CSIRO PUBLISHING
www.publish.csiro.au/journals/pasa

Corrigendum

Populating the Galaxy Velocity Dispersion – Supermassive Black Hole Mass Diagram: A Catalogue of (M_{bh}, σ) Values

Alister W. Graham

Publications of the Astronomical Society of Australia, 2008, **25**, pp. 167–175

An error was made in the title. It should be:

Populating the Galaxy Velocity Dispersion – Supermassive Black Hole Mass Diagram: A Catalogue of (M_{bh}, σ) Values

not

Populating the Galaxy Velocity Dispersion: Supermassive Black Hole Mass Diagram, A Catalogue of (M_{bh}, σ) Values

 10.1071/AS08013_CO 1323-3580/09/03001

CSIRO PUBLISHING
Open Access
www.publish.csiro.au/journals/pasa
Publications of the Astronomical Society of Australia, 2008, **25**, 167–175

Populating the Galaxy Velocity Dispersion: Supermassive Black Hole Mass Diagram, A Catalogue of ($M_{\rm bh}$, σ) Values

Alister W. Graham[A]

[A] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia. Email: agraham@astro.swin.edu.au

Received 2008 June 18, accepted 2008 July 4

Abstract: An updated catalogue of 76 galaxies, with direct measurements of supermassive black-hole mass ($M_{\rm bh}$) plus, when available, the central velocity dispersion (σ_0) of their host bulge is provided. Fifty of these mass measurements are considered reliable, while the others remain somewhat uncertain at this time. An additional nine stellar systems, including one stellar cluster and three globular clusters, are listed as hosting potential intermediate mass black holes $<10^6\ M_\odot$.

With this larger data set, the demographics within the $M_{\rm bh}$–σ_0 diagram are briefly explored. Many barred galaxies are shown to be offset from the $M_{\rm bh}$–σ_0 relation defined by the non-barred galaxies, in the sense that their velocity dispersions are too high. Furthermore, including 88 AGN with black-hole mass estimates from reverberation mapping studies, we speculate that barred AGN may follow this same general trend. We also show that some AGN with $\sigma_0 < 100\,{\rm km\,s^{-1}}$ tend to reside up to (∼0.6 dex) ∼1.0 dex above the (barless) $M_{\rm bh}$–σ_0 relation. Finally, it is shown that 'core galaxies' appear not to define an additional subdivision of the $M_{\rm bh}$–σ_0 diagram, although improved methods for measuring σ_0 values may be valuable.

Keywords: catalogues — black hole physics — galaxies: bulges — galaxies: fundamental parameters — galaxies: kinematics and dynamics — galaxies: nuclei

1 Introduction

Scaling relations between the intrinsic properties of galaxies provide clues to the physical mechanisms which operate within these systems. In general, the tighter a relation is, i.e. the less scatter it has, the more fundamental the relation is expected to be. Therefore, it is perhaps not surprising that there has been a huge interest in the $M_{\rm bh}$–σ relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000) which was reported to have very little or no intrinsic scatter. In addition to providing an indirect means to measure supermassive black hole (SMBH) masses in many galaxies, the $M_{\rm bh}$–σ relation (Merritt & Ferrarese 2001a; Tremaine et al. 2002; Ferrarese & Ford 2005; Novak, Faber & Dekel 2006), along with the equally strong $M_{\rm bh}$–n relation (Graham & Driver 2007a) and $M_{\rm bh}$–L relation (Kormendy & Richstone 1995; Magorrian et al. 1998; McLure & Dunlop 2002; Marconi & Hunt 2003; Graham 2007), provides insight into the joint formation process of SMBHs and their host bulges. Such relations can also be applied to volume-limited galaxy samples, providing an estimate of the SMBH mass density in the Universe (e.g. Salucci et al. 1999; Graham & Driver 2007b, and references therein).

As the number of galaxies with direct SMBH mass measurements has increased, it has become possible to explore the demographics of the SMBH population within the $M_{\rm bh}$–σ diagram. Rather than delineating a single line, Graham (2008) and Hu (2008) have revealed a tendency for SMBHs in barred galaxies, or perhaps equivalently pseudobulges, to reside below the $M_{\rm bh}$–σ relation defined by non-barred galaxies. In addition, Hu (2008) has noted that there may be a third subdivision in the $M_{\rm bh}$–σ diagram such that 'core galaxies' (Ferrarese et al. 1994; Faber et al. 1997; Trujillo et al. 2004) define a steeper relation than non-core galaxies. Such departures from a single unifying expression offer the promise of further valuable clues into the coevolution of galaxies and the million to billion solar mass black holes which reside at their centres.

This paper presents the largest sample of galaxies for which direct SMBH mass estimates are available. While the structure within the updated $M_{\rm bh}$–σ diagram is explored here, it is additionally hoped that this database will be a helpful resource, or rather stepping stone, for future investigations.

2 $M_{\rm bh}$ Versus σ_0

2.1 The Data

Ferrarese & Ford (2005) presented a highly useful list of 38 galaxies for which SMBH mass estimates had been obtained from resolved dynamical studies. Scouring the literature, one finds that this number has doubled over the past three years. While some galaxies have most likely been inadvertently overlooked, Tables 1 and 2 are believed to represent the most complete sample of galaxies with direct SMBH mass estimates published to date.

10.1071/AS08013 1323-3580/08/04167

Table 1. Fifty galaxies with direct SMBH mass measurements

Galaxy	Type	Core	Distance (Mpc)	σ_0 (km s^{-1})	M_{bh} (10^8 $M_\odot$)	Reference
Circinus	Sb	…	2.8 [1]	75	$0.011^{+0.002}_{-0.002}$	m-8
Cygnus A	E	…	232 [2]	270	$25.0^{+7.0}_{-7.0}$	g-9
IC 2560	SBb	…	40.7 [2]	144 [6]	[a]$0.044^{+0.044}_{-0.022}$	m-10,11
Milky Way	SBbc	n	0.008 [3]	100	$0.037^{+0.002}_{-0.002}$	p-12
NGC 221	S0	n	0.8	72	$0.025^{+0.005}_{-0.005}$	s-13
NGC 224	Sb	n	0.8	170	$1.4^{+0.9}_{-0.3}$	s-14,15
NGC 821	E	n	24.1	200	$0.85^{+0.35}_{-0.35}$	s-16
NGC 1023	SB0	n	11.4	204	$0.44^{+0.05}_{-0.05}$	s-17
NGC 1300	SBbc	…	20.7 [2]	229	$0.73^{+0.69}_{-0.35}$	g-18
NGC 1399	E	y	20.0	329	$4.8^{+0.7}_{-0.7}$	s-19,20
NGC 2778	SB0	n	22.9	162	$0.14^{+0.08}_{-0.09}$	s-21
NGC 2787	SB0	…	7.5	210	$0.41^{+0.04}_{-0.05}$	g-22
NGC 3031	Sb	…	3.9	162	$0.76^{+0.22}_{-0.11}$	g-23
NGC 3079	SBcd	…	20.7 [2]	146	[a]$0.024^{+0.024}_{-0.012}$	m-24,25,26
NGC 3115	S0	n	9.7	252	$9.1^{+10.3}_{-2.8}$	s-27
NGC 3227	SB	…	20.3 [2]	133	$0.14^{+0.10}_{-0.06}$	g,s-28
NGC 3245	S0	…	20.9	210	$2.1^{+0.5}_{-0.5}$	g-29
NGC 3377	E5	n	11.2	139	$0.8^{+0.05}_{-0.06}$	s-21,30
NGC 3379	E	y	10.6	207	$1.4^{+2.7}_{-1.0}$	s-31
NGC 3384	SB0	n	11.6	148	$0.16^{+0.01}_{-0.02}$	s-21
NGC 3608	E2	y	22.9	192	$1.9^{+1.0}_{-0.6}$	s-21
NGC 3998	S0	…	14.1	305	$2.2^{+2.0}_{-1.7}$	s-32
NGC 4151	SBab	…	20.0 [2]	156	$0.65^{+0.07}_{-0.07}$	g,s-33
NGC 4258	SBbc	…	7.2 [4]	134	$0.39^{+0.01}_{-0.01}$	m-34,4
NGC 4261	E2	y	31.6	309	$5.2^{+1.0}_{-1.1}$	g-35
NGC 4291	E2	y	26.2	285	$3.1^{+0.8}_{-2.3}$	s-21
NGC 4342	S0	…	17.0 [5]	253	$3.3^{+1.9}_{-1.1}$	s-36,37
NGC 4374	E	y	18.4	281	$4.64^{+3.46}_{-1.83}$	g-38
NGC 4459	S0	…	16.1	178	$0.70^{+0.13}_{-0.13}$	g-22

NGC 4473	E5	y	15.7	179	$1.1^{+0.4}_{-0.8}$	s-21
NGC 4486	E0	y	16.1	332	34^{+10}_{-10}	g-39
NGC 4486a	E	…	17.0 [5]	110 [32]	$0.13^{+0.08}_{-0.08}$	s-40
NGC 4564	S0	n	15.0	157	$0.56^{+0.03}_{-0.08}$	s-21
NGC 4596	SB0	…	17.0 [5]	149	$0.79^{+0.38}_{-0.33}$	g-22
NGC 4649	E1	y	16.8	335	20^{+4}_{-6}	s-21
NGC 4697	E4	n	11.7	174	$1.7^{+0.2}_{-0.1}$	s-21
NGC 4945	SBcd	…	3.8 [1]	100	[a]$0.014^{+0.014}_{-0.007}$	m-41
NGC 5077	E	y	41.2 [2]	255	$7.4^{+4.7}_{-3.0}$	g-42
NGC 5128	S0	n	3.8 [1]	120	$0.49^{+0.18}_{-0.11}$	g-43,44
NGC 5252	S0	…	103.5 [2]	190	$10.6^{+16.3}_{-5.0}$	g-45
NGC 5845	E3	n	25.9	233	$2.4^{+0.4}_{-1.4}$	s-21
NGC 6251	E	…	104.6 [2]	311	$5.9^{+2.0}_{-2.0}$	g-46
NGC 7052	E4	y	66.4 [2]	277	$3.7^{+2.6}_{-1.5}$	g-47
NGC 7582	SBab	…	22.0 [2]	156	$0.55^{+0.26}_{-0.19}$	g-48
Preliminary SAURON/OASIS data						
NGC 2974	E	n	21.5	227	$1.7^{+0.3}_{-0.3}$	s-7a
NGC 3414	S0	n	25.2	237	$2.5^{+0.4}_{-0.4}$	s-7a
NGC 4552	S0	y	15.3	252	$4.8^{+0.8}_{-0.8}$	s-7a
NGC 4621	E	n	18.3	225	$4.0^{+0.6}_{-0.6}$	s-7a
NGC 5813	E	y	32.2	239	$7.0^{+1.1}_{-1.1}$	s-7a
NGC 5846	E	…	24.9	237	$11.0^{+2.0}_{-2.0}$	s-7a

Unless otherwise specified, the distances have come from Tonry et al. (2001). The distances from NED are the (Virgo + GA + Shapley)-corrected Hubble-flow distances. The velocity dispersions have come from HyperLeda (`http://leda.univ-lyon1.fr`) (Paturel et al. 2003) unless otherwise noted. M_{bh} has been adjusted to the distance given in column 4.

[a]A factor of two uncertainty has been assigned to these SMBH masses.

References: 1, Karachentsev et al. 2007; 2, NED (`http://nedwww.ipac.caltech.edu/`); 3, Eisenhauer et al. 2003; 4, Herrnstein et al. 1999; 5, Jerjen et al. 2004; 6, Cid Fernandes et al. 2004; 7, Hu 2008; 7a, Preliminary values determined by Hu 2008 from figures of Cappellari et al. 2006, 2008; 8, Greenhill et al. 2003a; 9, Tadhunter et al. 2003; 10, Ishihara et al. 2001; 11, Nakai et al. 1998; 12, Ghez et al. 2005; 13, Verolme et al. 2002; 14, Bacon et al. 2001; 15, Bender et al. 2005; 16, Richstone et al. 2008; 17, Bower et al. 2001; 18, Atkinson et al. 2005; 19, Houghton et al. 2006; 20, Gebhardt et al. 2007; 21, Gebhardt et al. 2003; 22, Sarzi et al. 2001; 23, Devereux et al. 2003; 24, Trotter et al. 1998; 25, Yamauchi et al. 2004; 26, Kondratko et al. 2005; 27, Emsellem, Dejonghe & Bacon 1999; 28, Davies et al. 2006 and Hicks & Malkan 2008; 29, Barth et al. 2001; 30, Copin, Cretton & Emsellem 2004; 31, Shapiro et al. 2006, stellar dynamical measurement; 32, De Francesco et al. 2006; 33, Onken et al. 2007 and Hicks & Malkan 2008; 34, Miyoshi et al. 1995; 35, Ferrarese et al. 1996; 36, Cretton & van den Bosch 1999; 37, Valluri, Merritt & Emsellem 2004; 38, Maciejewski & Binney 2001; 39, Macchetto et al. 1997; 40, Nowak et al. 2007; 41, Greenhill, Moran & Herrnstein 1997; 42, De Francesco et al. 2008; 43, Marconi et al. 2006; 44, Neumayer et al. 2007; 45, Capetti et al. 2005; 46, Ferrarese & Ford 1999; 47, van der Marel & van den Bosch 1998; 48, Wold et al. 2006.

Table 2. Additional galaxies

Galaxy	Type	Core	Distance (Mpc)	σ_0 (km s^{-1})	M_{bh} ($10^8\ M_\odot$)	Reference and comment
Twenty six galaxies with somewhat uncertain M_{bh} values						
Abell 1836	BCG	…	157	…	48^{+8}_{-7}	g-4, no refereed publication
A2052/UGC 9799	BCG	y?	155	234	<73	g-4, no refereed publication
A3565/IC 4296	BCG	…	40.7	336	13^{+3}_{-4}	g-4, no refereed publication
ESO 269-G012	S0	…	59.6	…	0.01–0.1	m-5, maser, modelling uncertain
IC 1459	E3	y	29.2 [1]	306	3–36	g,s-6, gas/stellar dynamics differ
NGC 1068	Sb	…	15.2	151	$0.084^{+0.003}_{-0.003}$	m-7, maser, modelling uncertain
NGC 1386	SB0	…	16.5 [1]	166	[a]$0.012^{+0.012}_{-0.006}$	m-8, maser, modelling uncertain
NGC 2639	SBa	…	49.6	198	$0.16(r/0.1\ \mathrm{pc})^2$	m-9, maser, modelling uncertain
NGC 2748	Sbc	…	25.1	92	$0.48^{+0.38}_{-0.39}$	g-10 & 11, dust an issue
NGC 2960	Sa	…	72.8	…	$0.12^{+0.03}_{-0.03}$	m-12, maser, modelling uncertain
NGC 3393	SBab	…	55.2	197	$0.31^{+0.02}_{-0.02}$	m-13, maser, modelling uncertain
NGC 4041	Sbc	…	23.3	95 [14]	<0.24	m-14, disk dynamically decoupled(?)
NGC 4303	SBbc	…	16.1 [2]	109	0.006–0.160	g-15, poorly known disk inclination
NGC 4350	S0	…	17.0 [3]	181	1.5–9.8	g,s-16, high M_{bh}/M_{bulge}
NGC 4435	SB0	…	14.0	157	<0.075	g-17, possibly no black hole
NGC 4486B	cE	n	17.0 [3]	169	6^{+3}_{-2}	s-18, $M_{bh}/M_{bulge} = 0.09$
NGC 4594	Sa	…	9.8 [1]	240	1.7–17	s-19, no 3-integral model
NGC 4742	E4	n	15.5 [1]	109	$0.14^{+0.04}_{-0.05}$	s-20, no refereed publication
NGC 5055	Sbc	…	8.7	101	$8.5^{+1.9}_{-1.9}$	g-21, possibly no black hole
NGC 5495	Sb	…	103	…	[a]$0.12^{+0.12}_{-0.06}$	m-13, maser, modelling uncertain
NGC 5793	Sb	…	53.3	…	[a]$\sim 0.1^{+0.1}_{-0.1}$	m-22, maser, modelling uncertain
NGC 6926	SBbc	…	84.0	…	0.01–0.1	m-5, maser, modelling uncertain
NGC 7332	S0	n	23.0 [1]	135	$0.13^{+0.06}_{-0.05}$	s-23, no refereed publication
NGC 7457	S0	n	13.2 [1]	69	$0.035^{+0.011}_{-0.014}$	s-24, AGN/NC distinction blurred
NGC 7469	SBa	…	67.0	153 [25]	<0.5	g-26, possibly no black hole
UGC 3789	Sab	…	48.4	…	[a]$0.09^{+0.09}_{-0.04}$	m-27, maser, modelling uncertain
Nine intermediate-mass black hole candidates						
G1	GC	…	0.8 [1a]	25	$1.8^{+0.5}_{-0.5} \times 10^{-4}$	s-34, but see s-35
M15	GC	…	0.01 [28]	14	$0.5^{+2.5}_{-0.5} \times 10^{-5}$	s-36, consistent with no IMBH (s-37)
M33	Scd	n	0.8 [29]	24	$<3 \times 10^{-5}$	s-38 & 39, consistent with no IMBH
MGG-11	Irr	n	3.6 [30]	11.4 [30]	$1.0^{+4.0}_{-0.8} \times 10^3$	x-40
NGC 205	E5	n	0.82 [31]	23	$<2.2 \times 10^{-4}$	s-41, consistent with no IMBH
NGC 4395	Sm	n	4.3 [32]	20–35	[b]10^{-4}–10^{-3}	42, consistent with no IMBH
ω Cen	GC	…	0.0048 [33]	20–23	$4.0^{+0.75}_{-1.0} \times 10^{-4}$	s-43, alternatives not ruled out
Pox 52	dE	n	98.8	36	[a,b]$3.2^{+1.0}_{-1.0} \times 10^{-3}$	44 & 45, indirect estimates
X7 in NGC6946	ULX	n	5.5 [46]	…	1–4×10^{-6}	46, indirect estimate

Unless otherwise specified, the distances have come from NED, and are the (Virgo + GA + Shapley)-corrected Hubble-flow distances. The velocity dispersions have come from HyperLeda (`http://leda.univ-lyon1.fr`) (Paturel et al. 2003) unless noted otherwise. M_{bh} has been adjusted to the distance given in column 4.

[a] A factor of two uncertainty has been assigned to these BH masses.

[b] BH mass obtained from the line width–luminosity–mass relation rather directly probing resolved kinematics about the BH.

References: 1, Tonry et al. 2001; 1a, the Tonry et al. 2001 distance to NGC 224 (M31) is used; 2, Ferrarese et al. 1996; 3, Jerjen et al. 2004; 4, Dalla Bontà et al. 2006; 5, Greenhill et al. 2003b; 6, Cappellari et al. 2002; 7, Lodato & Bertin 2003; 8, Braatz et al. 1997; 9, Wilson et al. 1995; 10, Atkinson et al. 2005; 11, Hu 2008; 12, Henkel et al. 2002; 13, Kondratko et al. 2006; 14, Marconi et al. 2003; 15, Pastorini et al. 2007; 16, Pignatelli, Salucci & Danese 2001; 17, Coccato et al. 2006; 18, Kormendy et al. 1997; 19, Kormendy 1988; 20, Tremaine et al. 2002; 21, Blais-Ouellette et al. 2004; 22, Hagiwara et al. 2001; 23, Häring & Rix 2004; 24, Gebhardt et al. 2003; 25, Peterson et al. 2004; 26, Hicks & Malkan 2008; 27, Braatz et al. 2008; 28, Harris 1996; 29, Argon et al. 2004; 30, McCrady, Gilbert & Graham 2003; 31, McConnachie et al. 2005; 32, Thim et al. 2004; 33, van de Ven et al. 2006; 34, Gebhardt et al. 2005; 35, Baumgardt et al. 2003b; 36, Gerssen et al. 2003 and van den Bosch et al. 2006; 37, Baumgardt et al. 2003a; 38, Gebhardt et al. 2001; 39, Merritt, Ferrarese & Joseph 2001; 40, Patruno et al. 2006; 41, Valluri et al. 2005; 42, Filippenko & Ho 2003; 43, Noyola, Gebhardt & Bergmann 2008; 44, Barth et al. 2004; 45, Thornton et al. 2008; 46, Senorita Devi et al. 2008.

The reference for each SMBH mass is provided in the final column of each table. A total of 50 galaxies are listed in Table 1. They are considered to have reasonably reliable measurements of their SMBH mass. The second table contains almost three dozen stellar systems whose SMBH masses are not yet secure, for the reasons noted in Table 2. It is of course hoped that in the near future many of these galaxies will migrate into Table 1.

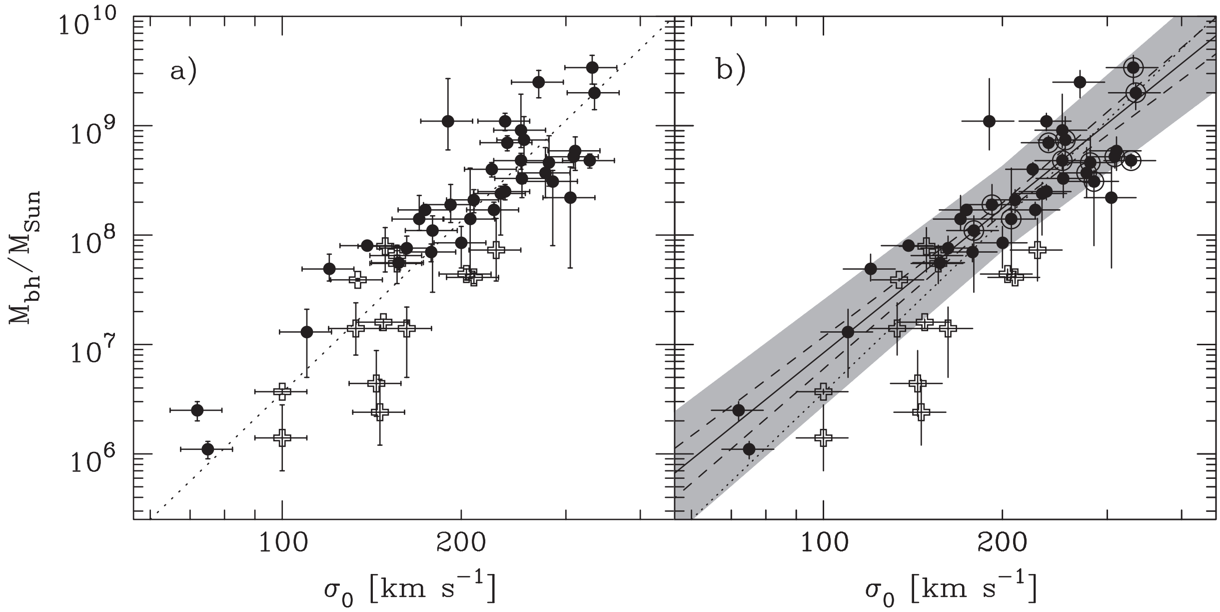

Figure 1 50 galaxies in the M_{bh}–σ_0 diagram (see Table 1). The 14 barred galaxies are denoted by the crosses. Known 'core galaxies' have been circled in panel b. The solid line is the optimal linear regression to the non-barred galaxies, as given by Equation (1), while the dashed lines delineate the 1-σ uncertainty for this relation. The shaded area extends this boundary by 0.33 dex in the log M_{bh} direction. The dotted line is the linear regression to all 50 data points.

When this paper's adopted distance to a given galaxy differed from the distance used in the paper which derived the SMBH mass, the mass has been rescaled here to the new distance. The adopted distances are listed in Tables 1 and 2 along with a reference to the new distance.

The basic morphological Hubble type has been taken from NED[1], with the exception that the galaxies noted in Graham (2008) to be barred are labelled as such, as is NGC 2639 (Márquez et al. 1999). In addition, following Graham & Driver (2007a), early-type galaxies with discs are labelled as lenticular (S0) rather than elliptical (E).

Many giant elliptical galaxies are known to possess partially depleted stellar cores relative to the inward extrapolation of their outer light profile (e.g. Kormendy 1985; Lauer 1985). A long-standing idea for the production of such cores is from the gravitational scouring and ejection of stars by SMBHs (Begelman, Blandford & Rees 1980; Ebisuzaki, Makino & Okumura 1991; Makino & Ebisuzaki 1996; Quinlan 1996; Quinlan & Hernquist 1997). Typical central deficits in stellar mass are on the order of the mass of the central SMBH (Graham 2004; Ferrarese et al. 2006, their Section 5.2; Merritt 2006). The gravitational recoil of the final, merged SMBH may also contribute to this reduction of the central stellar density (e.g. Gualandris & Merritt 2008). One may therefore expect the so-called 'core galaxies', formed via dry merger events, to display a different distribution in the M_{bh}–σ_0 diagram. Whether or not a galaxy contains a partially-depleted core is noted in Tables 1 and 2 using the identifications in Faber et al. (1997), Quillen et al. (2000), Ravindranath et al. (2001) and Rest et al. (2001).

As an inspection of HyperLeda[2] will reveal, the published central velocity dispersion, σ_0 of many galaxies can vary quite substantially. Most galaxies do not have flat velocity dispersion profiles, and so the radius within which one measures the velocity dispersion is an issue[3]. Jorgensen, Franx & Kjaergaard (1995) provide a correction from σ_0 to σ_e, the luminosity-weighted velocity dispersion within one effective radius R_e. It does however assume that the same normalised velocity dispersion profile exists for all galaxies. Potential, and indeed expected, systematic changes in the velocity dispersion profile shape with host bulge magnitude are therefore ignored by this adjustment. Rather than try and determine which value is the most appropriate, this paper has effectively placed its trust in the averaging process employed by HyperLeda and simply uses the (February 2008) HyperLeda-supplied central velocity dispersions, σ_0.

2.2 The Diagram

Figure 1 presents the SMBH masses versus the central velocity dispersions for the 50 galaxies listed in Table 1.

2.2.1 (Non-)Barred Galaxies

Galaxies known to possess a bar have been designated with a cross in Figure 1. As observed in Graham (2008, his Figure 5), many barred galaxies display a tendency to reside below the M_{bh}–σ_0 relation defined by the non-barred galaxies. A similar behavior was identified by Hu (2008) for SMBHs deemed to reside in 'pseudobulges'. It is important to realise that the claim is not that *all*

[1] `http://nedwww.ipac.caltech.edu/`

[2] `http://leda.univ-lyon1.fr/`

[3] In addition, for small apertures, the seeing conditions can influence the measurements even when the sampling radius remains unchanged.

barred galaxies are offset in this diagram, only that some are — perhaps due to the streaming motions of their stars influencing the measured velocity dispersion of the host bulge.

Using the (symmetrical) bisector linear regression routine BCES from Akritas & Bershady (1996), and assigning a 10 per cent uncertainty to the Hyperleda velocity dispersions, for the 36 non-barred galaxies one obtains the relation

$$\log\left(\frac{M_{\rm bh}}{M_\odot}\right) = (8.25 \pm 0.05) + (4.39 \pm 0.32) \times \log\left(\frac{\sigma_0}{200\,{\rm km\,s^{-1}}}\right). \quad (1)$$

The slope is 4.28 and 4.58 when using an uncertainty of 5 and 15 per cent for the velocity dispersion, respectively. Although this expression was not obtained by minimising the scatter in the log $M_{\rm bh}$ direction, the *total* RMS scatter in this direction is 0.33 dex.

Using all 50 galaxies, and a 10% uncertainty on the velocity dispersion, a bisector linear regression gives

$$\log\left(\frac{M_{\rm bh}}{M_\odot}\right) = (8.13 \pm 0.06) + (5.22 \pm 0.40) \times \log\left(\frac{\sigma_0}{200\,{\rm km\,s^{-1}}}\right). \quad (2)$$

2.2.2 Core Galaxies

Hu (2008) reveals that 'core galaxies' may have a steeper slope in the $M_{\rm bh}$–σ_0 diagram than galaxies without partially depleted cores. This is interesting because it may reflect the different formation history of the galaxies involved. Hu notes, however, that the different behavior only appears when using the velocity dispersions corrected to $R_{e/8}$ via the prescription given by Jorgensen et al. (1995). The difference is not evident when using the velocity dispersions within R_e from Tremaine et al. (2002). This mixed result was also evident in the figures of Wyithe (2006a). In Figure 1b, using the central velocity dispersions from HyperLeda, and without applying the formula from Jorgensen et al. (1995), no obvious difference to the relation defined by the core and non-core galaxies is apparent.

Given that the luminosity–σ_0^α relation has an exponent $\alpha \sim 4$ for luminous elliptical galaxies (Faber & Jackson 1976), but $\alpha \sim 2$ for dwarf elliptical galaxies (e.g. de Rijcke et al. 2005; Matković & Guzmán 2005, and references therein), then, as noted in Graham & Driver (2007a, their section 3.2), if the $M_{\rm bh}$–luminosity relation is linear (Graham 2007) one would expect the $M_{\rm bh}$–σ_0 relation to have two different slopes. While 'core' galaxies occupy the massive-end of this diagram, neither they nor the other big elliptical galaxies appear to define a different (steeper) relation to the 'non-core galaxies'. The answer may be due to the prevalence of disc galaxy bulges, rather than dwarf elliptical galaxies, at the low mass end of the $M_{\rm bh}$–σ_0 diagram, and it is concluded that an increased galaxy sample with reliable black hole mass measurements and velocity dispersions would be beneficial in resolving this issue.

2.2.3 Active Galaxies

Feedback from Active Galactic Nuclei (AGN) has long been proposed as a mechanism to curtail both SMBH growth and quench star formation in the host bulge (Begelman, de Kool & Sikora 1991; Silk & Rees 1998; Fabian 1999; Benson et al. 2003; Begelman & Nath 2005). This popular idea has been implemented in semi-analytical simulations of galaxies to shut off stellar growth in massive elliptical galaxies and explain both the $M_{\rm bh}$–σ_0 relation and the exponential decline at the bright end of the galaxy luminosity function (Granato et al. 2004; Bower et al. 2006; Croton et al. 2006).

In spite of AGN clearly signalling the presence of SMBHs, with the exception of NGC 4395 and Pox 52, only galaxies with direct dynamical measurements of material orbiting around their central black hole have been tabulated here; galaxies with active nuclei — whose black holes are thus currently under construction at some level — have not been included. Reverberation mapping estimates of SMBH masses do however exist for an increasing number of such galaxies, although the relatively larger uncertainty on their SMBH masses is not so desirable.

From a sample of 15 Seyfert-1 galaxies, Barth, Greene & Ho (2005) reported that they followed the same $M_{\rm bh}$–σ relation as defined by the local inactive sample from Tremaine et al. (2002). In contradiction to this, Wyithe (2006a,b) subsequently argued that a fraction resided above the standard $M_{\rm bh}$–σ_0 relation, evident over the velocity dispersion interval from $\sim$30 to $\sim$90 km s^{-1} (see also Zhang et al. 2008 who used Type II AGN). With an increased sample of 88 Type I AGN, and updated SMBH mass estimates, Greene & Ho (2006) have noted that there is indeed some evidence of a flatter slope to the $M_{\rm bh}$–σ relation at the low black hole mass end of the distribution. This can be seen in Figure 2 where these 88 AGN have been included. If not due to selection biases or over-estimated SMBH masses, this result may then signal an additional (third, after the barred galaxies) zone in the $M_{\rm bh}$–σ plane.

Also evident, but previously unrecognised, is the overlap of some AGN with the barred galaxies that deviate from the barless $M_{\rm bh}$–σ relation. It would be of interest to identify if the AGN which fall below the barless $M_{\rm bh}$–σ relation also have bars, and it is speculated here that they probably do. This is under investigation in Graham & Li (in preparation).

3 Outlook

With the increasing spatial resolution available from current and upcoming instruments, the number of SMBHs with resolved spheres-of-influence (Merritt & Ferrarese 2001b) is set to increase. Indeed, the community anxiously await the measurements of SMBH masses in some

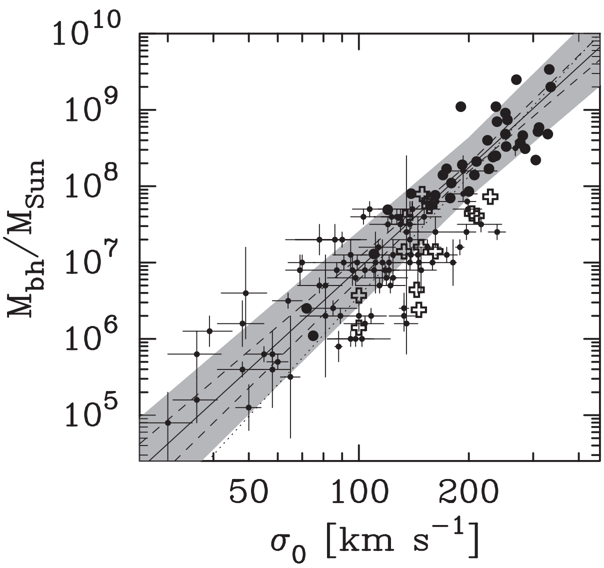

Figure 2 Similar to Figure 1b except that the 88 AGN (small points) from Greene & Ho (2006) have been added.

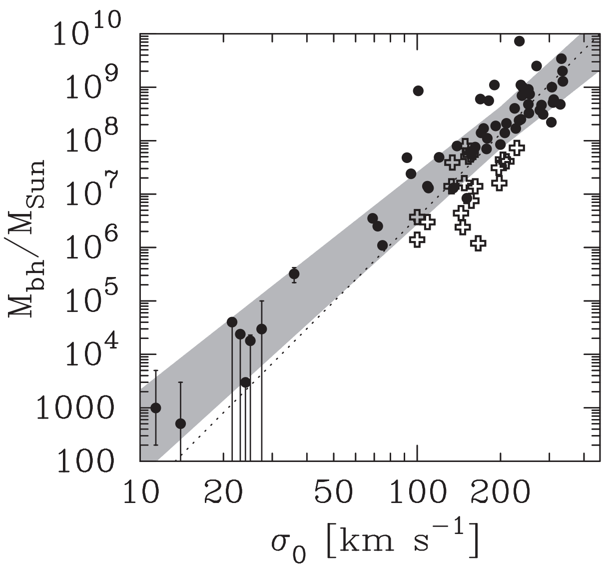

Figure 3 69 galaxies with both SMBH mass estimates and σ_0 values, plus 8 stellar systems with IMBH mass estimates (taken from Tables 1 and 2). The 21 barred galaxies are denoted by the crosses. For reference, the shaded area and dotted line is the same as that shown in Figure 1.

twenty galaxies from the combination of SAURON/WHT and OASIS/WHT data (Capellari et al. 2008). The M_{bh}–σ_0 diagram shown in Figure 3 is similar to Figure 1 except that the SMBH data from both Tables 1 and 2 are shown. While one can see that the inclusion of the additional (less secure) data has increased the scatter, due no doubt to the greater uncertainties on these SMBH masses, many barred galaxies still display a tendency to reside beneath the barless relation established previously (Equation 1). While the intermediate mass black holes (IMBHs) appear to follow the barless M_{bh}–σ_0 relation defined by the more massive systems, it is noted that most of the IMBH masses are not yet securely established and they may in fact not exist at all, as noted in their parent papers.

Another issue that we can expect to see unfold in the future pertains to the coexistence of SMBHs and nuclear star clusters (NC). Graham & Spitler (2008, in prep) have already identified that (at least) ten of the galaxies listed here also harbour a nuclear star cluster. If barred galaxies are preferentially nucleated, then the use of the combined SMBH + NC mass may help to reduce their discrepant behaviour in the M_{bh}–σ_0 diagram.

At present, for most galaxies only an upper-limit on their SMBH mass exists (e.g. Beifiori et al. 2008). 'Active Optics'-enhanced integral field spectrograph data from instrument/telescope combinations such as NIFS/Gemini, OSIRIS/Keck, SINFONI/VLT, LUCIFER/LBT and ATLANTIS/GTC are capable of providing comparable or better image resolution than acquired with STIS/HST and promise to further populate the useful and insightful M_{bh}–σ_0 diagram in the future. They of course additionally offer the ability to provide two-dimensional velocity dispersion (and rotational) information and thereby take us beyond the use of simple central velocity dispersion measurements and thereby better constrain the kinetic energy and mass of each galaxy or bulge.

Acknowledgments

I am happy to thank David Merritt and Stuart Wyithe for enjoyable discussions pertaining to aspects of this work. I acknowledges use of the HyperLeda database (`http://leda.univ-lyon1.fr`) and the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

Akritas, M. G. & Bershady, M. A., 1996, ApJ, 470, 706
Atkinson, J. W. et al., 2005, MNRAS, 359, 504
Bacon, R., Emsellem, E., Combes, F., Copin, Y., Monnet, G. & Martin, P., 2001, A&A, 371, 409
Barth, A. J., Sarzi, M., Rix, H.-W., Ho, L. C., Filippenko, A. V. & Sargent, W. L. W., 2001, ApJ, 555, 685
Barth, A. J., Ho, L. C., Rutledge, R. E. & Sargent, W. L. W., 2004, ApJ, 607, 90
Baumgardt, H., Hut, P., Makino, J., McMillan, S. & Portegies Zwart, S., 2003a, ApJ, 582, L21
Baumgardt, H., Makino, J., Hut, P., McMillan, S. & Portegies Zwart, S., 2003b, ApJ, 589, L25
Begelman, M. C. & Nath, B. B., 2005, MNRAS, 361, 1387
Begelman, M. C., Blandford, R. D. & Rees, M. J., 1980, Natur, 287, 307
Begelman, M., de Kool, M. & Sikora, M., 1991, ApJ, 382, 416
Beifiori, A., Sarzi, M., Corsini, E. M., Dalla Bontà, E., Pizzella, A., Coccato, L. & Bertola, F., 2008, ApJ, in press (arXiv:0809.5103)
Bender, R. et al., 2005, ApJ, 631, 280
Benson, A. J., Bower, R. G., Frenk, C. S., Lacey, C. G., Baugh, C. M. & Cole, S., 2003, ApJ, 599, 38
Blais-Ouellette, S., Amram, P., Carignan, C. & Swaters, R., 2004, A&A, 420, 147
Bower, G. A. et al., 2001, ApJ, 550, 75

Bower, R. G., Benson, A. J., Malbon, R., Helly, J. C., Frenk, C. S., Baugh, C. M., Cole, S. & Lacey, C. G., 2006, MNRAS, 370, 645
Braatz, J. A., Greenhill, L., Moran, J., Wilson, A. & Herrnstein, J., 1997, BAAS, 29, 1374
Braatz, J. A. & Gugliucci, N. E., 2008, ApJ, 678, 96
Capetti, A., Marconi, A., Macchetto, D. & Axon, D., 2005, A&A, 431, 465
Cappellari, M., Verolme, E. K., van der Marel, R. P., Kleijn, G. A. V., Illingworth, G. D., Franx, M., Carollo, C. M. & de Zeeuw, P. T., 2002, ApJ, 578, 787
Cappellari, M. et al., 2006, MNRAS, 366, 1126
Cappellari, M. et al., 2008, in IAUS 245, Formation and Evolution of Galaxy Bulges, Eds. Bureau, M., Athanassoula, E. & Barbuy, B., 215
Cid Fernandes, R., Gu, Q., Melnick, J., Terlevich, E., Terlevich, R., Kunth, D., Rodrigues Lacerda, R. & Joguet, B., 2004, MNRAS, 355, 273
Coccato, L., Sarzi, M., Pizzella, A., Corsini, E. M., Dalla Bontà, E. & Bertola, F., 2006, MNRAS, 366, 1050
Copin, Y., Cretton, N. & Emsellem, E., 2004, A&A, 415, 889
Cretton, N. & van den Bosch, F., 1999, ApJ, 514, 704
Croton, D. J. et al., 2006, MNRAS, 365, 11
Davies, R. I. et al., 2006, ApJ, 646, 754
de Rijcke, S., Michielsen, D., Dejonghe, H., Zeilinger, W. W. & Hau, G. K. T., 2005, A&A, 438, 491
Devereux, N. A., Ford, H. C., Tsvetanov, Z. & Jacoby, G., 2003, AJ, 125, 1226
Ebisuzaki, T., Makino, J. & Okumura, S. K., 1991, Natur, 354, 212
Eisenhauer, F. et al., 2003, ApJ, 597, L121
Emsellem, E., Dejonghe, H. & Bacon, R., 1999, MNRAS, 303, 495
Faber, S. M. & Jackson, R. E., 1976, ApJ, 204, 668
Faber, S. M. et al., 1997, AJ, 114, 1771
Fabian, A. C., 1999, MNRAS, 308, L39
Ferrarese, L. & Ford, H. C., 1999, ApJ, 515, 583
Ferrarese, L. & Ford, H. C., 2005, SSRv, 116, 523
Ferrarese, L. & Merritt, D., 2000, ApJ, 539, L9
Ferrarese, L., van den Bosch, F. C., Ford, H. C., Jaffe, W. & O'Connell, R. W., 1994, AJ, 108, 1598
Ferrarese, L., Ford, H. C. & Jaffe, W., 1996a, ApJ, 470, 444
Ferrarese, L. et al., 1996b, ApJ, 464, 568
Ferrarese, L. et al., 2006, ApJS, 164, 334
Filippenko, A. V. & Ho, L. C., 2003, ApJ, 588, L13
Gebhardt, K. et al., 2000, ApJ, 539, L13
Gebhardt, K. et al., 2001, AJ, 122, 2469
Gebhardt, K. et al., 2003, ApJ, 583, 92
Gebhardt, K., Rich, R. M. & Ho, L. C., 2005, ApJ, 634, 1093
Gebhardt, K. et al., 2007, ApJ, 671, 1321
Gerssen, J., van der Marel, R. P., Gebhardt, K., Guhathakurta, P., Peterson, R. C. & Pryor, C., 2003, AJ, 125, 376
Ghez, A. M. et al., 2005, ApJ, 620, 744
Graham, A. W., 2004, ApJ, 613, L33
Graham, A. W., 2007, MNRAS, 379, 711
Graham, A. W., 2008, ApJ, 680, 143
Graham, A. W. & Driver, S. P., 2007a, ApJ, 655, 77
Graham, A. W. & Driver, S. P., 2007b, MNRAS, 380, L15
Granato, G. L., De Zotti, G., Silva, L., Bressan, A. & Danese, L., 2004, ApJ, 600, 580
Greene, J. E. & Ho, L. C., 2006, ApJ, 641, L21
Greenhill, L. J., Moran, J. M. & Herrnstein, J. R., 1997, ApJ, 481, L23
Greenhill, L. J. et al., 2003a, ApJ, 590, 162
Greenhill, L. J., Kondratko, P. T., Lovell, J. E. J., Kuiper, T. B. H., Moran, J. M., Jauncey, D. L. & Baines, G. P., 2003b, ApJ, 582, L11
Gualandris, A. & Merritt, D., 2008, in 2007 STScI Spring Symposium: Black Holes, Eds. Livio, M. & Koekemoer, A. M. (Cambridge University Press), in press (arXiv:0708.3083)
Hagiwara, Y., Diamond, P. J., Nakai, N. & Kawabe, R., 2001, ApJ, 560, 119
Häring, N. & Rix, H.-W., 2004, ApJ, 604, L89
Harris, W. E., 1996, AJ, 112, 1487
Henkel, C., Braatz, J. A., Greenhill, L. J. & Wilson, A. S., 2002, A&A, 394, 23
Herrnstein, J. R. et al., 1999, Natur, 400, 539
Hicks, E. K. S. & Malkan, M. A., 2008, ApJS, 174, 31
Houghton, R. C. W., Magorrian, J., Sarzi, M., Thatte, N., Davies, R. L. & Krajnović, D., 2006, MNRAS, 367, 2
Hu, J., 2008, MNRAS, 386, 2242
Ishihara, Y., Nakai, N., Iyomoto, N., Makishima, K., Diamond, P. & Hall, P., 2001, PASJ, 53, 215
Jerjen, H., Binggeli, B. & Barazza, F. D., 2004, AJ, 127, 771
Jorgensen, I., Franx, M. & Kjaergaard, P., 1995, MNRAS, 276, 1341
Karachentsev, I. D. et al., 2007, AJ, 133, 504
Kondratko, P. T., Greenhill, L. J. & Moran, J. M., 2005, ApJ, 618, 618
Kondratko, P. T. et al., 2006, ApJ, 638, 100
Kormendy, J., 1985, ApJ, 292, L9
Kormendy, J., 1988, ApJ, 335, 40
Kormendy, J. et al., 1997, ApJ, 482, L139
Kormendy, J. & Richstone, D. O., 1995, ARA&A, 33, 581
Lauer, T. R., 1985, ApJ, 292, 104
Lodato, G. & Bertin, G., 2003, A&A, 398, 517
Macchetto, F., Marconi, A., Axon, D. J., Capetti, A., Sparks, W. & Crane, P., 1997, ApJ, 489, 579
Maciejewski, W. & Binney, J., 2001, MNRAS, 323, 831
Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C. & Fruchter, A., 1996, MNRAS, 283, 1388
Magorrian, J. et al., 1998, AJ, 115, 2285
Makino, J. & Ebisuzaki, T., 1996, ApJ, 465, 527
Marconi, A. & Hunt, L. K., 2003, ApJ, 589, L21
Marconi, A. et al., 2003, ApJ, 586, 868
Marconi, A., Pastorini, G., Pacini, F., Axon, D. J., Capetti, A., Macchetto, D., Koekemoer, A. M. & Schreier, E. J., 2006, A&A, 448, 921
McConnachie, A. W., Irwin, M. J., Ferguson, A. M. N., Ibata, R. A., Lewis, G. F. & Tanvir, N., 2005, MNRAS, 356, 979
McCrady, N., Gilbert, A. M. & Graham, J. R., 2003, ApJ, 596, 240
McLure, R. J. & Dunlop, J. S., 2002, MNRAS, 331, 795
Merritt, D., 2006, ApJ, 648, 976
Merritt, D. & Ferrarese, L., 2001a, ApJ, 547, 140
Merritt, D. & Ferrarese, L., 2001b, The Central Kiloparsec of Starbursts and AGN: The La Palma Connection, 249, 335
Merritt, D., Ferrarese, L. & Joseph, C. L., 2001, Sci, 293, 1116
Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P. & Inoue, M., 1995, Natur, 373, 127
Nakai, N., Inoue, M., Hagiwara, Y., Miyoshi, M. & Diamond, P. J., 1998, IAUC 164: Radio Emission from Galactic and Extragalactic Compact Sources, 144, 237
Neumayer, N., Cappellari, M., Reunanen, J., Rix, H.-W., van der Werf, P. P., de Zeeuw, P. T. & Davies, R. I., 2007, ApJ, 671, 1329
Novak, G. S., Faber, S. M. & Dekel, A., 2006, ApJ, 637, 96
Nowak, N., Saglia, R. P., Thomas, J., Bender, R., Pannella, M., Gebhardt, K. & Davies, R. I., 2007, MNRAS, 379, 909
Noyola, E., Gebhardt, K. & Bergmann, M., 2008, ApJ, 676, 1008
Onken, C. A. et al., 2007, ApJ, 670, 105
Pastorini, G. et al., 2007, A&A, 469, 405
Patruno, A., Portegies Zwart, S., Dewi, J. & Hopman, C., 2006, MNRAS, 370, L6
Paturel, G., Petit, C., Prugniel, P., Theureau, G., Rousseau, J., Brouty, M., Dubois, P. & Cambrésy, L., 2003, A&A, 412, 45
Peterson, B. M. et al., 2004, ApJ, 613, 682
Pignatelli, E., Salucci, P. & Danese, L., 2001, MNRAS, 320, 124
Quinlan, G. D., 1996, NewA, 1, 35
Quinlan, G. D. & Hernquist, L., 1997, NewA, 2, 533
Ravindranath, S., Ho, L. C., Peng, C. Y., Filippenko, A. V. & Sargent, W. L. W., 2001, AJ, 122, 653
Rest, A., van den Bosch, F. C., Jaffe, W., Tran, H., Tsvetanov, Z., Ford, H. C., Davies, J. & Schafer, J., 2001, AJ, 121, 2431
Richstone, D. et al., 2008, ApJ, submitted (astro-ph/0403257)

Salucci, P., Szuszkiewicz, E., Monaco, P. & Danese, L., 1999, MNRAS, 307, 637
Sarzi, M., Rix, H.-W., Shields, J. C., Rudnick, G., Ho, L. C., McIntosh, D. H., Filippenko, A. V. & Sargent, W. L. W., 2001, ApJ, 550, 65
Senorita Devi, A., Misra, R., Shanthi, K. & Singh, K. Y., 2008, ApJ, 682, 218
Shapiro, K. L., Cappellari, M., de Zeeuw, T., McDermid, R. M., Gebhardt, K., van den Bosch, R. C. E. & Statler, T. S., 2006, MNRAS, 370, 559
Silk, J. & Rees, M. J., 1998, A&A, 331, L1
Tadhunter, C., Marconi, A., Axon, D., Wills, K., Robinson, T. G. & Jackson, N., 2003, MNRAS, 342, 861
Thim, F., Hoessel, J. G., Saha, A., Claver, J., Dolphin, A. & Tammann, G. A., 2004, AJ, 127, 2322
Thornton, C. E., Barth, A. J., Ho, L. C., Rutledge, R. E. & Greene, J. E., ApJ, in press (arXiv:0807.1535)
Tonry, J. L., Dressler, A., Blakeslee, J. P., Ajhar, E. A., Fletcher, A. B., Luppino, G. A., Metzger, M. R. & Moore, C. B., 2001, ApJ, 546, 681
Tremaine, S. et al., 2002, ApJ, 574, 740
Trotter, A. S., Greenhill, L. J., Moran, J. M., Reid, M. J., Irwin, J. A. & Lo, K., 1998, ApJ, 495, 740
Trujillo, I., Erwin, P., Asensio Ramos, A. & Graham, A. W., 2004, AJ, 127, 1917
Valluri, M., Merritt, D. & Emsellem, E., 2004, ApJ, 602, 66
Valluri, M., Ferrarese, L., Merritt, D. & Joseph, C. L., 2005, ApJ, 628, 137
van de Ven, G., van den Bosch, R. C. E., Verolme, E. K. & de Zeeuw, P. T., 2006, A&A, 445, 513
van den Bosch, R., de Zeeuw, T., Gebhardt, K., Noyola, E. & van de Ven, G., 2006, ApJ, 641, 852
van der Marel, R. P. & van den Bosch, F. C., 1998, AJ, 116, 2220
Verolme, E. K. et al., 2002, MNRAS, 335, 517
Wilson, A. S., Braatz, J. A. & Henkel, C., 1995, ApJ, 455, L127
Wold, M., Lacy, M., Käufl, H. U. & Siebenmorgen, R., 2006, A&A, 460, 449
Wyithe, J. S. B., 2006a, MNRAS, 365, 1082
Wyithe, J. S. B., 2006b, MNRAS, 371, 1536
Yamauchi, A., Nakai, N., Sato, N. & Diamond, P., 2004, PASJ, 56, 605
Younger, J. D., Hopkins, P. F., Cox, T. J. & Hernquist, L., 2008, ApJ, submitted (arXiv:0804.2672)
Zhang, S.-Y., Bian, W.-H. & Huang, K.-L., 2008, A&A, submitted (arXiv:0806.2485)