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# A FUNDAMENTAL RELATION BETWEEN SUPERMASSIVE BLACK HOLES AND THEIR HOST GALAXIES

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## ABSTRACT

The masses of supermassive black holes correlate almost perfectly with the velocity dispersions of their host bulges, $M_{\rm bh} \propto \sigma^{\alpha}$, where $\alpha = 4.8 \pm 0.5$. The relation is much tighter than the relation between $M_{\rm bh}$ and bulge luminosity, with a scatter no larger than expected on the basis of measurement error alone. Black hole masses recently estimated by Magorrian et al. lie systematically above the $M_{\rm bh}$-$\sigma$ relation defined by more accurate mass estimates, some by as much as 2 orders of magnitude. The tightness of the $M_{\rm bh}$-$\sigma$ relation implies a strong link between black hole formation and the properties of the stellar bulge.

*Subject headings:* black hole physics — galaxies: evolution — galaxies: kinematics and dynamics

## 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 $M_{\rm bh}$ 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 $M_{\rm bh}$-$B_T^0$ relation suffers from observational biases and exhibits a large scatter that 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 type 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 two columns 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 $\sigma$ 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 $\sigma$ 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 in Table 1). Our choice will be justified in § 3. To bring all values of $\sigma$ 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 et al. 1995). Raw and corrected $\sigma$ are listed in columns (7) and (8) of Table 1. For the Milky Way, we adopt the mean velocity dispersion compiled by Kent (1992) within $r_e/8$.

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TABLE 1

Database of Secure Black Hole Mass Estimates and Properties of the Host Galaxies (Sample A)

| Galaxy (1) | Revised Hubble Type (2) | T Type (3) | Distance[a] (Mpc) (4) | $B_T^0$ (mag) (5) | Black Hole Mass ($10^8\ M_\odot$) (6) | $\sigma$[b] (km s$^{-1}$) (7) | $\sigma_c$ (km s$^{-1}$) (8) | Method[c] (9) | References (10) |
|---|---|---|---|---|---|---|---|---|---|
| Milky Way ...... | SbI–II | ... | $8.0 \pm 0.9$[a] | $-19.13 \pm 0.50$ | $0.0295 \pm 0.0035$ | $100 \pm 20$ | $100 \pm 20$ | PM | 1 |
| IC 1459 ......... | E3 | $-5.0 \pm 0.3$ | $30.3 \pm 4.0$ | $-21.50 \pm 0.32$ | $4.6 \pm 2.8$ | $322 \pm 41$ | $312 \pm 41$ | G | 2 |
| NGC 221 ........ | cE2 | $-6.0 \pm 0.3$ | $0.8 \pm 0.1$ | $-15.76 \pm 0.18$ | $0.039 \pm 0.009$ | $80 \pm 10$ | $76 \pm 10$ | S | 3 |
| NGC 3115 ...... | S0$^-$ | $-3.0 \pm 0.3$ | $9.8 \pm 0.6$ | $-19.74 \pm 0.52$ | $9.2 \pm 3.0$ | $291 \pm 38$ | $278 \pm 36$ | S | 4 |
| NGC 3379 ...... | E1 | $-5.0 \pm 0.3$ | $10.8 \pm 0.7$ | $-20.03 \pm 0.14$ | $1.35 \pm 0.73$ | $210 \pm 27$ | $201 \pm 26$ | S | 5 |
| NGC 4258 ...... | SAB(s)bc | $4.0 \pm 0.3$ | $7.2 \pm 0.3$ | $-18.26 \pm 0.51$ | $0.3901 \pm 0.034$ | $146 \pm 19$ | $138 \pm 18$ | M | 6 |
| NGC 4261 ...... | E2 | $-5.0 \pm 0.3$ | $33.0 \pm 3.2$ | $-21.26 \pm 0.22$ | $5.4^{+1.2}_{-1.2}$ | $306 \pm 40$ | $290 \pm 38$ | G | 7 |
| NGC 4342 ...... | S0$^-$ | $-3.0 \pm 0.5$ | $16.7 \pm 1.0$ | $-17.24 \pm 0.52$ | $3.3^{+1.9}_{-1.1}$ | $255 \pm 33$ | $261 \pm 34$ | S | 8 |
| NGC 4374 ...... | E1 | $-5.0 \pm 0.3$ | $18.7 \pm 1.2$ | $-21.44 \pm 0.15$ | $17^{+12}_{-6.7}$ | $304 \pm 39$ | $286 \pm 37$ | G | 9 |
| NGC 4486 ...... | E0pec | $-4.0 \pm 0.3$ | $16.7 \pm 1.0$ | $-21.61 \pm 0.14$ | $35.7 \pm 10.2$ | $370 \pm 48$ | $345 \pm 45$ | G | 10 |
| NGC 6251 ...... | E | $-5.0 \pm 0.8$ | $104 \pm 10$ | $-21.94 \pm 0.28$ | $5.9 \pm 2.0$ | $293 \pm 38$ | $297 \pm 39$ | G | 11 |
| NGC 7052 ...... | E | $-5.0 \pm 0.7$ | $66.1 \pm 6.4$ | $-21.33 \pm 0.38$ | $3.7^{+2.6}_{-1.5}$ | $270 \pm 35$ | $261 \pm 34$ | G | 12 |

[a] 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 (J. Huchra & J. Mader 1998: ZCAT, available at http://cfa-www.harvard.edu/~huchra) 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 kiloparsecs (from Genzel et al. 2000).

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

[c] Codes for the methods used in estimating the masses: G is gas kinematics from *HST* optical spectra; S is stellar kinematics from *HST* optical spectra, using axisymmetric dynamical models with three-integral distribution functions; M is kinematics of water maser clumps, derived from Very Long Baseline Array data; PM is proper-motion measurements of the SgA star cluster.

References.—(1) Genzel et al. 2000; (2) Verdoes Kleijn et al. 2000; (3) van der Marel et al. 1998; (4) Emsellem et al. 1999; (5) Gebhardt et al. 2000; (6) Miyoshi et al. 1995; (7) Ferrarese, Ford, & Jaffe 1996; (8) Cretton & van den Bosch 1999; (9) Bower et al. 1998; (10) Macchetto et al. 1997; (11) Ferrarese & Ford 1999; (12) van der Marel & van den Bosch 1998.

## 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 in $M_{\rm bh}$ 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; 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 that 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 $M_{\rm bh}$. Close seconds are estimates in 10 additional galaxies, based on data from high-resolution *Hubble Space Telescope* (*HST*) observations, either absorption-line stellar spectra or observations of the motion of nuclear dust/gas disks. These 12 galaxies constitute our sample A. Additional galaxies with less secure BH mass detections are Arp 102B ($M_{\rm bh}$ obtained from fitting accretion disk models to variable optical emission lines; Newman et al. 1997) and all galaxies for which $M_{\rm bh}$ 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 $\log M_{\rm bh}$ 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; $M_{\rm bh}$ 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 $M_{\rm bh}$ and bulge magnitude $B_T^0$ (Figs. 1*a* and 1*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 $M_{\rm bh}$ is simply proportional to the bulge mass, it is apparent from the figure, and from the reduced $\chi_r^2$ 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 $M_{\rm bh}$-$B_T^0$ relation remains significantly larger than the reported errors. No subsample of galaxies, selected either by Hubble type or by method used in deriving $M_{\rm bh}$, defines a tight linear relation between $M_{\rm bh}$ and $B_T^0$.

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

$$\log M_{\rm bh} = 4.80(\pm 0.54) \log \sigma_c - 2.9(\pm 1.3), \qquad (1)$$

with $M_{\rm bh}$ in units of $M_\odot$ and $\sigma_c$ in kilometers per second. The slope of the relation remains unaltered, albeit with a larger

TABLE 2

Results of the Linear Regression Fits, $Y = \alpha X + \beta$

| $X$, $Y$ Variables[a] | Sample[b] | $N$ | $\alpha$ | $\beta$ | $\chi_r^2$ |
|---|---|---|---|---|---|
| $\log \sigma_c$, $\log M_{\rm bh}$ ....... | A | 12 | $4.80 \pm 0.54$ | $-2.9 \pm 1.3$ | 0.79 |
| $\log \sigma_c$, $\log M_{\rm bh}$ ....... | B | 29 | $5.81 \pm 0.43$ | $-4.6 \pm 1.0$ | 2.3 |
| $\log \sigma$, $\log M_{\rm bh}$ ........ | A | 12 | $4.81 \pm 0.48$ | $-3.0 \pm 1.1$ | 0.61 |
| $\log v_{\rm rms}$, $\log M_{\rm bh}$ ...... | A | 10 | $4.61 \pm 0.79$ | $-2.3 \pm 1.9$ | 8.0 |
| $B_T^0$, $\log M_{\rm bh}$ ........... | A | 12 | $-0.36 \pm 0.09$ | $1.2 \pm 1.9$ | 23 |
| $B_T^0$, $\log M_{\rm bh}$ ........... | B | 30 | $-0.48 \pm 0.10$ | $-0.8 \pm 2.0$ | 25 |

[a] Units are in solar masses for $M_{\rm bh}$, kilometers per second for $\sigma$ and $\sigma_c$, and magnitudes for $B_T^0$.

[b] See § 3 for a definition of the samples.

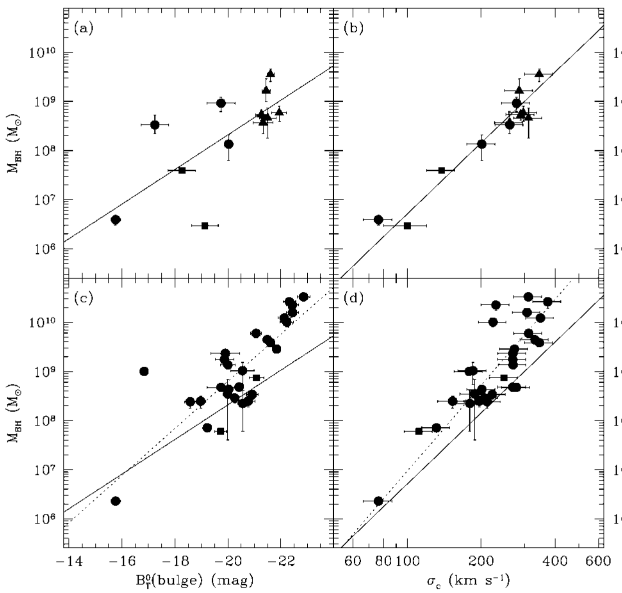


FIG. 1.—(*a*) BH mass vs. absolute blue luminosity of the host elliptical galaxy or bulge for our most reliable sample A. The solid line is the best linear fit (Table 2). Circles and triangles represent mass measurements from stellar and dust/gas disk kinematics, respectively. The squares are the Milky Way ($M_{bh}$ determined from stellar proper motions) and NGC 4258 ($M_{bh}$ based on water maser kinematics), the only two spiral galaxies in the sample. (*b*) Again for sample A, BH mass vs. 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 (*a*). (*c*) Same (*a*), but for sample B. Circles are elliptical galaxies; squares are spiral galaxies. The solid line is the same least-squares fit shown in (*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 (*b*), but for sample B. Symbols are as in (*c*).

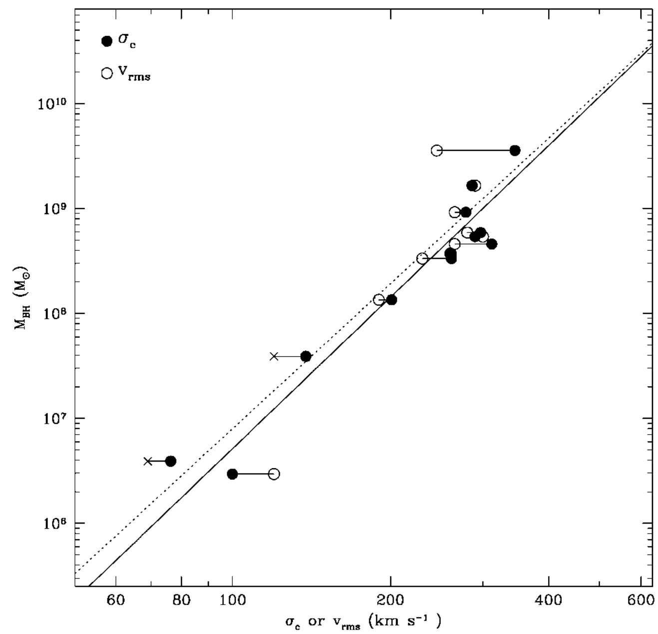


FIG. 2.—BH mass vs. the central velocity dispersion $\sigma_c$ of the host elliptical galaxy or bulge (*filled circles*) or the rms velocity $v_{rms}$ measured at one-fourth of the effective radius (*open circles*). Crosses represent lower limits in $v_{rms}$. The solid and dashed lines are the best linear fits using $\sigma_c$ (as in Fig. 1*b*) and $v_{rms}$, respectively.

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 $\chi^2$ of the fit (Table 2) is only 0.8, consistent with a scatter that derives entirely from measurement errors. The first incarnation of equation (1) was suggested by Merritt (2000) (the "Faber-Jackson law for black holes").

The galaxies in sample B define a much weaker correlation between $M_{bh}$ and $\sigma_c$ (Fig. 1*d*). 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 $M_{bh}$ estimates and the method used to derive the BH masses. About one-half 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 values of $\sigma_c$ and $M_{bh}$, even though the determination of $M_{bh}$ 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 the $M_{bh}$ predicted by equation (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 noncircular motions of the gas. It seems likely that the different correlations defined by the two samples result largely from errors in the determination of $M_{bh}$ for the galaxies in sample B.

Our choice of aperture-corrected, central velocity dispersions is convenient but not unique. We note first that correcting $\sigma$ 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 aperture corrections could be avoided by using a measurement of the rms velocity at some fiducial distance from the center. Figure 2 plots $M_{bh}$ versus the rms stellar velocity $v_{rms}$ at $r_e/4$, with $v_{rms} = [(\sigma^2 + v_r^2/\sin^2 i)_{r_e/4}]^{1/2}$. Here $\sigma$ 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 $M_{bh}$-$v_{rms}$ plane. Nevertheless, for our sample A, linear regression fits (Table 2) show that the slopes of $M_{bh}$ versus bulge velocity are coincident whether $\sigma_c$ or $v_{rms}$ is used.

An interesting question is whether the tight correlation between $M_{bh}$ and $\sigma_c$ 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 $\sigma_c$ 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 $\sigma$ 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 $M_{bh}$ and $\sigma_c$ 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 $M_{bh}$. Figure 1*b* suggests that $M_{bh}$ can be predicted with an accuracy of ~30% or better from a single, low-resolution observation of a galaxy's velocity dispersion. This is a remarkable result.

## 4. DISCUSSION

We have found a nearly perfect correlation between the masses of nuclear BHs and the velocity dispersions of their host bulges, $M_{\rm bh} \propto \sigma^{\alpha}$, $\alpha = 4.8 \pm 0.5$. 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. 1*d*), some by as much as 2 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 equation (1) correctly predicts $M_{\rm bh}$, 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, equation (1) predicts $M_{\rm bh} \sim 2.8 \times 10^8\ M_{\odot}$ for NGC 4874, a full 2 orders of magnitude smaller than the Magorrian et al. estimate; the implied radius of influence is ∼24 pc ∼ 0″.05. In support of this idea, we note that the best-fitting $M_{\rm bh}$ found by Magorrian et al. in five of their 36 galaxies was negative, while an additional three galaxies—altogether, one-fourth of their sample—were consistent with $M_{\rm bh} < 0$. 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.

In passing, we caution against the indiscriminate extrapolation of equation (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 $M_{\rm bh}$ and bulge mass, with $\sigma$ 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 $M_{\rm bh}$-$\sigma$ relation of Figure 1*b* 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 $\sigma$ alone should be a good predictor of galaxy mass.

Another possibility is that $\sigma$ measures the depth of the potential well in which the BH formed. A number of authors (Silk & Rees 1998; Haehnelt et al. 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 $\sigma^5$ (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).

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