A FUNDAMENTAL RELATION BETWEEN SUPERMASSIVE BLACK HOLES AND THEIR HOST GALAXIES

Laura Ferrarese[1]

University of California, Los Angeles, CA, 90095, laura@astro.ucla.edu

David Merritt

Rutgers University, New Brunswick, NJ, 08854, merritt@physics.rutgers.edu

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ABSTRACT

The masses of supermassive black holes correlate almost perfectly with the velocity dispersions of their host bulges, $M_\bullet \propto \sigma^\alpha$, where $\alpha = 4.8 \pm 0.5$. The relation is much tighter than the relation between $M_\bullet$ and bulge luminosity, with a scatter no larger than expected on the basis of measurement error alone. Black hole masses estimated by Magorrian et al. (1998) lie systematically above the $M_\bullet - \sigma$ relation defined by more accurate mass estimates, some by as much as two orders of magnitude. The tightness of the $M_\bullet - \sigma$ relation implies a strong link between black hole formation and the properties of the stellar bulge.

1. INTRODUCTION

After decades of indirect and circumstantial evidence, the motion of gas and stars on parsec scales has provided irrefutable dynamical evidence for the presence of $10^7 - 10^9$ M$_\odot$ black holes (BHs) in about a dozen elliptical and a handful of spiral galaxies (Kormendy & Richstone 1995). While efforts to build a larger, statistically significant sample continue, we have now moved from debating the existence of supermassive BHs, to asking what regulates their formation and evolution, and how their presence influences, and is influenced by, their host galaxies.

In an early review based on eight detections, Kormendy & Richstone (1995) found that BH masses $M_\bullet$ scale linearly with the absolute blue luminosity of the host bulge or elliptical galaxy. This correlation was later strengthened by Magorrian et al. (1998) using a larger (~ 30) sample of galaxies to which simple stellar dynamical models were applied. At the same time, it has been noted (e.g. Jaffe 1999) that the $M_\bullet - B_T^0$ relation suffers from observational biases and exhibits a large scatter which is not accounted for by the uncertainties in the individual measurements.

By understanding how the properties of BHs relate to those of their host galaxies, we can hope to learn about the formation and evolution of both. In this Letter, the connection between BH masses and the stellar velocity dispersion of the host galaxy is investigated for the first time. We find a remarkably tight correlation with negligible intrinsic scatter when using galaxies with well-determined BH masses (roughly speaking, those galaxies in which the observations have resolved the sphere of gravitational influence of the BH). Our results suggest that the stellar velocity dispersion may be the fundamental parameter regulating the evolution of supermassive BHs in galaxies.

2. DATABASE

All secure BH mass estimates available to date (see §3), together with a compilation of properties of the host galaxies, are given in Table 1. Revised Hubble and T-type (from the Third Reference Catalogue, RC3, de Vaucouleurs et al. 1991) are found in columns 2 and 3, while column 4 lists distances to the host galaxy. With a few exceptions detailed in the footnotes,

all distances are from surface brightness fluctuation (SBF) data (Tonry et al. 2000) calibrated as in Ferrarese et al. (2000).

Total apparent magnitudes m$_B$, uncorrected for Galactic absorption, are from the RC3 for all elliptical galaxies (T-type = -4 or smaller), and from de Vaucouleurs & Pence (1978) for the Milky Way. For the lenticular and spiral galaxies (T-type = -3 and larger), m_B for the bulge is derived using the empirical correlation between T-type and the ratio between bulge and total luminosity (Simien & de Vaucouleurs 1986), and is deemed to be accurate within 0.5 mag. Finally, all magnitudes are corrected for Galactic extinction using the DIRBE/IRAS maps of Schlegel, Finkbeiner & Davis (1998) and an extinction law following Cardelli, Clayton & Mathis (1989), and converted to absolute magnitudes (col. 5) given the distances in column 4.

The methods used in deriving the BH masses, and references to the original papers are listed in the last column of Table 1. Because the masses depend linearly on the assumed distance to the host galaxies, the values in column 6 have been corrected to adhere to our homogeneous set of distances. This correction is random in nature, and negligible with the exception of IC 1459, which is twice as distant as assumed in the original paper. Uncertainties in the host galaxies' distances have been incorporated in the errors in the BH masses.

Elliptical galaxies and bulges of spirals have radial velocity gradients, hence a measure of the velocity dispersion σ will depend on the distance to the galaxy, the size of the aperture used, and the location of the aperture with respect to the galaxy core (e.g. Davies et al. 1987). For this work, we have chosen the same definition of σ used for studies of the fundamental plane of elliptical galaxies, namely the *central* velocity dispersion, typically measured in an aperture a few arcseconds in diameter (Davies et al. 1987, and references listed in the footnotes of Table 1). Our choice will be justified in §3. To bring all values of σ to a common system, we have adopted the prescription of Jorgensen, Franx & Kjaergaard (1995) and transformed all velocity dispersions to the equivalent of an aperture of radius $r_e/8$, where r_e is the galaxy (or bulge) effective radius. The applied corrections are very small (rarely exceeding 5%) and are deemed accurate to within 1% (Jorgensen, Franx & Kjaergaard 1995). Raw and corrected σ are listed in columns 7 and 8 of

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[1]Current Address: Department of Physics and Astronomy, Rutgers University, New Brunswick, NJ 08854

Table 1.   Database of secure black hole mass estimates and properties of the host galaxies (Sample A)

Galaxy Name	Rev. Hubble Type	T-type	Distance[1] (Mpc)	B_T^0 (mag)	BH Mass (10^8 M$_\odot$)	$\sigma^{[2]}$ (km s^{-1})	σ_c (km s^{-1})	Method and References[3]
MW	SbI-II	$\cdots$	$8.0\pm0.9^{[1]}$	-19.13 ± 0.50	0.0295 ± 0.0035	100 ± 20	100 ± 20	PM; Ge00
I1459	E3	-5.0 ± 0.3	30.3 ± 4.0	-21.50 ± 0.32	4.6 ± 2.8	322 ± 41	312 ± 41	G; VK00
N221	cE2	-6.0 ± 0.3	0.8 ± 0.1	-15.76 ± 0.18	0.039 ± 0.009	80 ± 10	76 ± 10	S; vdM98
N3115	S0$^-$	-3.0 ± 0.3	9.8 ± 0.6	-19.74 ± 0.52	9.2 ± 3.0	291 ± 38	278 ± 36	S; EDB99
N3379	E1	-5.0 ± 0.3	10.8 ± 0.7	-20.03 ± 0.14	1.35 ± 0.73	210 ± 27	201 ± 26	S; G00
N4258	SAB(s)bc	4.0 ± 0.3	7.2 ± 0.3	-18.26 ± 0.51	0.3901 ± 0.034	146 ± 19	138 ± 18	M; M95
N4261	E2	-5.0 ± 0.3	33.0 ± 3.2	-21.26 ± 0.22	$5.4^{+1.2}_{-1.2}$	306 ± 40	290 ± 38	G; FFJ96
N4342	S0$^-$	-3.0 ± 0.5	16.7 ± 1.0	-17.24 ± 0.52	$3.3^{+1.9}_{-1.1}$	255 ± 33	261 ± 34	S; CB99
N4374	E1	-5.0 ± 0.3	18.7 ± 1.2	-21.44 ± 0.15	$17^{+12}_{-6.7}$	304 ± 39	286 ± 37	G; B98
N4486	E0pec	-4.0 ± 0.3	16.7 ± 1.0	-21.61 ± 0.14	35.7 ± 10.2	370 ± 48	345 ± 45	G; M97
N6251	E	-5.0 ± 0.8	104 ± 10	-21.94 ± 0.28	5.9 ± 2.0	293 ± 38	297 ± 39	G; FF99
N7052	E	-5.0 ± 0.7	66.1 ± 6.4	-21.33 ± 0.38	$3.7^{+2.6}_{-1.5}$	270 ± 35	261 ± 34	G; MB98

[1] For lack of independent determinations, distances to NGC 6251 and NGC 7052 are derived as v/H_0, where the systemic velocities v are from the CfA redshift survey (Huchra et al. 1998) and $H_0 = 71 \pm 7$ km s^{-1} Mpc^{-1} (Mould et al. 2000). The distance to NGC 4258 is geometrically determined from the proper motion of its nuclear water masers (Herrnstein et al. 1999). NGC 4342 has been assumed to be at the same SBF distance as the nearby NGC 4472. The distance to the galactic center is in kpc (from Genzel et al. 2000).

[2] All velocity dispersions are from Davies et al. (1987), except for the Milky Way (Kent 1992), NGC 4258 (Terlevich et al. 1990), NGC 6251 (Heckman et al. 1985) and NGC 7052 (Wagner et al. 1988).

[3] Codes for the original papers are given in the references. Codes for the methods used in estimating the masses are: G = gas kinematics from HST optical spectra; S = stellar kinematics from HST optical spectra, using axisymmetric dynamical models with 3-integral distribution functions; M = kinematics of water maser clumps, derived from VLBA data; PM = proper motion measurements of the SgA star cluster.

Table 1. For the Milky Way, we adopt the mean velocity dispersion compiled by Kent (1992) within $r_e/8$.

3. ANALYSIS

We did not make any attempt to homogenize the error estimates on the BH masses. Except for adding in quadrature the (small) uncertainty in the galaxies' distances, the errors on $M_\bullet$ listed in Table 1 are those quoted by the respective authors. However, the real uncertainties are often much larger. For instance, Magorrian et al. (1998) derived BH masses based on fitting a simple class of dynamical models to ground-based kinematical data. In almost all of these galaxies, the data can equally well be fit by a more general class of model with no BH at all; thus the Magorrian et al. mass estimates might conservatively be interpreted as upper limits (e.g. van der Marel 1997). The same is true for the majority of ground-based, stellar-kinematical BH detections.

In view of this fact, we list in Table 1 only the galaxies which we deem to have reliable BH mass estimates. The proper motion studies of the Sagittarius A star cluster and the dynamics of the water maser disk in NGC 4258 lead to the most robust determinations of $M_\bullet$. Close seconds are estimates in 10 additional galaxies, based on data from high-resolution HST observations, either absorption-line stellar spectra or observations of the motion of nuclear dust/gas disks. These 12 galaxies comprise our "Sample A." Additional galaxies with less secure BH mass detections are Arp 102B ($M_\bullet$ obtained from fitting accretion disk models to variable optical emission lines, Newman et al. 1997), and all galaxies for which $M_\bullet$ is estimated based on stellar kinematics obtained from the ground (e.g. the Magorrian et al. 1998 sample). These galaxies define our "Sample B": the data are tabulated in Merritt & Ferrarese (2000).

We then searched for linear correlations between $\log M_\bullet$ and both B_T^0 and $\log\sigma_c$. We used the bivariate linear regression routine of Akritas & Bershady (1996), which accommodates intrinsic scatter as well as measurement errors in both variables. $M_\bullet$ was taken as the dependent variable. The results of the regression fits, applied to each sample of N galaxies, are summarized in Table 2 and Figure 1.

The correlation between $M_\bullet$ and bulge magnitude B_T^0 (Fig. 1a,c) is poor, both for Sample A and Sample B. Although the best linear fit to the data has a slope close to the value of -0.4 expected if $M_\bullet$ is simply proportional to the bulge mass, it is apparent from the figure, and from the reduced χ_r^2 of the fit (Table 2), that even by restricting the sample to the galaxies with the most accurately determined BH masses, the intrinsic scatter in the $M_\bullet-B_T^0$ relation remains significantly larger than the reported errors. No sub-sample of galaxies, selected either by Hubble Type or method used in deriving $M_\bullet$, defines a tight linear relation between $M_\bullet$ and B_T^0. This implies that differences in the mass-to-light ratio between Hubble types, or systematic biases affecting any particular method, are unlikely to account for the large scatter.

Figures 1b and 1d show the dependence of $M_\bullet$ on the central stellar velocity dispersion σ_c of the host bulge or elliptical galaxy. The correlation is remarkable: Sample A, which shows a large scatter in the $M_\bullet-B_T^0$ plots, now defines a linear relation with negligible intrinsic scatter. The best-fit linear relation is

$$\log M_\bullet = 4.80(\pm0.54)\log\sigma_c - 2.9(\pm1.3) \qquad (1)$$

with $M_\bullet$ in units of $M_\odot$ and σ_c in km s^{-1}. The slope of the relation remains unaltered, albeit with a larger uncertainty, if the two galaxies at the low-velocity-dispersion end of the distribution (the Milky Way and M32) are excluded from the fit. The reduced χ^2 of the fit (Table 2) is only 0.8, consistent with a

scatter that derives entirely from measurement errors. The first incarnation of Eq. (1) was suggested by Merritt (2000) (the "Faber-Jackson law for black holes").

The galaxies in Sample B define a much weaker correlation between $M_\bullet$ and σ_c (Fig. 1d). Furthermore, the BH masses in this sample lie systematically above the mean line defined by Sample A, some by factors of $\sim 10^2$. Two factors distinguish the two samples: the reliability of the $M_\bullet$ estimates; and the method used to derive the BH masses. About 1/2 of the mass determinations in Sample A are based on gas motions while almost all of the Sample B masses are derived from stellar kinematics. We see no evidence for a systematic difference between the two types of mass determination; for instance, NGC 4342 and NGC 7052 have identical σ_c and $M_\bullet$, even though the determination of $M_\bullet$ in NGC 4342 is based on stellar kinematics and in NGC 7052 on rotation of a gas disk. In the case of IC 1459, for which $M_\bullet$ predicted by Eq. 1 is 2.5 times larger than measured, Verdoes-Kleijn et al. (2000) suggest that the true BH mass could be a factor $3-4$ greater than their best estimate due to non-circular motions of the gas. It seems likely that the different correlations defined by the two samples result largely from errors in the determination of $M_\bullet$ for the galaxies in Sample B.

Our choice of aperture-corrected, central velocity dispersions is convenient but not unique. We note first that correcting σ for the effect of aperture size does not introduce a bias in either the slope or the intercept (see Table 1). However, the need for

Table 2. Results of the Linear Regression Fits: $Y = \alpha X + \beta$

X,Y Variables[1]	Sample[2]	N	α	β	χ_r^2
$\log(\sigma_c), \log(M_\bullet)$	A	12	4.80 ± 0.54	-2.9 ± 1.3	0.79
$\log(\sigma_c), \log(M_\bullet)$	B	29	5.81 ± 0.43	-4.6 ± 1.0	2.3
$\log(\sigma), \log(M_\bullet)$	A	12	4.81 ± 0.48	-3.0 ± 1.1	0.61
$\log(v_{rms}), \log(M_\bullet)$	A	10	4.61 ± 0.79	-2.3 ± 1.9	8.0
$B_T^0, \log(M_\bullet)$	A	12	-0.36 ± 0.09	1.2 ± 1.9	23
$B_T^0, \log(M_\bullet)$	B	30	-0.48 ± 0.10	-0.8 ± 2.0	25

[1] Units are $M_\odot$ for $M_\bullet$, km s^{-1} for σ and σ_c, and magnitudes for B_T^0

[2] See §3 for a definition of the samples

aperture corrections could be avoided by using a measurement of the rms velocity at some fiducial distance from the center. Figure 2 plots $M_\bullet$ vs. the rms stellar velocity v_{rms} at $r_e/4$, with $v_{rms} = \sqrt{(\sigma^2 + v_r^2/\sin^2 i)_{r_e/4}}$. Here σ and v_r are the measured stellar velocity dispersion and mean line-of-sight velocity respectively. A complication with this approach is the typically poorly-constrained value of the inclination angle i between the rotation axis and the line of sight. Estimates for i are available only for NGC 3115 (Emsellem, Dejonghe & Bacon 1999) and NGC 4342 (Scorza & van den Bosch 1998). Neglecting or wrongly estimating $\sin i$ will increase the scatter in the relation and bias the slope too low, by moving faint, rapidly-rotating galaxies to the left in the $M_\bullet - v_{rms}$ plane. Nevertheless, for our sample A, linear regression fits (Table 2) show that the slopes of $M_\bullet$ vs bulge velocity are coincident whether σ_c or v_{rms} is used.

An interesting question is whether the tight correlation between $M_\bullet$ and σ_c might simply reflect the influence of the BH on the stellar kinematics of the nucleus. The coincidence of the slopes obtained when v_{rms} is substituted for σ_c is the most convincing evidence that this is not the case, since v_{rms} is measured well beyond the radius at which the BH could have a measurable effect. In addition, most of the measurements of σ listed in Table 1 were carried out using apertures much larger than the expected radius of gravitational influence of the BH. We stress that – even if the correlation between $M_\bullet$ and σ_c were due in part to the gravitational influence of the BH on the motion of stars in the nucleus – this would not vitiate the usefulness of the relation as a predictor of $M_\bullet$. *Figure 1b suggests that $M_\bullet$ can be predicted with an accuracy of $\sim 30\%$ or better from a single, low-resolution observation of a galaxy's velocity dispersion.* This is a remarkable result.
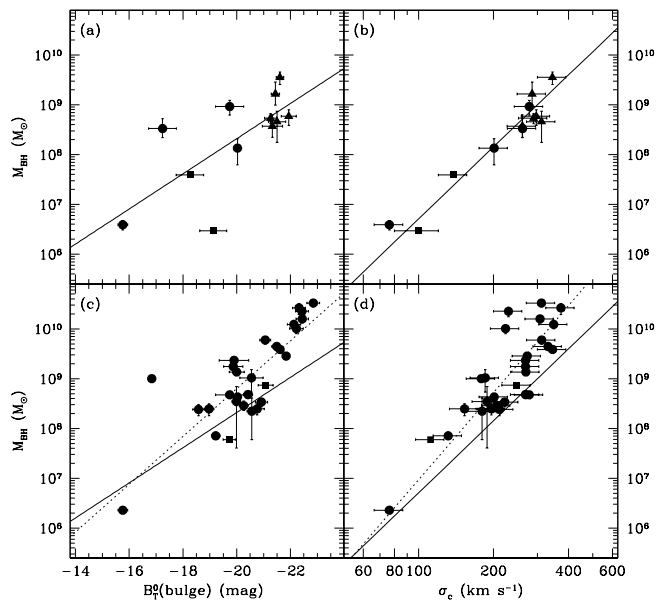

FIG. 1.— (a): BH mass versus absolute blue luminosity of the host elliptical galaxy or bulge for our most reliable Sample A. The solid line is the best linear fit (Table 2). Circles and triangles represent mass measurements from stellar and dust/gas disk kinematics respectively. The squares are the Milky Way ($M_\bullet$ determined from stellar proper motions) and NGC 4258 ($M_\bullet$ based on water maser kinematics), the only two spiral galaxies in the sample. (b) Again for Sample A, BH mass versus the central velocity dispersion of the host elliptical galaxy or bulge, corrected for the effect of varying aperture size as described in §2. Symbols are as in panel (a). (c): Same as panel (a) but for Sample B. Circles are elliptical galaxies, squares are spiral galaxies. The solid line is the same least-squares fit shown in panel (a); the dashed line is the fit to Sample B. All BH mass estimates in this sample are based on stellar kinematics. (d): Same as panel (b) but for Sample B. Symbols are as in panel (c).

4. DISCUSSION

We have found a nearly perfect correlation between the masses of nuclear BHs and the velocity dispersions of their host bulges, $M_\bullet \propto \sigma^\alpha$, $\alpha = 4.8 \pm 0.5$. Here we examine some of the implications of this correlation.

The Magorrian et al. (1998) mass estimates fall systematically above the tight correlation defined by our Sample A (Fig. 1d), some by as much as two orders of magnitude. The discrepancy is a strong function of distance to the galaxy, particularly at the high-mass end: nine of the Magorrian et al. galaxies have BH masses that are larger than the largest BH mass in our Sample A ($3.6 \times 10^9 M_\odot$, in NGC 4486), and six of these are more distant than 50 Mpc. A number of authors (van der Marel 1997; Ho 1998) have suggested on other grounds that the Magorrian et al. mass estimates may be systematically high. If our Eq.

(1) correctly predicts $M_\bullet$, the gravitational radius of influence of the BHs in most of these galaxies would be far too small to have been resolved from the ground. For example, Eq. (1) predicts $M_\bullet \sim 2.8 \times 10^8 M_\odot$ for NGC 4874, a full two orders of magnitudes smaller than the Magorrian et al. estimate; the implied radius of influence is ~ 24 pc $\sim 0''.05$. In support of this idea, we note that the best-fitting $M_\bullet$ found by Magorrian et al. in five of their 36 galaxies was negative, while an additional three galaxies – altogether, $1/4$ of their sample – were consistent with $M_\bullet < 0$. In view of this, we suggest that correlation studies based on the Magorrian et al. masses (e.g. Merrifield, Forbes & Terlevich 2000) be interpreted with caution.
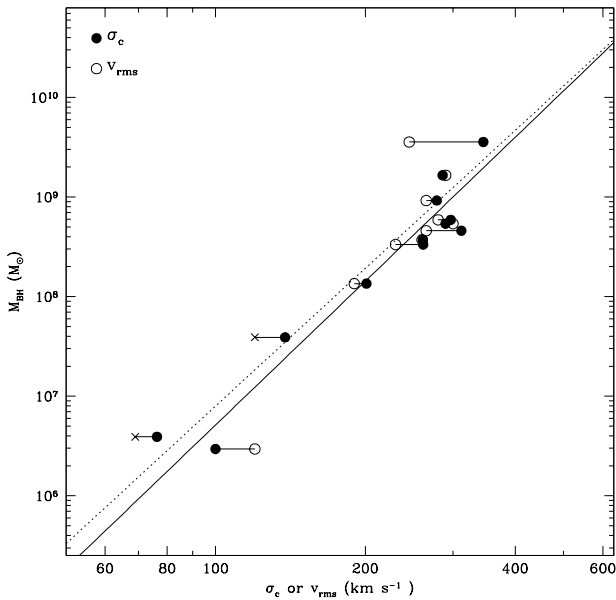

FIG. 2.— BH mass versus the central velocity dispersion σ_c of the host elliptical galaxy or bulge (solid circles) or the rms velocity v_{rms} measured at 1/4 of the effective radius (open circles). Crosses represent lower limits in v_{rms}. The solid and dashed lines are the best linear fits using σ_c (as in Figure 1b) and v_{rms} respectively.

In passing, we caution against the indiscriminate extrapolation of Eq. (1) much below the range plotted in Figure 1 (for example to the range appropriate to dwarf elliptical galaxies or globular clusters), as the formation mechanism of BHs with masses smaller than $\sim 10^5$ M$_\odot$ might differ from that of more massive systems (Haehnelt, Natarajan & Rees 1998).

Why should BH masses be so tightly correlated with bulge velocity dispersions? One possibility is a fundamental connection between $M_\bullet$ and bulge mass, with σ a good predictor of bulge mass – a better predictor, for instance, than B_T^0. This explanation is superficially plausible, since the masses of early-type galaxies scale with their luminosities as $M \sim L^{5/4}$ (Faber et al. 1987) and $L \sim \sigma^4$, hence $M \sim \sigma^5$. The $M_\bullet - \sigma$ relation of Figure 1b would therefore imply a rough proportionality between BH mass and bulge mass, i.e. that a universal fraction of the baryonic mass was converted into BHs. However early-type galaxies appear to be two-parameter systems (Djorgovski & Davis 1987) and it is not clear that σ alone should be a good predictor of galaxy mass.

Another possibility is that σ measures the depth of the potential well in which the BH formed. A number of authors (Silk & Rees 1998; Haehnelt, Natarajan & Rees 1998) have suggested that quasar outflows might limit BH masses by inhibiting accretion of gas. Equating the energy liberated in one dynamical time of the bulge to the gravitational binding energy, and assuming accretion at the Eddington rate, gives a maximum BH mass that scales as σ^5 (Silk & Rees 1998), again consistent with the observed relation. This dependence could be maintained in the face of mergers only if BHs continued to grow by gas accretion during all stages of the merger hierarchy (Kauffmann & Haehnelt 2000).

REFERENCES

Akritas, M. G. & Bershady, M. A. 1996, ApJ, 470, 706
Bower, G.A., et al. 1998, ApJL, 492, L111 (B98)
Cardelli, J. A., Clayton, G. C. & Mathis, J. S. 1989, ApJ, 345, 245
Cretton, N., & van den Bosch, F.C. 1999, ApJ, 514, 704 (CB99)
Davies, M. et al. 1987, ApJ, 64, 581
de Vaucouleurs, G. & Pence, W. D. 1978, AJ, 83, 1163
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Buta, R. J., Paturel, G. & Fouque, P. 1991, Third Reference Catalog of Bright Galaxies (New York: Springer) (RC3)
Djorgovski, S. & Davis, M. 1987, ApJ, 313, 59
Emsellem, E., Dejonghe, H., & Bacon, R. 1999, MNRAS, 303, 495 (EDB99)
Faber, S. et al. 1987, in Nearly Normal Galaxies, ed. S. Faber (Springer: New York), 175
Ferrarese, L., & Ford, H.C. 1999 ApJ 515, 583 (FF99)
Ferrarese, L., Ford, H.C., & Jaffe, W. 1996, ApJ, 470, 444 (FFJ96)
Ferrarese, L., et al. 2000, ApJ, 529, 745
Gebhardt, K., et al. 2000, AJ, 119, 1157 (G00)
Genzel, R., et al. 2000, astroph/0001428 (Ge00)
Haehnelt, M. G., Natarajan, P. & Rees, M. J. 1998, MNRAS, 300, 817
Heckman, T. M., Illingworth, G. D., Miley, G. K., van Breugel, W. J. M. 1985, ApJ, 299, 41
Herrnstein, J.R., et al. 1999, Nature, 400, 539
Ho, L. C. 1998, in Observational Evidence for Black Holes in the Universe, ed. S. K. Chakrabarti (Dordrecht: Reidel), 157
Huchra, J., & Mader, J. 1998, http://cfa-www.harvard.edu/~huchra, ZCAT Version July 15, 1998
Jaffe, W. 1999, in Galaxy Dynamics, Astron. Soc. Pac. Conf. Ser. Vol 182 (ed. D. Merritt, J. A. Sellwood & M. Valluri), p. 13
Jefferys, W. H. 1980, AJ, 85, 177

Jorgensen, I., Franx, M. & Kjaergaard, P. 1995, MNRAS, 276, 1341
Kauffmann, G. & Haehnelt, M. 2000, MNRAS, 311, 576
Kent, S. 1992, ApJ, 387, 181
Kormendy, J. & Richstone, D. O. 1995, ARAA, 33, 581
Macchetto, F., et al. 1997, ApJ, 489, 579 (M97)
Magorrian, J. et al. 1998, AJ, 115, 2285
Merrifield, M. R., Forbes, D. A. & Terlevich, A. I. 2000, MNRAS, 313, 29
Merritt, D. 2000, in Dynamics of Galaxies: from the Early Universe to the Present, Eds.: F. Combes, G. A. Mamon, and V. Charmandaris, ASP Conference Series, Vol. 197, p. 221.
Merritt, D., & Ferrarese, L. 2000, ApJL, in press
Miyoshi, M. et al. 1995, Nature, 373, 127 (M95)
Mould, J. R. et al. 2000, ApJ, 529, 786
Newman, J.A., et al. 1997, ApJ, 485, 570 (N97)
Schlegel, D. J., Finkbeiner, D. P. & Davis, M. 1998, ApJ, 500, 525
Scorza, C., & van den Bosch, F. C. 1998, MNRAS, 300, 469
Silk, J. & Rees, M. J. 1998, A& A, 331, L4
Simien, F. & de Vaucouleurs, G. 1986, ApJ, 302, 564
Terlevich, E., Diaz, A. I. & Terlevich, R. 1990, MNRAS, 242, 271
Tonry, J. L., et al. 2000, ApJS, submitted
van der Marel, R. P. 1997, in Galaxy Interactions at Low and High Redshift, Proc. IAU Symposium 186 (Kluwer: Dordrecht), p.102
van der Marel, R.P., Cretton, N., de Zeeuw, P.T., Rix, H.W. 1998, ApJ, 493, 613 (vdM98)
van der Marel, R.P., & van den Bosch, F.C. 1998, AJ, 116, 2220 (MB98)
Verdoes Kleijn, G.A., van der Marel, R., Carollo, C. M. & de Zeeuw, P. T. 2000, astroph/0003433 (VK00)
Wagner, S. J., Bender, R. & Moellenhoff, C. 1988, A& A, 195, L5