitudes from Faber et al. (1989, 1997). Unless noted otherwise, the absolute B-band magnitudes, M_B, have come from Tremaine et al. (2002) with modifications for NGC 6251 and NGC 7052 such that we adjusted the Tremaine et al. values (-21.81 and -21.31 mag) to our adopted distance. The SMBH masses are also from the compilation in Tremaine et al. (2002), except for NGC 821 (Richstone et al. 2007), NGC 3379 (Gebhardt et al. 2000; see also Shapiro et al. 2006), and NGC 4486 (Macchetto et al. 1997). Our sample includes two additional galaxies not used in Tremaine et al. The SMBH mass for NGC 1399 is from Houghton et al. (2006) and the mass for NGC 4374 is from Maciejewski & Binney (2001, with updated errors taken from Kormendy & Gebhardt 2001).

Galaxy	Dist. [Mpc]	m_B [mag]	M_B [mag]	$M_{\rm bh}$ [$10^8 M_\odot$]
NGC 221	0.81	(9.28)[a]	(−14.50)[b]	$0.025^{+0.005}_{-0.005}$
NGC 821[c]	24.1	11.57	−20.41	$0.85^{+0.35}_{-0.35}$
NGC 1399	20.0	10.55	(−20.96)[d]	12^{+5}_{-6}
NGC 3377[e]	11.2	11.13	−19.05	$1.00^{+0.9}_{-0.1}$
NGC 3379	10.6	10.43	−19.94	$1.35^{+0.73}_{-0.73}$
NGC 3608	22.9	11.68	−19.86	$1.90^{+1.0}_{-0.6}$
NGC 4261	31.6	11.32	−21.09	$5.20^{+1.0}_{-1.1}$
NGC 4291	26.2	12.42	−19.63	$3.10^{+0.8}_{-2.3}$
NGC 4374	18.4	10.13	(−21.19)[f]	$4.64^{+3.46}_{-1.83}$
NGC 4473	15.7	11.21	−19.89	$1.10^{+0.40}_{-0.79}$
NGC 4486	16.1	9.52	−21.53	$34.3^{+9.7}_{-9.7}$
NGC 4649	16.8	9.77	−21.30	$20.0^{+4.0}_{-6.0}$
NGC 4697	11.7	10.03	−20.24	$1.70^{+0.2}_{-0.1}$
NGC 4742	15.5	12.03	−18.94	$(0.14^{+0.04}_{-0.05})$[g]
NGC 5845	25.9	13.35	−18.72	$2.40^{+0.4}_{-1.4}$
NGC 6251	$101h_{73}^{-1}$	(13.64)[h]	−21.99	$5.80^{+1.8}_{-2.0}$
NGC 7052	$60h_{73}^{-1}$	(12.73)[i]	−21.36	$3.40^{+2.4}_{-1.3}$

[a] Reduced using a B/T ratio of 0.62 (Graham 2002).
[b] R-band bulge magnitude from Graham (2002) with a $B-R=$ 1.84 mag adjustment (Lugger et al. 1992.
[c] SMBH sphere of influence not resolved.
[d] Derived from the apparent magnitude.
[e] SMBH sphere of influence not resolved.
[f] Derived from the apparent magnitude.
[g] This SMBH mass is based on M.E. Kaiser (2001, in prep.).
[h] RC3 $B(m_B^0)$ value. (No value in Faber et al. 1989.)
[i] RC3 $B(m_B^0)$ value. (No value in Faber et al. 1989.)

3.1.2 An R-band $M_{\rm bh}$-L relation

As already noted, the R-band relation from McLure & Dunlop (2002) was based on the Faber et al. (1989) B-band mag-

[4] Lenticular galaxies have typical bulge-to-total luminosity ratios of 1/4 (e.g., Balcells, Graham & Peletier 2004; Laurikainen, Salo & Buta 2005).

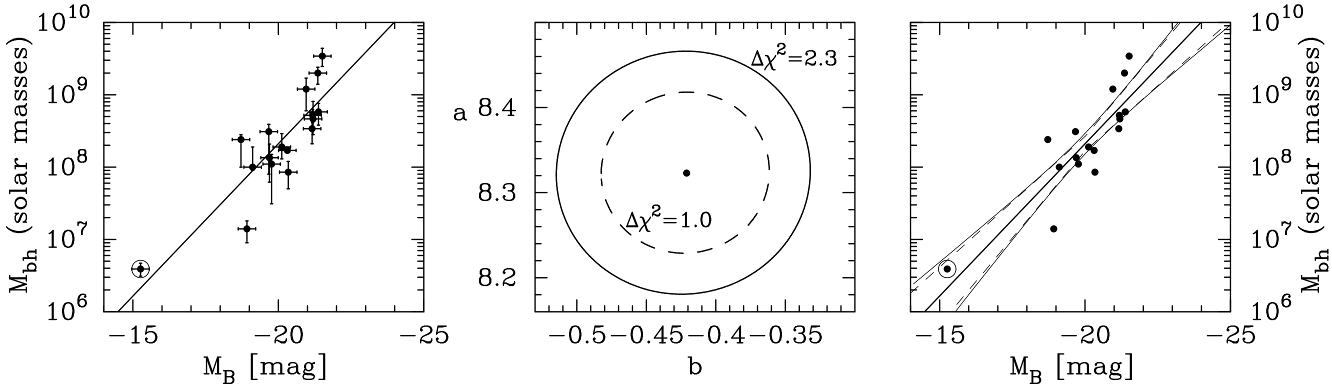

Figure 1. Correlation between an elliptical galaxy's supermassive black hole mass and the apparent B-band magnitudes listed in Table 1. The regression line shown in the left panel was obtained using equation 5. NGC 221 (M32) is plotted with a circle around it. The middle panel shows the $\Delta\chi^2 = 1.0$ and 2.3 boundaries around the optimal intercept, $a = 8.32$, and slope, $b = -0.42$. The projection of the $\Delta\chi^2 = 1.0$ ellipse onto the vertical and horizontal axis gives the 1-σ uncertainties δa and δb, respectively. The $\Delta\chi^2 = 2.3$ ellipse denotes the 1-σ *two-dimensional* confidence region. This latter quantity has been mapped into the right panel, and is traced by the two solid curves. The dashed lines in this panel are the (more commonly used) approximations obtained using $(a \pm \delta a)$ and $(b \pm \delta b)$. The two confidence regions agree well, although the region traced by the dashed lines is, as expected, smaller.

nitudes and an $B - R_c$ colour[5] equal to 1.57 mag. Adopting this same colour term, except for NGC 221 which has a $B-R$ colour of 1.84 (Lugger et al. 1992), and using the absolute magnitudes given in Table 1, one obtains the relation

$$\log(M_{\rm bh}/M_{\odot}) = -0.38(\pm0.06)[M_R + 21] + 8.11(\pm0.11). \quad (7)$$

For a dynamically hot spheroid with $M_R = -21$ mag, McLure & Dunlop's relation (equation 4) gives values of $\log M_{\rm bh}$ which are 0.52 dex less massive, i.e. roughly a factor of three less massive, and considerably offset from our refined zero-point at $M_R = -21$ mag, given by 8.11 ± 0.11. However it should be noted that most of this offset (at $M_R = -21$ mag) is simply due to the prior use of $H_0 = 50$ km s^{-1} Mpc^{-1} when deriving the absolute magnitudes used in equation 4. If a value of 73 km s^{-1} Mpc^{-1} is used there, then the masses are now only 0.11 dex smaller, which is consistent with the 0.11 dex uncertainty on the new zero-point.

3.1.3 A K-band $M_{\rm bh}$-L relation

We also update the K-band relation presented in McLure & Dunlop (2004, their equation 1), which was derived there using an $R - K$ colour of 2.7 mag applied to their R-band relation from McLure & Dunlop (2002). When McLure & Dunlop (2004) converted McLure & Dunlop's (2002) $M_{\rm bh}$-L relation, they also applied a Hubble conversion of log(50/70) to the black hole masses and 5 log(50/70) to the magnitudes. This is not applied here because equation 7 is, for practical purposes, independent of the Hubble constant (Section 3.1.1). Adopting an $R - K$ colour of 2.6 mag (Buzzoni 2005), equation 7 becomes

$$\log(M_{\rm bh}/M_{\odot}) = -0.38(\pm0.06)[M_K + 24] + 8.26(\pm0.11). \quad (8)$$

Using here an absolute K-band magnitude for the Sun of $M_{K,\odot} = 3.28$, this can alternatively be expressed as

$$\log(M_{\rm bh}/M_{\odot}) = 0.95(\pm0.15) \log \frac{L_{K,sph}}{10^{10.91} L_{K,\odot}} + 8.26(\pm0.11), \quad (9)$$

where $L_{K,sph}/L_{K,\odot}$ is the K-band luminosity of the spheroid component of the galaxy (i.e., the bulge or the elliptical galaxy itself) in solar units.

[5] From here on the subscript c shall be dropped from the term R_c.

4 INCLUDING THE DISC GALAXIES

More recent studies have included both elliptical galaxies and the bulges of disc galaxies. In this section we explore the $M_{\rm bh}$-L expressions obtained with both sets of objects.

4.1 Erwin, Graham & Caon (2002)

In 2002 Erwin, Graham & Caon presented a relation between black hole mass and host spheroid magnitude for a sample of 13 galaxies (8 elliptical and 5 disc galaxies). The study was presented at the Carnegie Observatories Astrophysics conference "Coevolution of Black Holes and Galaxies" and posted to astro-ph that same year. For the disc galaxies, the bulge magnitudes were obtained from an $R^{1/n}$-bulge plus exponential-disc decomposition (Graham et al. 2001). This was the first study, albeit small in number, to show that the inclusion of bulge galaxies resulted in a total scatter of 0.35 dex in $\log M_{\rm bh}$, considerably less than past reports of ∼0.6 dex and comparable to the scatter in the $M_{\rm bh}$-σ and $M_{\rm bh}$-n relations.

Using the data points shown in Figure 1.4 of Erwin et al. (2004), along with a 0.3 mag uncertainty on the magnitudes, we have performed a regression of $\log M_{\rm bh}$ against these R-band magnitudes (i.e., applied equation 2). Doing so gives

$$\log(M_{\rm bh}/M_{\odot}) = -0.24 \pm 0.05[M_R + 21] + 8.01 \pm 0.11, \quad (10)$$

with a total scatter of 0.35 dex. This is shown in Figure 2a.

This relation has a noticeably shallower slope than the value in equation 7 of $-0.38(\pm0.06)$ obtained using our refined elliptical galaxy sample from McLure & Dunlop (2002). When $M_R = -24$ mag, equation 10 gives masses of $\sim 5 \times 10^8 M_{\odot}$ — three times smaller than that obtained

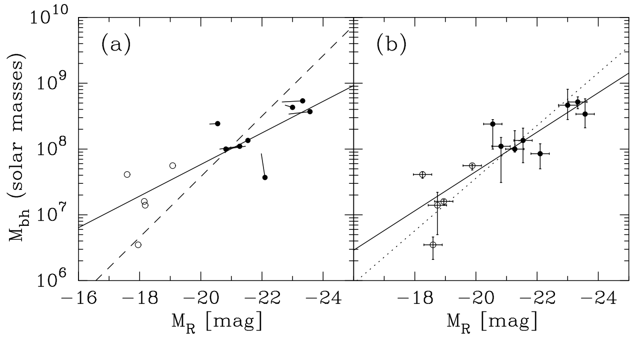

Figure 2. The long solid line shows the $M_{\rm bh}$-L relation (equation 10 and 12) using the 8 elliptical galaxies (filled circles) plus the bulges of 5 lenticular/spiral galaxies (open circles) given in Erwin et al. (2004). The short lines emanating from the elliptical galaxy data points in panel a) show the location of these galaxies as used in Section 3.1 to obtain equation 7 (shown by the long dashed line). Panel a) shows the data points as seen in Erwin et al. (2004; their Figure 1.3). Panel b) shows the data points as given in Table 2, which uses slightly updated SMBH masses and, most importantly, dust-corrected bulge magnitudes (see Section 4.1.1). The dotted line has a slope of −0.4.

using equation 7. When $M_R = -27$ mag, equation 10 gives masses of $\sim 3\times10^9 M_\odot$. In this regard, equation 10 does not conflict with the $M_{\rm bh}$-σ relation. That is, compared to the $M_{\rm bh}$-σ relation, equation 10 does not predict significantly larger SMBH masses at the high mass end. However, even if the Sérsic bulge (and elliptical galaxy) magnitudes used in Erwin et al. are reliable, the low number of points (only 13) may make equation 10 prone to statistical fluctuations in the selected sample.

In Figure 2 we show the data points used by Erwin et al. (2004). Also shown, for the elliptical galaxies, is their location using the values adopted in the previous Section where a slope of −0.38 was obtained. The only data point which has shifted significantly is NGC 821. The reason is because the previous section used the SMBH mass from Richstone et al. (2007, $8.5\times10^7 M_\odot$), while Erwin et al. used the (at the time unpublished) value of $3.7\times10^7 M_\odot$ (Tremaine et al. 2002).

4.1.1 Dust

While, in general, elliptical galaxies and the bulges of disc galaxies are considered not to have dust, this does not mean that the dust in the discs of disc galaxies does not influence the emergent flux from the stars in the bulge. To illustrate this, consider an infinitely thin and optically opaque dust sheet running through the disc of a galaxy. Obviously, near edge-on orientations aside, one will only see the bulge (and disc) stars on the near-side of the disc. That is, one will only see half of the optical flux from the bulge, it will therefore be observed to be 0.75 mag fainter than it actually is. In reality, dust discs have a certain thickness, relative to the vertical scale-height of the stars in the disc. This results in a dust correction that depends on the inclination of the disc relative to our line of sight.

Here we modify the B-band inclination-attenuation correction for bulge magnitudes given in Driver et al. (2007, their equation 3). Specifically, we use the expression

$$(M_{\rm obs} - M_{\rm dust-free})_{R,{\rm bulge}} = 0.6\times\left[0.84 + 2.16\left(1-\frac{b}{a}\right)^{2.48}\right], \quad (11)$$

in which the 0.84 term provides the face-on attenuation-correction to the observed magnitude of the bulge, $M_{\rm obs}$, while the latter part of the expression provides the inclination-dependent component of the correction. Equation 11 only differs from the B-band relation due to our (simplistic) use of a 0.6 multiplier. This multiplicative factor stems from our knowledge of the disc extinction/attenuation in the B- and R-bands (e.g. Tully & Verheijen 1997; Tully et al. 1998).

The five bulge magnitudes listed in Table 2 are corrected for dust using equation 11. The values plotted in Erwin et al. (2004), and the left panel of Figure 2 are some 0.55 to 0.80 mag fainter. Re-performing the regression analysis, with the dust-corrected magnitudes, and using the Richstone et al. (2007) SMBH mass for NGC 821, we obtain

$$\log(M_{\rm bh}/M_\odot) = -0.30(\pm0.06)[M_R + 21] + 7.96(\pm0.10), \quad (12)$$

with a scatter of 0.31 dex in $\log M_{\rm bh}$. This is shown in Figure 2b.

We have repeated this regression after the jackknife removal of NGC 2787, a galaxy with an inner disc twice as luminous as its bulge (Erwin et al. 2003), and the faintest object in our sample. Doing so results in a slope and intercept of -0.35 ± 0.05 and 7.90 ± 0.09, respectively. and a total scatter of 0.29 dex.

To better gauge the uncertainty on the slope in equation 12, we have also used a bootstrap sampling of 13 data points (i.e. sampling with replacement from the original sample) and 1000 such Monte Carlo samples. The median $\pm2\sigma$ of the resultant distribution of 1000 slopes was -0.31 ± 0.11. For the intercept we obtained $7.96^{+0.16}_{-0.17}$.

4.2 Marconi & Hunt (2003)

4.2.1 A K-band $M_{\rm bh}$-L relation

Using images from *2MASS*[6], Marconi & Hunt (2003) obtained K-band magnitudes for 27 galaxies which had direct and reliable SMBH mass measurements. Recognising the need for bulge magnitudes rather than galaxy magnitudes, they also performed an $R^{1/n}$-bulge plus exponential-disc decomposition of the disc galaxies in their sample. With a sample size twice that used in Erwin et al. (2004), they confirmed Erwin et al.'s claim for a scatter of around 0.35 dex in the $M_{\rm bh}$-L relation for elliptical galaxies and the bulges of disc galaxies. In what follows we describe the manner and reason for why we have tweaked the masses and magnitudes for some of their galaxy sample.

- Due to the shallow nature of the *2MASS* images (only 8 seconds) the presence of a disc in NGC 2778[7] and NGC 4564 were missed. NGC 221 (M32) was also treated as a pure elliptical galaxy. From the R-band bulge/disc decomposition of these three galaxies in Graham & Driver (2007a) and

[6] Two micron all sky survey: Jarrett et al. (2000).

[7] Because we used Marconi & Hunt's preferred 27 "Group 1" galaxies (see their Table 1), NGC 2778 does not actually factor into the analysis here because it is tabulated as a "Group 2" galaxy.

Table 2. Revised sample of elliptical and disc galaxies from Erwin et al. (2004). A galaxy Type 'E' denotes an elliptical galaxy while a Type 'S' denotes either an S0 galaxy or a spiral galaxy. Distances are taken from Tonry et al. (2001, their table 1), except for NGC 7052 ($v_{\rm CMB}$=4411 km s^{-1}, Wegner et al. 2003) which is not listed in Tonry et al. A Hubble constant of $H_0 = 73$ km s^{-1} Mpc^{-1} has been used for this galaxy. The SMBH masses are from the compilation in Tremaine et al. (2002), except for NGC 821 (Richstone et al. 2007) and NGC 3379 (Gebhardt et al. 2000). Our sample includes one additional galaxy not used in Tremaine et al. The SMBH mass for NGC 4374 is from Maciejewski & Binney (2001, with updated errors taken from Kormendy & Gebhardt 2001). Disc inclinations, i.e. b/a axis ratios of the outer isophotes, have come from: NGC 2778 (Rix et al. 1999); NGC 2787 (Erwin et al. 2003); NGC 3384 (Faber et al. 1997); NGC 4564 (Faber et al. 1997, see also Graham & Driver 2007a); and NGC 7457 (Chapelon et al. 1999). The magnitudes are from Erwin et al. (2004), but corrected for dust attenuation using equation 11.

Galaxy	Type	Dist. [Mpc]	b/a	M_R [mag]	$M_{\rm bh}$ [$10^8 M_\odot$]
NGC 0821	E	24.1	...	-22.10	$0.85^{+0.35}_{-0.35}$
NGC 3377	E	11.2	...	-21.27	$1.00^{+0.9}_{-0.1}$
NGC 3379	E	10.6	...	-21.54	$1.35^{+0.73}_{-0.73}$
NGC 4261	E	31.6	...	-23.33	$5.20^{+1.0}_{-1.1}$
NGC 4374	E	18.4	...	-23.00	$4.64^{+3.46}_{-1.83}$
NGC 4473	E	15.7	...	-20.82	$1.10^{+0.40}_{-0.79}$
NGC 5845	E	25.9	...	-20.55	$2.40^{+0.4}_{-1.4}$
NGC 7052	E	$60h_{73}^{-1}$	...	-23.57	$3.40^{+2.4}_{-1.3}$
NGC 2778	S	22.9	0.72	-18.74	$0.14^{+0.08}_{-0.09}$
NGC 2787	S	7.5	0.57	-18.25	$0.41^{+0.04}_{-0.05}$
NGC 3384	S	11.6	0.45	-18.95	$0.16^{+0.01}_{-0.02}$
NGC 4564	S	15.0	0.45	-19.88	$0.56^{+0.03}_{-0.08}$
NGC 7457	S	13.2	0.59	-18.60	$0.035^{+0.011}_{-0.014}$

Graham (2002), the bulge-to-total flux ratios are 0.21, 0.24 and 0.62 respectively. We have used these ratios to obtain the bulge magnitudes for these galaxies. In passing we note that lenticular galaxies typically have B/T ratios of $\sim 0.25 \pm 0.10$ (Balcells et al. 2004; Laurikainen et al. 2005), the higher B/T value for M32 is to be expected if this is a partially disc-stripped lenticular galaxy (see Bekki et al. 2001; Graham 2002).

- We have excluded IC 1459 due to the order of magnitude uncertainty on its black hole mass (Cappellari et al. 2002), reducing our sample size from 27 to 26 galaxies (see Table 3).
- We have updated the SMBH mass and its associated uncertainty for NGC 5252 using the now published result in Capetti et al. (2005) together with a distance of 94.4 Mpc (slightly different to the value of 96.8 Mpc in Marconi & Hunt, and obtained using a recession velocity of 6888 km s^{-1} and $H_0 = 73$ km s^{-1} Mpc^{-1}) to give $M_{\rm bh} = 0.97^{+1.49}_{-0.46} \times 10^9 M_\odot$. While this distance and mass is only 2.5 per cent smaller than that given in Marconi & Hunt, the uncertainty on the mass is 2-3 times larger.
- We have also slightly modified the SMBH mass for Cygnus A by using the value $M_{\rm bh} = (2.6 \pm 0.7) \times 10^9 M_\odot$. This was obtained from the mass in Tadhunter et al. (2003) after using a redshift of 0.056 and adopting $H_0 = 73$ km s^{-1} Mpc^{-1} together with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. This gave a luminosity distance of 240 Mpc and an angular distance of 215 Mpc (c.f. 207 Mpc in Tadhunter et al.). This mass is still consistent with the value of $(2.9 \pm 0.7) \times 10^9 M_\odot$ used in Marconi & Hunt (2003).
- In addition to NGC 5252 and Cygnus A, Marconi & Hunt's sample includes a further four galaxies not listed in Tremaine et al. (2002). The SMBH mass we have used for NGC 3031 (M81) is from Devereux et al. (2003), the mass for NGC 5128 (Cen A) has come from Marconi et al. (2001) and the mass for NGC 4594 is from Kormendy et al. (1988). The mass for NGC 4374 (M84) has been taken from Maciejewski & Binney (2001, with updated errors taken from Kormendy & Gebhardt 2001). These masses are the same as used by Marconi & Hunt, except for NGC 4374.
- For the remaining 20 galaxies we have adopted the SMBH masses given in Tremaine et al. (2002), with only the following three exceptions: NGC 3379 (Gebhardt et al. 2000; see also Shapiro et al. 2006), NGC 4486 (M87, Macchetto et al. 1997) and NGC 3115 (Emsellem, Dejonghe, & Bacon 1999). Our mass for NGC 3379 is 35 per cent larger than that used by Marconi & Hunt, while the difference in mass for the other two galaxies is only ∼1 per cent from that used by Marconi & Hunt.
- We also note that Marconi & Hunt used a distance of 107 Mpc for NGC 6251, slightly greater than the value of 101 Mpc which we adopted in the previous section and which we use here for consistency. This results in our reduction of the SMBH mass for this galaxy by the fraction 101/107, and a dimming of the absolute magnitude by $5 \log(107/101)$.

Table 3 presents our updated and modified data set from Marconi & Hunt's Group 1 galaxies. Finally, we again note that we perform a non-symmetrical regression analysis, as is given in equation 2. Marconi & Hunt used the symmetrical bisector linear regression algorithm of Akritas & Bershady (1996) when reporting their optimal relation. As can be seen in their Figure 1, this results in a slightly steeper slope than obtained with an ordinary (non-symmetrical) least-squares fit to the data (see also Section 5.2 of this paper). Marconi (2007, priv. comm.) reports that the slope of their data using equation 2 is -0.41 ± 0.04.

Figure 3 shows the K-band $M_{\rm bh}$-L relation derived using our slightly updated Marconi & Hunt data set. One can also see, via the short lines, how each data point has moved from its previous location as given by Marconi & Hunt. Performing a linear regression (using equation 2), we obtain

$$\log(M_{\rm bh}/M_\odot) = -0.39(\pm 0.05)[M_K + 24] + 8.24(\pm 0.08), \quad (13)$$

with a total scatter of 0.35 dex in $\log M_{\rm bh}$. This equation has a slightly shallower slope than the expression given by Marconi & Hunt (2003, their Table 2): $\log(M_{\rm bh}/M_\odot) = 1.13(\pm 0.12)[\log(L_{K,\rm bulge}/L_{K,\odot}) - 10.9] + 8.21(\pm 0.07)$, or equivalently[8], using $M_{K,\odot} = 3.28$ mag, $\log(M_{\rm bh}/M_\odot) = -0.45(\pm 0.05)[M_{K,\rm bulge} + 23.97] + 8.21(\pm 0.07)$. However, as noted above, applying the same regression analysis to the data in Marconi & Hunt yields a consistent result.

[8] Dong & De Robertis (2006) obtain the same slope (−0.45) upon excluding the disc galaxies, but with a large uncertainty on the intercept.

Table 3. Updated sample of elliptical and disc galaxies from Marconi & Hunt's (2003) Group 1 galaxies. When available, distances from Tonry et al. (2001) have been used. The exceptions are NGC 5252, NGC 6251 and Cygnus A, as noted in Section 4.2.1. The magnitudes have come from Table 1 in Marconi & Hunt, adjusted here if a different distance was adopted (3 galaxies) or if we assigned a bulge-to-disc ratio not used by Marconi & Hunt (NGC 221 and NGC 4564). The source of the black hole masses is also provided in Section 4.2.1.

Galaxy	Type	Dist. [Mpc]	M_B [mag]	M_K [mag]	$M_{\rm bh}$ [$10^8 M_\odot$]
NGC 0221	S	0.8	-15.3	-19.3	$0.025^{+0.005}_{-0.005}$
NGC 1023	S	11.4	-18.4	-23.5	$0.44^{+0.05}_{-0.05}$
NGC 2787	S	7.5	-17.3	-21.3	$0.41^{+0.04}_{-0.05}$
NGC 3031	S	3.9	-18.2	-24.1	$0.76^{+0.22}_{-0.11}$
NGC 3115	S	9.7	-20.2	-24.4	$9.2^{+3.0}_{-3.0}$
NGC 3245	S	20.9	-19.6	-23.3	$2.1^{+0.5}_{-0.5}$
NGC 3377	E	11.2	-19.0	-23.6	$1.0^{+0.9}_{-0.1}$
NGC 3379	E	10.6	-19.9	-24.2	$1.35^{+0.73}_{-0.73}$
NGC 3384	S	11.6	-19.0	-22.6	$0.16^{+0.01}_{-0.02}$
NGC 3608	E	22.9	-19.9	-24.1	$1.9^{+1.0}_{-0.6}$
NGC 4258	S	7.2	-17.2	-22.4	$0.39^{+0.01}_{-0.01}$
NGC 4261	E	31.6	-21.1	-25.6	$5.2^{+1.0}_{-1.1}$
NGC 4291	E	26.2	-19.6	-23.9	$3.1^{+0.8}_{-2.3}$
NGC 4374	E	18.4	-21.4	-25.7	$4.64^{+3.46}_{-1.83}$
NGC 4473	E	15.7	-19.9	-23.8	$1.10^{+0.4}_{-0.79}$
NGC 4486	E	16.1	-21.5	-25.6	$34.3^{+9.7}_{-9.7}$
NGC 4564	S	15.0	-17.4	-21.9	$0.56^{+0.03}_{-0.08}$
NGC 4594	S	9.8	-21.3	-25.4	$10.0^{+10.0}_{-7.0}$
NGC 4649	E	16.8	-21.3	-25.8	$20.0^{+4.0}_{-6.0}$
NGC 4697	E	11.7	-20.2	-24.6	$1.7^{+0.2}_{-0.1}$
NGC 4742	E	15.5	-18.9	-23.0	$0.14^{+0.04}_{-0.05}$
NGC 5128	S	4.2	-20.8	-24.5	$2.4^{+3.6}_{-1.7}$
NGC 5252	S	94.4	-20.7	-25.5	$9.7^{+14.9}_{-4.6}$
NGC 5845	E	25.9	-18.7	-23.0	$2.4^{+0.4}_{-1.4}$
NGC 6251	E	101	-21.4	-26.5	$5.8^{+1.8}_{-2.0}$
Cygnus A	E	240	-21.8	-27.2	$26.0^{+7.0}_{-7.0}$

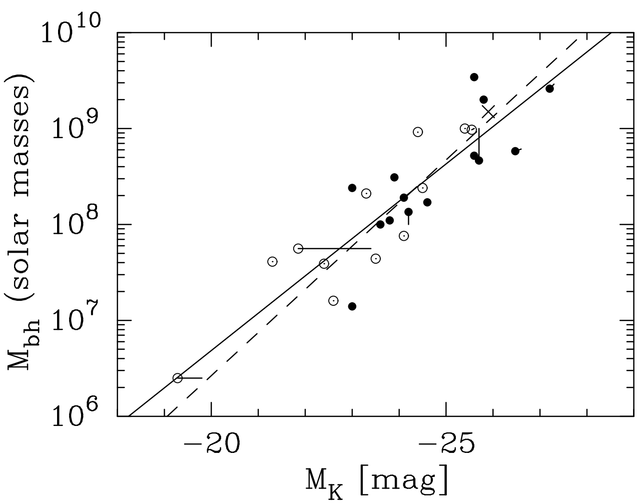

Figure 3. The long solid line shows the $M_{\rm bh}$-L relation (equation 13) using our updated values for the galaxies in Marconi & Hunt (2003). The short lines emanating from the data points show the location of the galaxies as used by Marconi & Hunt to obtain the long dashed line. The location of IC 1459 as used by Marconi & Hunt but excluded by us is shown by the cross.

4.2.2 Removing questionable data points

We repeated the above regression analysis removing four galaxies whose parameters are somewhat questionable. First, because the mass estimate for NGC 4742 has not yet appeared in a refereed paper, we hold off on its inclusion here. We also excluded NGC 1023 ($r_h = 0''.08$) and NGC 3377 ($r_h = 0''.46$) because their SMBH spheres of influence (r_h, Merritt & Ferrarese 2001c) have apparently not been resolved according to Table II in Ferrarese & Ford (2005) in which r_h/r_{res} ratios of 0.89 and 0.74 respectively. Finally, as noted by Ferrarese & Ford (2005), NGC 4594 has not yet had its SMBH mass acquired using a 3-integral model, and so it mass may therefore be in error. With our reduced sample of 22 objects, we obtain the relation

$$\log(M_{\rm bh}/M_\odot) = -0.37(\pm0.04)[M_K+24]+8.29(\pm0.08), \quad (14)$$

consistent with the expression given in equation 13. The total scatter about this relation is 0.33 dex, and the intrinsic scatter is $0.30^{+0.03}_{-0.05}$ dex in $\log M_{\rm bh}$.

Comparison of equation 14 (and 13) with our revised estimate of McLure & Dunlop's K-band relation (equation 8) reveals that we have resolved the disagreement noted in our Introduction. That is, our updated data sets and reanalysis of the McLure & Dunlop and the Marconi & Hunt studies has yielded $M_{\rm bh}$-L relations that agree with each other. Our preference is to use equation 14 because a) it was derived using both elliptical and disc galaxies and b) it has the smallest uncertainty on the slope and intercept.

4.2.3 Is the $M_{\rm bh}$-L relation non-linear

Using the above 22 data points, we have explored whether the $M_{\rm bh}$-L relation may be curved. The optimal log-quadratic relation, fitted in the same way as the $M_{\rm bh}$-n data in Graham & Driver (2007a), is

$$\begin{aligned}\log(M_{\rm bh}/M_\odot) &= -0.37(\pm0.05)[M_K+24]+8.32(\pm0.10) \\ &\quad -0.01(\pm0.02)[M_K+24]^2. \quad (15)\end{aligned}$$

The coefficient in front of the quadratic term is consistent with a value of zero, or in other words, it does not deviate from a value of zero at even the 1-sigma level. The 3σ range of values on this term is only ±0.05. One can therefore conclude that the $M_{\rm bh}$-L relation, defined with the present data set, is not curved.

4.2.4 Is the $M_{\rm bh}$-L relation the same for elliptical galaxies and bulges

For the 12 elliptical galaxies which comprise the sample of 22 galaxies used in Section 4.2.2, the best-fitting relation is

$$\log(M_{\rm bh}/M_\odot) = -0.33(\pm0.09)[M_K+24]+8.33(\pm0.15). \quad (16)$$

For the 10 disc galaxies, which includes NGC 221 and NGC 4564, one has

$$\log(M_{\rm bh}/M_\odot) = -0.39(\pm0.08)[M_K+24]+8.33(\pm0.16). \quad (17)$$

Consequently, there appears to be no significant difference between the relations defined by the elliptical galaxies and the bulges of disc galaxies.

4.2.5 *An R-band $M_{\rm bh}$-L relation*

The above sample of 22 galaxies consists of 12 E galaxies, 8 S0 galaxies, and only one Sb and one Sbc galaxy. Using an $R_c - K$ colour of 2.6 and 2.5 for the elliptical and lenticular galaxies respectively, and 2.3 for the late-type galaxies (Buzzoni 2005) we obtained the following R-band $M_{\rm bh}$-L relation

$$\log(M_{\rm bh}/M_\odot) = -0.38(\pm0.04)[M_R+21]+8.12(\pm0.08), \quad (18)$$

While this relation has overlapping error bars with the two independent R-band relations from the previous sections (equation 7 and 12), it is preferred for the reasons mentioned in Section 4.2.2.

4.2.6 *A B-band $M_{\rm bh}$-L relation*

Starting with the B-band magnitudes tabulated in Marconi & Hunt, (which have predominantly come from Tremaine et al. 2002 via Faber et al. 1997), we have modified these according to Section 4.2.1. Adjusting also the SMBH masses as in Section 4.2.1, we obtain the updated B-band expression

$$\log(M_{\rm bh}/M_\odot) = -0.40(\pm0.05)[M_B+19.5]+8.27(\pm0.08), \quad (19)$$

with a total scatter of 0.34 dex in $\log M_{\rm bh}$. Using $M_{B,\odot} = 5.47$ mag (Cox 2000), equation 19 has a marginally shallower slope than the solution in Marconi & Hunt: $\log(M_{\rm bh}/M_\odot) = -0.48(\pm0.05)[M_B + 19.53] + 8.18(\pm0.08)$.

This new B-band slope of -0.40 ± 0.05 (obtained using 22 galaxies) is comparable to the slope -0.42 ± 0.06 (equation 5) obtained in Section 3.1 using M32 plus the 16 elliptical galaxies from McLure & Dunlop (2002). However, given no correction for dust attenuation was used, and given that the past B-band bulge/disc separation could probably be improved upon, this may perhaps be fortuitous.

4.2.7 *Scatter in the $M_{\rm bh}$-$M_{\rm spheroid}$ relation*

Marconi & Hunt (2003) additionally presented a relation between the mass of the black hole and the mass of the host spheroid. They used $M_{\rm spheroid} = 3R_{\rm e}\sigma_{\rm e}^2/G$, in which $R_{\rm e}$ and $\sigma_{\rm e}$ are the effective half-light radius and velocity dispersion of each spheroid, respectively. They reported (for their 27 Group 1 galaxies) an intrinsic scatter of 0.25 dex (and 0.49 dex for the full sample). Using their Group 1 data, and fitting equation 2 — which is designed to minimise the scatter in $\log M_{\rm bh}$ — we measure the *total* scatter to be 0.30 dex. A fuller, proper investigation of this subject would however require checking the $R_{\rm e}$ values, which is beyond the scope of the current paper.

5 DISCUSSION AND CONCLUSIONS

Surprisingly, given the recent large body of work on SMBHs, there remains a strong need for high quality images for the sample of inactive galaxies with direct measurements of their supermassive black hole masses. In particular, near-infrared *NICMOS* images would enable an analysis of the core structure of these galaxies. Graham & Driver (2007a) have proposed that the central stellar density may be the fundamental parameter related to the mass of the black hole. This contrasts with current studies, including this one, which explore the SMBH connection with global rather than nuclear properties of the host spheroid. Given the known trend between central stellar density and host spheroid luminosity (e.g., Graham & Guzmán 2003; Merritt 2006, his Fig.5), the popular relations *may* all be secondary in nature. i.e., subsequential Specifically, the central density (prior to core-depletion[9] in massive spheroids — requiring the use of the core-Sérsic model, Graham et al. 2003), or the central density of less massive spheroids after modelling and excluding the flux from their additional nuclear components (e.g. Graham & Guzmán 2003) may be the key parameter connected to the SMBH mass. Due to the need for a bulge/disc decomposition for half of the current galaxy sample, such *HST* images should be mated with deep larger field-of-view ground-based images (e.g. Balcells et al. 2004) so as to adequately sample the domain of the disc.

Aside from the study by Erwin et al. (2004) with 13 galaxies, all of the optical $M_{\rm bh}$-L relations to date have been constructed using the aperture growth curve magnitudes obtained some 20 years ago and presented in Faber et al. (1989) or from the RC3 (de Vaucouleurs et al. 1991). A homogeneous set of high-resolution, deep, wide-field CCD images in the optical bands such as B and R would be highly useful for a) properly calibrating the $M_{\rm bh}$-L relation, b) acquiring accurate bulge sizes and central densities (both projected and deprojected) and c) subsequently calibrating the $M_{\rm bh}$-(spheroidal mass) relation (e.g. Marconi & Hunt 2003; Häring & Rix 2004). Not only would this allow a proper test for the optimal fundamental relation, but it would provide the community with improved relations for predicting SMBH masses in other galaxies.

Nonetheless, there does now appear to be agreement between the various $M_{\rm bh}$-L relations (see Table 4).

We plan to apply our B-band $M_{\rm bh}$-L relation (equation 19) to the Millennium Galaxy Catalogue (e.g., Driver et al. 2006). This catalogue contains structural parameters from the $R^{1/n}$-bulge plus exponential-disc decomposition of 10,095 nearby ($z \sim 0.1$) galaxies (Allen et al. 2006). While we have already been able to use the $M_{\rm bh}$-n relation in Graham & Driver (2007a) to predict the SMBH masses in these galaxies (Graham et al. 2007), the inconsistencies in the previously published $M_{\rm bh}$-L relations had prohibited their use. This will allow us to construct an updated SMBH mass function for both early- and late-type galaxies, which can then be integrated to obtain the local SMBH mass density.

5.1 Intermediate mass black holes

Using the linewidth-luminosity-mass scaling relation by Greene & Ho (2005), Dong et al. (2007) report on the existence of a $7 \times 10^4 M_\odot$ intermediate mass black hole (IMBH) in the dwarf disk galaxy SDSS J160531.84+174826.1 (see Figure 4). Applying McLure & Dunlop's (2002) R-band $M_{\rm bh}$-L relation to the central bulge/bar magnitude of this disk galaxy, they obtained a black hole mass one order of

[9] The apparent depletion of stars at the centres of giant galaxies may not have (only) arisen from the scouring action of coalescing SMBHs (see, for example, Boylan-Kolchin et al. 2004 and Nipoti et al. 2006).

Table 4. New $M_{\rm bh}$-L relations for predicting SMBH masses. The "origin" of the data is as follows. KG 2001 = Kormendy & Gebhardt (2001), not modified. MD 2002 = McLure & Dunlop (2002), modified (see Section 3.1 and Table 1). EGC 2004 = Erwin et al. (2004), modified (see Section 4.1 and Table 2). MH 2003 = Marconi & Hunt (2003), modified (see Section 4.1). and Table 3). The "sample" may consist of elliptical (E) galaxies or disc galaxies, denoted by 'S' for either S0 or Sp. The total scatter in the $\log M_{\rm bh}$ direction is denoted $\Delta_{\rm tot}$, while the intrinsic scatter in the $\log M_{\rm bh}$ direction is denoted $\epsilon_{\rm intrinsic}$.

Origin	Sample	Band	$M_{\rm bh}$-L relation	$\Delta_{\rm tot}$ [dex]	$\epsilon_{\rm intrinsic}$ [dex]
KG 2001	20E + 17S	B	$-0.38(\pm0.06)[M_B+19.5]+8.00(\pm0.09)$	0.56	$0.46^{+0.08}_{-0.06}$
MD 2002	16E + 1S	B	$-0.36(\pm0.06)[M_B+20]+8.33(\pm0.10)$	0.38	$0.35^{+0.03}_{-0.06}$
MH 2003	12E + 10S	B	$-0.40(\pm0.05)[M_B+19.5]+8.27(\pm0.08)$	0.34	$0.30^{+0.04}_{-0.05}$
MD 2002	16E + 1S	R	$-0.38(\pm0.06)[M_R+21]+8.11(\pm0.11)$	0.38	$0.35^{+0.03}_{-0.07}$
EGC 2004	08E + 5S	R	$-0.30(\pm0.06)[M_R+21]+7.96(\pm0.10)$	0.31	$0.28^{+0.03}_{-0.06}$
MH 2003	12E + 10S	R	$-0.38(\pm0.04)[M_R+21]+8.12(\pm0.08)$	0.33	$0.30^{+0.03}_{-0.05}$
MD 2002	16E + 1S	K	$-0.38(\pm0.06)[M_K+24]+8.26(\pm0.11)$	0.38	$0.35^{+0.03}_{-0.07}$
MH 2003	12E + 10S	K	$-0.37(\pm0.04)[M_K+24]+8.29(\pm0.08)$	0.33	$0.30^{+0.03}_{-0.05}$

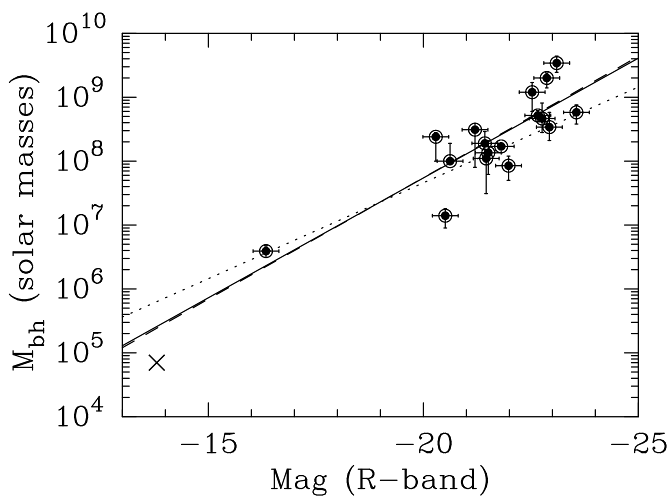

Figure 4. SDSS J160531.84+174826.1 (cross) has been added to the data points used to construct equation 7, shown here by the solid line. This dwarf galaxy, from Dong et al. (2007), has an intermediate mass black hole that has not been used in the fitting of the lines shown. The dashed line is equation 18 and the dotted line is equation 12.

magnitude smaller than obtained with Marconi & Hunt's (2003) relation. Dong et al. give a ($H_0 = 70$ km s^{-1} Mpc^{-1}) R-band magnitude of -13.9 mag. Adjusting this by 0.1 mag, to match our adopted value of $H_0 = 73$ km s^{-1} Mpc^{-1}, our updated R-band expression from equation 7 predicts a black hole mass of $2.4 \times 10^5 M_\odot$, while our updated relation in equation 18 also gives a value of $2.4 \times 10^5 M_\odot$. This compares well with the value of $1.5 \times 10^5 M_\odot$ obtained using the $M_{\rm bh}$-n relation from Graham & Driver (2007a).

We do not include the Seyfert 1 galaxy POX 52 as it appears to require a (yet to be performed) bulge/disc decomposition, with the disk accounting for the excess flux from 4-10 arcseconds seen in the Sérsic fit of Barth et al. (2004). Ideally, a bulge/disc decomposition is also required for the dwarf Seyfert 1, Sd galaxy NGC 4395. Inspection of figure 3 in Filippenko & Ho (2003) suggests that the excess flux seen from 1 to $\sim$2 arcseconds, peaking at $\sim$0.6 mag arcsec^{-2} above their fitted model, may be the bulge component of this late-typpe galaxy. However, due to the non-thermal point-source emission and nuclear-star cluster in this galaxy, it is difficult to know what may be the bulge component. While it appears that a Gaussian-like component should work well for the suggested bulge, we make no attempt to undertake this task here, but highlight the value of such a future investigation. The addition of more data points at the low-mass end of the $M_{\rm bh}$-L relation should provide further valuable clues as to a) the range and reliability of this relation, and b) help constrain models for the co-evolution of black holes and galaxies.

5.2 Implications for SMBH-galaxy coevolution

Before discussing intrinsic physical relations, we need to perform a symmetrical regression of $M_{\rm bh}$ and the magnitude. We have already seen that regressing $M_{\rm bh}$ on M_K gives a K-band slope of -0.37 ± 0.04 (equation 14). Reversing the regression (see the text after equation 2) gives the relation $\log(M_{\rm bh}/M_\odot) = -0.44(\pm0.05)[M_K+24]+8.30(\pm0.09)$, and so the average slope is ~ 0.40. This is consistent with the slope of -0.45 ± 0.05 from the symmetrical regression in Marconi & Hunt (2003). It is interesting to note that a slope of -0.40 implies a linear scaling between luminosity and black hole mass, such that $M_{\rm bh} \propto L^{1.00}$. That is, the SMBH mass to spheroid luminosity ratio is constant, as predicted by Chien (2007).

Our updated data and new relation supports the "dry merger" scenario in which the SMBH mass doubles as the luminosity doubles. While this paints a consistent picture at the high-mass end, where "core galaxies" exist and dry mergers are considered the order of the day, this is unlikely to hold at lower masses.

SMBH accretion of ISM gas derived from stellar winds is believed to fuel some AGN activity today (Fabbiano et al. 2004, Pellegrini 2005; Soria et al. 2006). Indeed, stellar mass loss in elliptical galaxies produces $> 10^2$ times more mass than that found in the central SMBH (Ciotti & Ostriker 2007). As these Authors note, when fuelling SMBHs with the recycled gas from the stellar population, almost by definition, the amount of fuel is proportional to the host galaxy's stellar mass. Ciotti & Ostriker also show how radiative heating from such AGN feedback is responsible for the self-regulated coevolution of galaxy and SMBH. Our results provide a valuable new constraint on these models, setting the proportionality constant to one.

Moreover, the level of total scatter in the $M_{\rm bh}$-L relation (0.31 to 0.34 dex) makes it competitive with both the $M_{\rm bh}$-n (Graham et al. 2001; Graham & Driver 2007a: 0.31 dex) and the $M_{\rm bh}$-σ relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000). While modelling the 31 galaxies from Tremaine et al. (2002) gives an intrinsic scatter of 0.27 dex, the total scatter about the relation presented there is 0.34 dex.

This opens the question as to whether the stellar (baryonic) or total (stars plus dark matter) mass is the driver of the SMBH-galaxy connection. Which of these, or some other quantity may be the fundamental parameter connecting galaxies and their black holes is not yet clear.

6 ACKNOWLEDGMENTS

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APPENDIX A: POTENTIAL SAMPLE BIAS

Bernardi et al. (2007) have suggested that the local sample of inactive galaxies with direct SMBH mass measurements may be biased with regard to the greater population. They argue that, relative to the total population, there is a bias such that these galaxies have overly large velocity dispersions for their luminosities. If correct, the result is such that the $M_{\rm bh}$–L relation will over-predict the SMBH masses (in other galaxies) relative to the $M_{\rm bh}$–σ relation. We explore this issue with our updated data set.

Using $r - R = 0.24$ (Fukugita 1995), the SDSS L-σ relation from Tundo et al. (2007, their equation 4) is such that

$$\log\sigma = 0.27 - 0.092M_R. \quad \text{(A1)}$$

We compare this with our updated R-band data from Erwin et al. (2004) and our updated K-band data from Marconi & Hunt transformed into the R-band using the tables in Buzzoni (2005), as done in Section 4.2.5. The results are shown in Figure A1.

Applying equation 2 to our updated Marconi & Hunt data set, in which we have minimised the scatter in the $\log\sigma$ direction, we obtain

$$\log\sigma = 2.268 - 0.082(M_R + 21), \quad \text{(A2)}$$

which is shown by the solid line in Figure A1. Compared to the dashed line (from the SDSS data set), the local sample of inactive galaxies therefore appears to have larger velocity dispersions for a given magnitude.

While the local sample of galaxies with direct SMBH mass measurements may be biased, it is also possible that the magnitudes used to construct the SDSS L-σ relation may have been under-estimated due to dust, or over-estimated

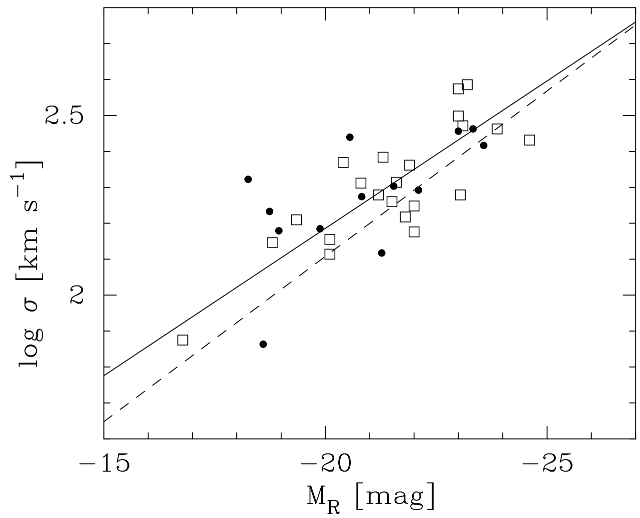

Figure A1. The solid line (equation A2) shows the regression of $\log\sigma$ on M_R using our updated Marconi & Hunt data set, denoted by the open squares. Our updated Erwin et al. data points are shown by the filled circles but are not used in the linear regression shown here. The dashed line (equation A1) is the equivalent regression using SDSS data (Tundo et al. 2007, their equation 4). A slight offset is evident.

due to the bulge-disc separation. That is, *they* may be the biased data set. Unlike the Erwin et al. (2004) and Marconi & Hunt (2003) bulge data, no Sérsic $R^{1/n}$-bulge + exponential-disc fit was performed in acquiring the SDSS bulge magnitudes. The use of $R^{1/4}$ models is known to overestimate the bulge flux for bulges with stellar distributions having $n < 4$ (e.g. Graham & Driver 2007b, their Table 3), which may be the bulk of the S0 galaxy population (e.g., Balcells et al. 2003). A second concern is that faint elliptical galaxies have a different slope in the L-σ diagram than luminous elliptical galaxies. The successive inclusion of fainter galaxies should therefore lead to a progressive change in the slope of the L-σ relation.

Ignoring the above issues for now, the average velocity dispersion excess is given by differencing the above two equations, to give $\Delta\log\sigma = 0.30 + 0.011M_R$. Therefore, if one wished to correct for this (possible) sample bias, the local galaxy magnitudes M_R (i.e., those with direct SMBH mass measurements) could be adjusted by ΔM, such that

$$\Delta M = 0.109[M_R + 27.60]. \quad \text{(A3)}$$

This would bring the two lines in Figure A1 into agreement. The same trick was performed in Tundo et al. (2007, at the end of their Section 3), although using different bulge magnitudes to our updated values. In a future paper we intend to better address such a potential offset in the L–σ diagram using the dust-corrected $R^{1/n}$-bulge magnitudes from the Millennium Galaxy Catalogue's 10 095 galaxies (Allen et al. 2006).

At the low luminosity end the situation is different to presented above. This is because the L–σ relation is not linear, having a well-recognised slope of $\sim$4 at the bright end and a less well known, but long established, slope of $\sim$2 at the faint end (Tonry 1981; Davies et al. 1983; Held et al. 1992; De Rijcke et al. 2005). Matković & Guzmán (2005) argue that the transitional magnitude occurs near $M_R \sim -22$

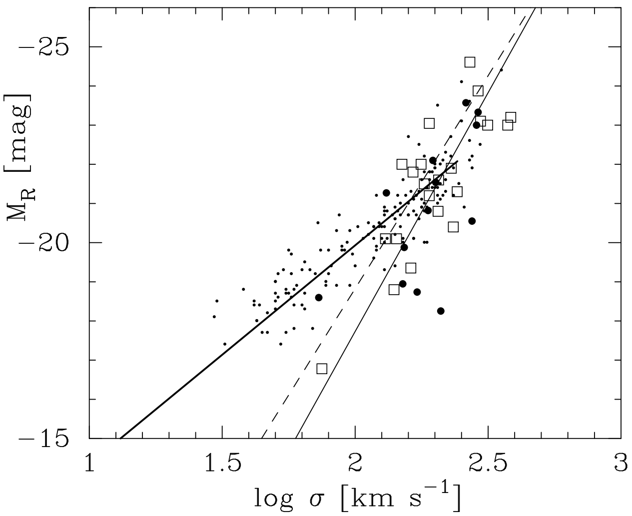

Figure A2. The solid and dashed lines have the same meaning as in Figure A1, as do the squares and large filled circles. The small dots are data taken from Matković & Guzmán (2005, their Figure 4, adjusted from H_0=70 to 73 km s^{-1} Mpc^{-1}) and the thick solid line is their H_0-adjusted ($\log\sigma \mid M_R$) regression for faint galaxies.

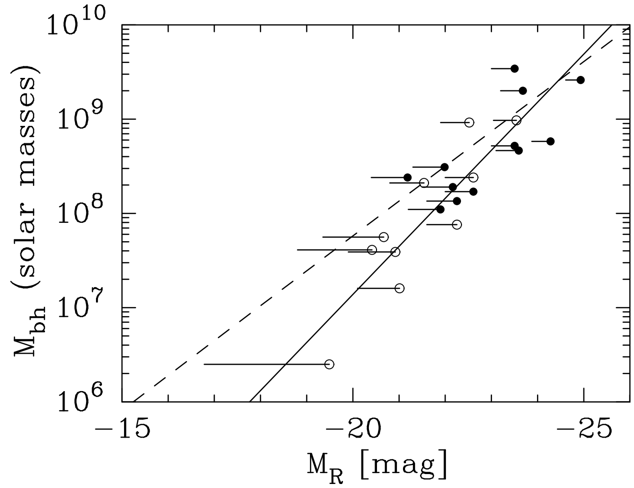

Figure A3. The data points have the same meaning as in Figure 3, although here we only show those 22 galaxies from Section 4.2.2. The short lines emanating from each data point show their location prior to the magnitude-adjustment performed in Section A. The location of the data points show their magnitude-adjusted location. The dashed line shows the regression prior to this adjustment (equation 18) while the solid line shows the new regression (equation A7).

mag, coinciding with the onset of dry merging and the break seen in the luminosity - central surface brightness diagram (Graham & Guzmán 2003, their figure 9c). What is also apparent in Figure 4 from Matković & Guzmán is the subtle nature of this transition, and the need for a long baseline in magnitude for it to be recognised.

Fitting a *single* power-law to the L-σ data should yield a slope that is dependent on one's luminosity range and thus sample selection. This has not received much attention in the literature, most likely because of the subtle nature of the transition due to the scatter about the relation. For this reason, the change in slope only really becomes obvious in samples containing magnitudes fainter than $M_R \sim -20$ mag.

Performing a regression of $\log\sigma$ on M_R, Matković & Guzmán (2005) report a faint-end relation of

$$M_R = (-5.585 \pm 0.210)\log\sigma - 8.755(\pm 0.444), \quad \text{(A4)}$$

or simply

$$\log\sigma = -0.179 M_R - 1.508, \quad \text{(A5)}$$

which has been adjusted here to H_0=73 km s^{-1} Mpc^{-1}. Their data and this relation can be seen in Figure A2, along with our sample of galaxies with direct SMBH mass measurements. One can see that the low-luminosity extrapolation of the L-sigma relation obtained using the updated Marconi & Hunt data set (equation A2) does not follow the trend defined by the fainter galaxy population (equation A5). The problem is such that for a given velocity dispersion, the magnitudes predicted from the (SMBH sample)-derived L-σ relation are too faint, compared to the general population. The magnitudes predicted using equation A2 need to brightened by

$$\Delta M = 0.542[M_R + 21.78]. \quad \text{(A6)}$$

If the sample of galaxies with direct SMBH masses have normal masses and velocity dispersions, but biased luminosities, as argued by Bernardi et al. (2007), then one can apply the above magnitude corrections to this sample. At $M_R = -20.28$ mag we switch from using corrective equation A3 to corrective equation A6. With our modified set of galaxy magnitudes, corrected to represent the general population, one can repeat the regression analysis to obtain a new $M_{\rm bh}$-L relation. Doing so, one has

$$\log(M_{\rm bh}/M_\odot) = -0.51(\pm 0.06)[M_R + 22] + 8.16(\pm 0.09), \quad \text{(A7)}$$

with a total scatter of 0.36 dex, and an intrinsic scatter of $0.31^{+0.05}_{-0.06}$.

Compared to equation 18, which was obtained prior to this magnitude adjustment, for magnitudes fainter than $M_R \sim -24.5$ mag the new relation predicts smaller SMBH masses (see Figure A3). Extrapolation of the relations to brighter magnitudes results in greater SMBH masses. This is a consequence of the L-σ relations from Figure A1 that we have used to derive the magnitude adjustment in equation A3).

An alternative scenario is that the $M_{\rm bh}$-L relation may have two slopes, described by a broken power-law with the transition denoting the onset of dry merging. Indeed, the above prescription should generate such a relation. If one accepts that $M_{\rm bh} \propto \sigma^4$, then at the luminous end, where $L \propto \sigma^4$, one naturally obtains $M_{\rm bh} \propto L^{1.0}$. For magnitudes fainter than $M_R \sim -22$ mag, one has $L \propto \sigma^2$, and if $M_{\rm bh} \propto \sigma^4$ over this domain, then one should expect to find $M_{\rm bh} \propto L^{0.5}$. However, we feel that to properly address this scenario will require more data than is available at present.