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SUPERMASSIVE BLACK HOLES IN GALACTIC NUCLEI[1]

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RESUMEN

El resumen será traducido al español por los editores.
Dynamical searches find central dark objects – candidate supermassive black holes (BHs) – in 22 galaxies. Their demographics lead to the following conclusions:

(1) BH mass is consistent with predictions based on quasar energetics.

(2) BH mass correlates with the luminosity of the "bulge" but not the disk component of the host galaxy.

(3) BH mass correlates with the luminosity of the high-density central component in disk galaxies independent of whether this is a real bulge (a mini-elliptical) or a "pseudobulge" (believed to form via inward transport of disk material).

(4) BH results increasingly support the hypothesis that the major event that forms a giant elliptical and the main AGN phase of the BH are the same event.

Issues that need further work include:

(i) BH masses from reverberation mapping are a factor of ~ 5 smaller than those from detailed dynamical studies. Contributing factors are identified that suggest that this discrepancy may not be fundamental.

(ii) Do any bulges or ellipticals lack BHs? Are there BHs in pure disk galaxies?

(iii) We need to know whether some of the mass detected in dynamical studies is in dark clusters of objects and not in BHs.

ABSTRACT

Dynamical searches find central dark objects – candidate supermassive black holes (BHs) – in 22 galaxies. Their demographics lead to the following conclusions:

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Key Words: **BLACK HOLE PHYSICS — GALAXIES: KINEMATICS AND DYNAMICS — GALAXIES: NUCLEI**

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1. CENSUS OF BH CANDIDATES

Table 1 lists the 22 BH candidates that are available for demographic studies effective 2000 April. The number of detections is growing rapidly as the *Hubble Space Telescope* (HST) pursues the search. There will certainly be more by the time this paper appears. An up-to-date list is maintained on the WWW at URL http://chandra.as.utexas.edu/~kormendy/bhsearch.html.

The detections in Table 1 are listed in three groups based on stellar dynamics, ionized gas dynamics and maser dynamics (top to bottom, respectively). Within each group, the galaxies are ordered by distance D. Distances are based on a local large-scale flow field solution and a Hubble constant of $H_0 = 80$ km s^{-1} Mpc^{-1}. More details about search techniques, about many of these object, and about their implications are given in review papers by Kormendy & Richstone (1995), Richstone *et nuk.* (1998), Ho (1999), Ho & Kormendy (2000), Kormendy & Ho (2000), and many others.

Table 1

Census of Black Hole Candidates

Galaxy	Type	D (Mpc)	$M_{B,\mathrm{bulge}}$	$M_\bullet$ ($M_\odot$)	$\log \frac{M_\bullet}{M_{\mathrm{bulge}}}$
Galaxy	Sbc	0.0085	−17.65	3×10^6	−3.62
M 31	Sb	0.7	−18.82	3×10^7	−3.31
M 32	E	0.7	−15.51	3×10^6	−2.27
NGC 3115	S0/	8.4	−19.90	1×10^9	−1.92
NGC 4594	Sa/	9.2	−21.21	1×10^9	−2.69
NGC 3377	E	9.9	−18.80	8×10^7	−2.24
NGC 3379	E	9.9	−19.79	1×10^8	−2.96
NGC 4697	E	10.1	−19.92	1×10^8	−3.09
NGC 1023	SB0	10.2	−18.16	4×10^7	−2.87
NGC 4342	S0	15.3	−17.04	3×10^8	−1.64
NGC 4473	E	15.3	−19.83	1×10^8	−3.04
NGC 4486B	E	15.3	−16.66	6×10^8	−1.03
NGC 5845	E	28.2	−18.90	4×10^8	−2.01
NGC 821	E	30.6	−20.93	5×10^7	−3.73
M 87	E	15.3	−21.42	3×10^9	−2.32
NGC 4374	E	15.3	−20.96	1×10^9	−2.53
NGC 4261	E	29.	−20.89	5×10^8	−2.92
NGC 7052	E	59.	−21.31	3×10^8	−3.31
NGC 6251	E	106.	−21.81	6×10^8	−3.18
NGC 4945	Scd/	3.7	−15.1	1×10^6	···
NGC 4258	Sbc	7.5	−17.3	4×10^7	−2.05
NGC 1068	Sb	15.	−18.8	1×10^7	···

The last column of Table 1 gives the ratio of BH mass to the mass in stars in the bulge (or bulge-like: § 4) component of the galaxy. The mass in stars is calculated from the B-band absolute magnitude (column 4) and the mass-to-light ratio given by the dynamical models at large radii where the BH has no effect. The median BH mass fraction is 0.17 % (mean for NGC 1023 and NGC 4594, the Sombrero galaxy). The quartiles are 0.07 % and 0.9 % in NGC 6251 and NGC 4258, respectively.

My oral paper reviewed four BH detections – the excellent maser case, NGC 4258 (Miyoshi *et al.* 1995), the first HST STIS detection based on optical emission lines, NGC 4374 (Bower *et al.* 1997, 1998), the stellar dynamical case with the largest nuclear velocity dispersion, NGC 3115 (Kormendy *et nuk.* 1996), and our Galaxy. The first three are discussed extensively in the above reviews. Here, I will discuss only one example of a stellar dynamical BH detection, the special case of our Galaxy.

2. THE STRONGEST BH CASE: OUR GALAXY

Unlike discoveries that happen in a clearly datable event, finding a BH usually takes place through a series of measurements of increasing spatial resolution that improve the case for a central dark object until it becomes bomb-proof. At this stage, it is likely that a supermassive BH has been detected, but it is still possible that the dark object is a cluster of smaller objects. Astrophysically, the most plausible BH alternatives are brown dwarf stars and stellar remnants, but more exotic possibilities exist. Still further improvement in the spatial resolution may then reduce the maximum possible radius that a dark cluster can have until astrophysical constraints rule out the above BH alternatives. This has happened in two cases, NGC 4258 and our Galaxy.

In fact, since the original BH detection reports based on gas and stellar radial velocities (Lacy *et al.* 1980; Serabyn & Lacy 1985; Genzel *et al.* 1985; Sellgren *et al.* 1987, 1990; Rieke & Rieke 1988; McGinn *et al.* 1989), the BH case has improved more in our Galaxy than in any other. Reviews of the Galactic center and its BH case are given in Genzel, Hollenbach, & Townes (1994), Kormendy & Richstone (1995), and Morris & Serabyn (1996). Here, I concentrate on a spectacular recent development that for the first time tells us all three components of the velocity dispersion of stars near a galactic center BH.

Two independent groups led by Reinhard Genzel and Andrea Ghez have used speckle imaging to measure proper motions in a cluster of stars at radii $r \lesssim 0\farcs5 \simeq 0.02$ pc from Sgr A* (Eckart & Genzel 1997; Genzel *et al.* 1997, 2000; Ghez *et al.* 1998). Figure 1 illustrates some of the results. The proper motions of stars near Sgr A* are easily detectable, and the measurements of them have been getting steadily more accurate as the time baseline has improved. Several stars move remarkably rapidly. For example, star S1 has a total proper motion of 1600 ± 200 km s^{-1}. Stars at this radius revolve around the Galactic center in a human lifetime! Already preliminary accelerations have been measured (Ghez *et al.* 2000), and within a few more years, significant arcs along the orbits should have been observed.

When these data are combined with radial velocity measurements at larger radii, the velocity dispersion is found to increase smoothly to radial and tangential values of $\sigma_r = 503 \pm 88$ km s^{-1} and $\sigma_t = 334 \pm 58$ km s^{-1} at $r \simeq 0.01$ pc (Genzel *et al.* 2000). Velocity anisotropy is no longer an uncertainty; it is measured directly. Overall, the dispersion is not very anisotropic, but the stars nearest the center tend to have $\sigma_r > \sigma_t$, while the stars at larger radii tend to have $\sigma_r < \sigma_t$. The youngest stars have the most tangential orbits. It is reasonable to expect that the error bars on the anisotropy measurements will shrink with time and that the remaining uncertainty in $M(r)$ that is caused by velocity anisotropy will thereby become less important.

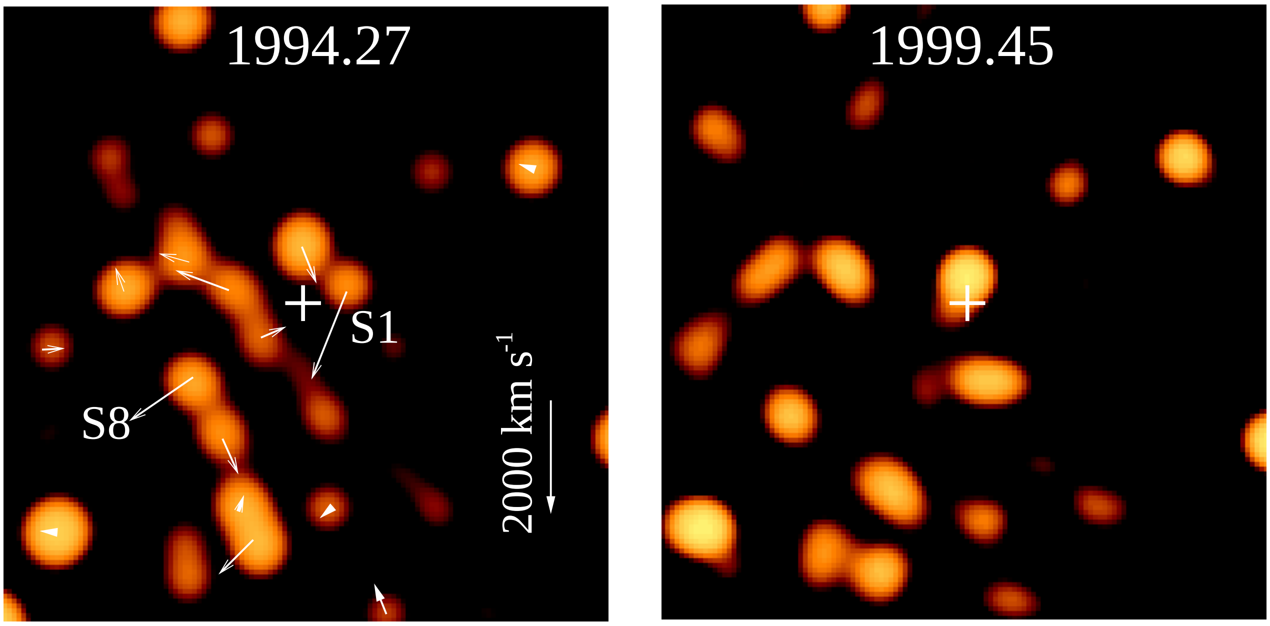

Fig. 1. Images of the star cluster surrounding Sgr A* (cross) at the epochs indicated. The field of view is $1\farcs4$ square. The arrows in the left frame show approximately where the stars have moved in the right frame. This figure is updated from Eckart & Genzel (1997) and was kindly provided by A. Eckart.

The mass $M(r)$ inside radius r is shown in Figure 2. Outside a few pc, the mass distribution is dominated by stars (long dashed curve). However, as $r \to 0$, $M(r)$ flattens to a constant, $M_\bullet = (2.9 \pm 0.4) \times 10^6\ M_\odot$.

The conclusion that $M(r)$ is constant over a significant radius range (or, more or less equivalently, the observation that the velocity dispersion profile is Keplerian over the same radius range) puts powerful constraints on how small the dark mass $M_\bullet$ must be. These constraints eliminate dark stars as BH alternatives. The argument is as follows (Maoz 1995, 1998). The largest dark cluster that is consistent with the data in Fig. 2 would have a central density of 4×10^{12} M$_\odot$ pc^{-3} (short dashed curve). The most plausible BH alternatives are clusters of dark objects produced by ordinary stellar evolution. These come in two varieties, failed stars and dead stars. Failed stars – brown dwarfs – have masses $m_* \lesssim 0.08$ M$_\odot$. Because they have low masses, they would be numerous; as a result, their collision times would be short. Stars generally merge when they collide. A dark cluster of low-mass objects would become luminous because brown dwarfs would turn into stars. Alternatively, a dark cluster could be made of stellar remnants: white dwarfs, which have typical masses of 0.6 M$_\odot$; neutron stars, which typically have masses of ~ 1.4 M$_\odot$, and black holes with masses of several M$_\odot$. Galactic bulges are believed to form in violent starbursts, so massive stars that turn quickly into dark remnants would be no surprise. However, high-mass remnants such as white dwarfs, neutron stars, and stellar BHs would be relatively few in number. The dynamical evolution of star clusters is relatively well understood; a sparse cluster of stellar remnants would evaporate completely in $\lesssim 10^8$ yr (Maoz 1995, 1998; Genzel *et al.* 1997, 2000. Therefore the case for a BH in our own Galaxy is now very compelling.

Similar arguments and timescales apply to the central dark object in NGC 4258 (Maoz 1995, 1998).

Exotic BH alternatives are not ruled out by such arguments. For example, the dark matter that makes up galactic halos and that accounts for most of the mass of the Universe may in part be elementary particles that are cold enough to cluster easily. It is not out of the question that these could explain the dark objects in galactic centers. So the BH case is not rigorously proved. What makes it compelling is the combination of dynamical evidence and the evidence from AGN observations. These particularly include observations of relativistic velocities in circumnuclear material and in jets (see Kormendy & Richstone 1995; Ho & Kormendy 2000 for reviews).

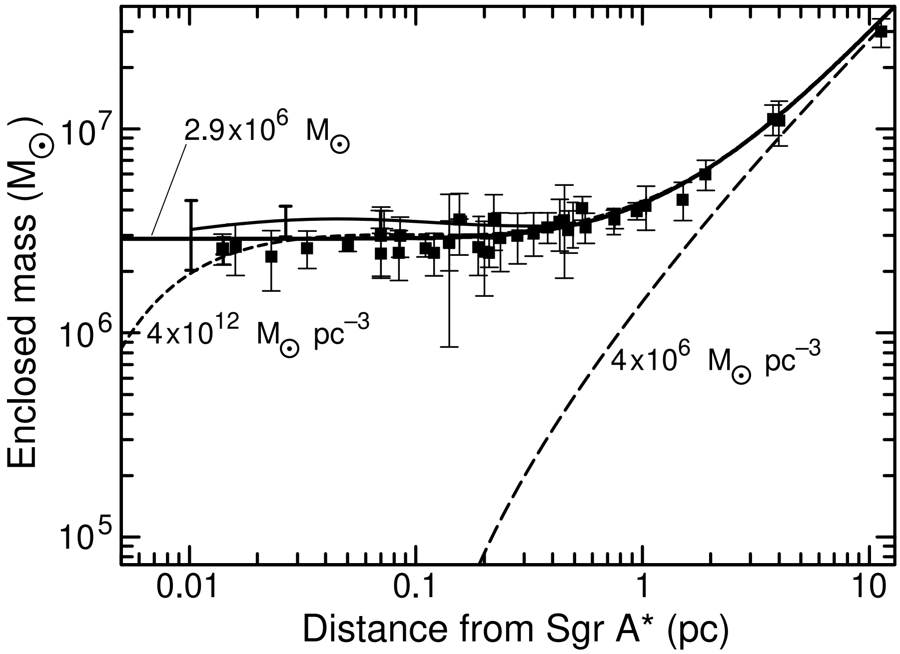

Fig. 2. Mass distribution implied by proper motion and radial velocity measurements (data points and upper curve with representative error bars). Long dashes (right curve) show the mass distribution of stars if the K-band mass-to-light ratio is 2. The solid curve labeled with $M_\bullet$ represents the stars plus a point mass $M_\bullet = 2.9 \times 10^6$ M$_\odot$. Short dashes provide an estimate of how non-pointlike the dark mass could be: its χ^2 value is $1\,\sigma$ worse than the solid curve. This dark cluster has a core radius of 0.0042 pc and a central density of 4×10^{12} M$_\odot$ pc^{-3}. This figure is updapted from Genzel *et al.* (1997) and was kindly provided by R. Genzel.

3. THE $M_\bullet$ – $M_{B,\mathrm{bulge}}$ CORRELATION

The main new demographic result that has emerged from BH detections is an apparent correlation between BH mass and the luminosity of the "bulge" part of the galaxy. This was first illustrated by Kormendy (1993a) and has been updated with new detections in most BH reviews since. Magorrian *et nuk.* (1998) carried out a sanity check by analyzing ground-based kinematic data that mostly were not taken for the BH search and that therefore have low resolution. Even these data are consistent with the $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation, although the derived BH masses are somewhat too high. An up-to-date version of the correlation is shown in Fig. 3.

The scatter is large – the total range of BH masses is about two orders of magnitude at a given $M_{B,\mathrm{bulge}}$. There are also one or two exceptions with unusually high BH masses. But the most extreme case, NGC 4486B (Kormendy *et nuk.* 1997), is still based on ground-based data and isotropic models. Its BH mass may decrease when STIS spectroscopy is published (Green *et al.* 2000). Despite the scatter, the 22 detections imply a robust correlation. The main uncertainty is selection effects: big black holes in dwarf galaxies are easy to detect and are therefore genuinely rare, but small black holes in giant galaxies are hard to find and could be missing from the census. Many authors have noted that the apparent $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation could be the upper envelope of a distribution that extends to smaller $M_\bullet$. This possibility gets less likely as ongoing searches find BHs in essentially every galaxy observed. It is important to note that the BHs represented in Figure 3 would still have been detected even if they had been significantly farther away. Thus the evidence is beginning to suggest that the correlation is real, although a small number of exceptions with unusually large or small $M_\bullet$ would be no surprise. A test of whether the correlation is real is in progress (Kormendy, Gebhardt, & Richstone 2000).

Since M/L varies little from bulge to bulge, Fig. 3 implies a correlation between BH mass and bulge mass. This, of course, is the astrophysically interesting result. I have not plotted $M_\bullet$ against M_{bulge} even though stellar dynamical models provide M/L_{bulge}. There are two reasons: (i) The sample would have been smaller, because M/L_{bulge} is not available for cases based on gas dynamics. (ii) The scatter would be larger. The parameters plotted in Figure 3 are almost independent, although the χ^2 ellipses are inevitably elongated in the same sense as the correlation because of distance errors. However, when we make stellar dynamical models, velocities due to $M_\bullet$ can be traded off against velocities due to M_{bulge} while keeping the total velocities constant. Therefore a plot of $M_\bullet$ against M_{bulge} has χ^2 ellipses that (apart from distance errors) are perpendicular to the correlation. Until these errors get small, it is better to look for the correlation by plotting $M_\bullet$ versus $M_{B,\mathrm{bulge}}$.

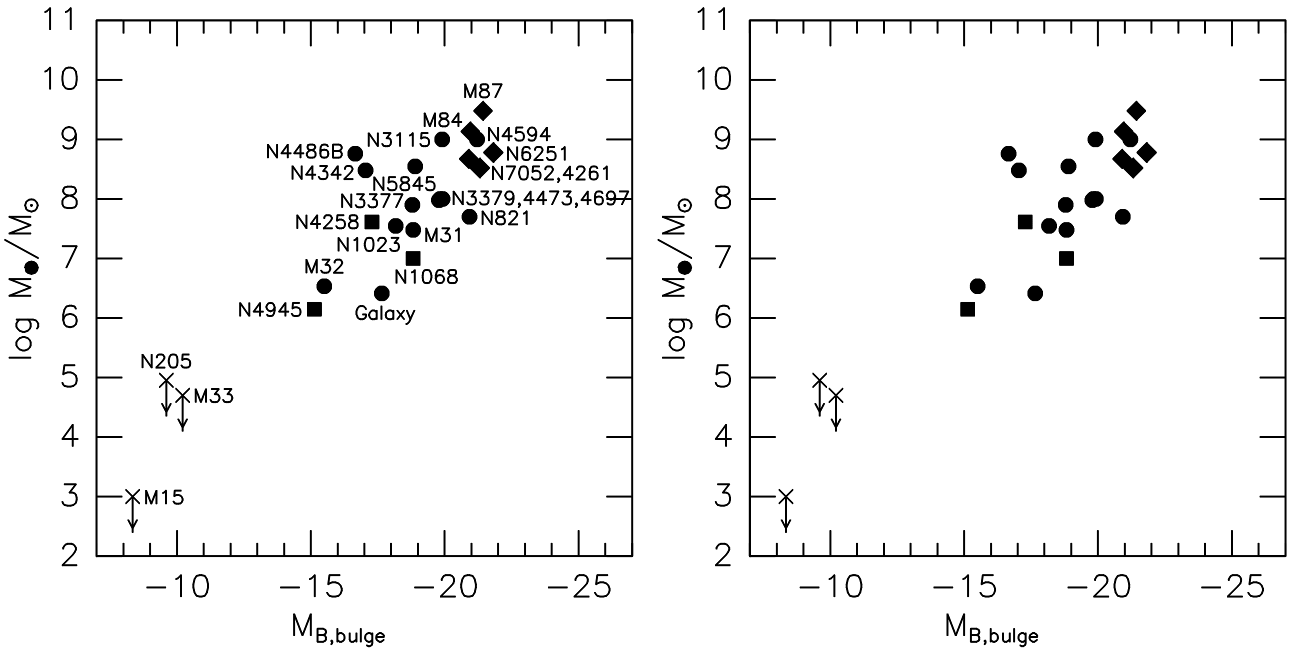

Fig. 3 Correlation of BH mass with the absolute magnitude of the "bulge" component of the host galaxy. Filled circles indicate $M_\bullet$ measurements based on stellar dynamics, diamonds are based on ionized gas dynamics, and squares are based on maser disk dynamics. All three techniques are consistent with the same correlation.

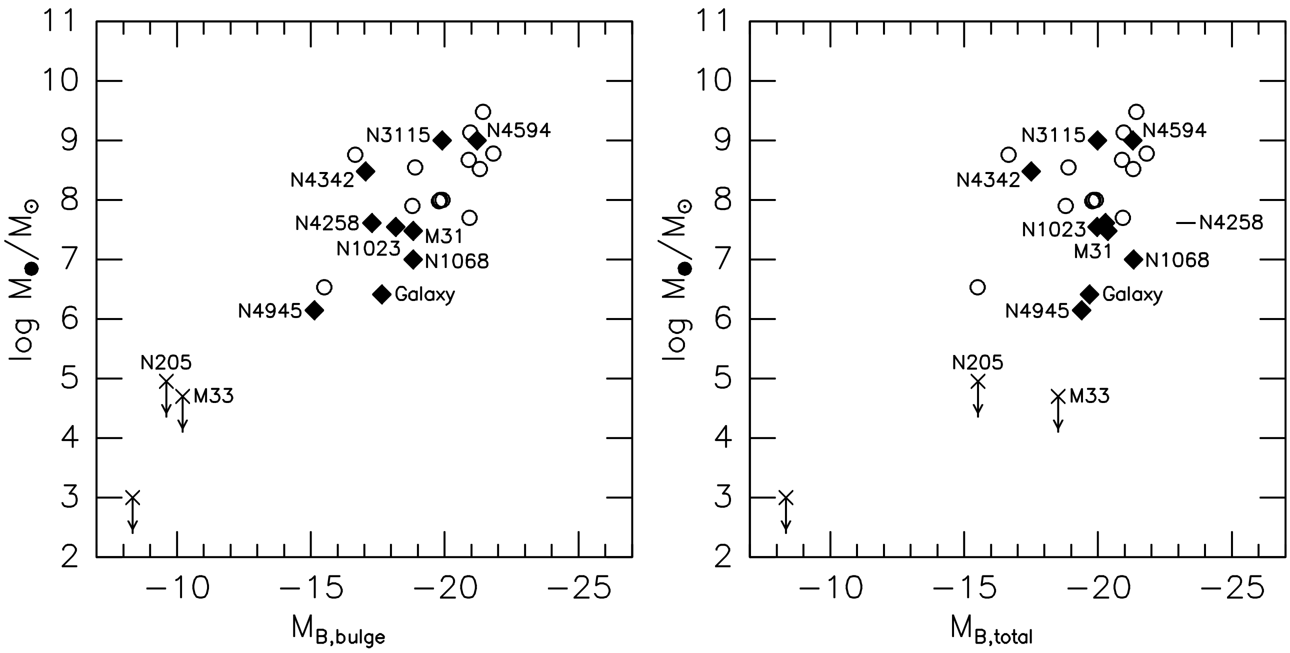

Fig. 4 (left) $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation, distinguishing bulges (diamonds) and elliptical galaxies (open circles). (right) Plot of $M_\bullet$ against the total absolute magnitude of the host galaxy.

Figure 4 (left) shows the $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation with bulges identified. This emphasizes a point that is not apparent in Figure 3: the bulges span a large enough luminosity range to provide leverage on the correlation, but the elliptical galaxies do not. If we had observed only the ellipticals, we might suspect that there is a correlation, but this would be based on only one galaxy (M 32) and another (NGC 4486B) would suggest just as strongly that there may be no correlation at all. The most convincing demonstration of a correlation depends on the combination of bulges and elliptical galaxies. But we should be asking whether bulges and ellipticals do or do not have the same $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation. Therefore we need more measurements of high-luminosity bulges and low-luminosity ellipticals.

It is important to note that BH mass correlates much better with bulge luminosity than with the total luminosity of the host galaxy. When $M_\bullet$ is plotted against total absolute magnitude (Figure 4, right), disk galaxies with small bulge-to-total luminosity ratios destroy the reasonably good correlation seen in Fig. 4 (left). Because the highest-luminosity bulges live in bulge-dominated galaxies while the lowest-luminosity bulges are in disk-dominated galaxies, the $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation implies a correlation between $M_\bullet$ and bulge-to-disk ratio. But Figure 4 (right) shows that BH masses do not “know about” galaxy disks; rather, they correlate with the high-density bulge-like component in galaxies.

M 33 and NGC 205 are bulgeless galaxies – an Sc and a spheroidal, respectively – with strong BH mass limits that are plotted in Figures 3 and 4 against the absolute magnitudes of their nuclei. Nuclei are central star clusters that are not clearly connected with either the bulge or the disk component of galaxies (Kormendy & Djorgovski 1989). Current searches concentrate on the question of whether small BHs – ones that are significantly below the apparent correlation or ones that are in pure disk galaxies – can be found or excluded.

4. THE $M_\bullet$ – $M_{B,\mathrm{bulge}}$ CORRELATION. II. BULGES VERSUS PSEUDOBULGES

So far, I have discussed elliptical galaxies and the bulges of disk galaxies as if they were equivalent. In terms of BH content, they are indistinguishable: they are consistent with the same $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation. But it has become clear in the past decade that there are two different kinds of high-density central components in disk galaxies. Both have steep surface brightness profiles like those of elliptical galaxies. But, while classical bulges in (mostly) early-type galaxies really are like little ellipticals living in the middle of a disk, the “pseudobulges” of (mostly) late-type galaxies are physically unrelated to ellipticals. This section discusses the difference and asks the question: Do bulges and pseudobulges have similar BH content?

Pseudobulges are reviewed in Kormendy (1993b). Their photometric and kinematic properties suggest that they are manufactured by secular evolution of disks. Evidence for disklike dynamics includes (i) velocity dispersions σ that are smaller than those predicted by the Faber-Jackson (1976) $\sigma - M_B$ correlation, (ii) rapid rotation $V(r)$ that implies V/σ values well above the "oblate line" describing rotationally flattened, isotropic spheroids in the V/σ – ellipticity diagram, and (iii) spiral structure that dominates the $r^{1/4}$ part of the galaxy. In these galaxies, the steep central brightness profiles belong not to bulges but to disks. These observations and n-body simulations imply that high-density central disks can form out of disk gas that is transported toward the center by bars and oval distortions. High surface densities μ are unstable until they heat themselves up to bulgelike velocity dispersions – i. e., until the Toomre (1964) stability parameter $Q = \sigma\kappa/3.36G\mu$ is safely above 1 (κ is the epicyclic frequency). The n-body models further show that vertical heating of the resulting pseudobulges can result from scattering of stars off of bars (Pfenniger & Norman 1990). In fact, in n-body simulations, bars (which are a disk phenomenon) rapidly come to look like box-shaped bulges when seen edge-on (Combes *et al.* 1990). Kormendy (1993b) concludes that most early-type galaxies contain traditional bulges, that later-type galaxies tend to contain pseudobulges, and that only pseudobulges are seen in Sc – Sm galaxies.

Andredakis & Sanders (1994), Andredakis, Peletier, & Balcells (1995), Courteau, de Jong, & Broeils (1996) and others have shown that the "bulges" of many late-type galaxies have nearly exponential surface brightness profiles. It is likely that these are to be identified with the pseudobulges discussed above, especially since bluer colors imply that they are younger than classical bulges (Balcells & Peletier 1994).

HST observations greatly strengthen the evidence for pseudobulges. Carollo *et al.* (1997, 1998a, b) find that the bulges of many spiral galaxies have disky properties, including young stellar populations, spiral structure and central bars. It seems safe to say that no-one who saw these would invent a folklore in which bulges are mini-ellipticals living in the middle of a disk. Rather, a morphologist who saw these structures and who did not know that they are the central parts of (often: early-type) galaxies would assign late – even Im – Hubble types. Again, many of these structures have exponential brightness profiles. To be sure, Peletier *et al.* (2000) find that early-type galaxies generally have bulges with red colors implying an age spread of $\lesssim 2$ Gyr. Their colors are similar to those of Coma cluster ellipticals, suggesting that they are old. True bulges that are similar to elliptical galaxies do exist; M 31 and NGC 4594 contain examples. But the lesson from the Carollo papers is that pseudobulges are more important than we expected even in early-type galaxies. Like Kormendy (1993b) and Courteau *et al.* (1996), Carollo and collaborators argue that these are not real bulges but instead are formed via gas inflow in disks.

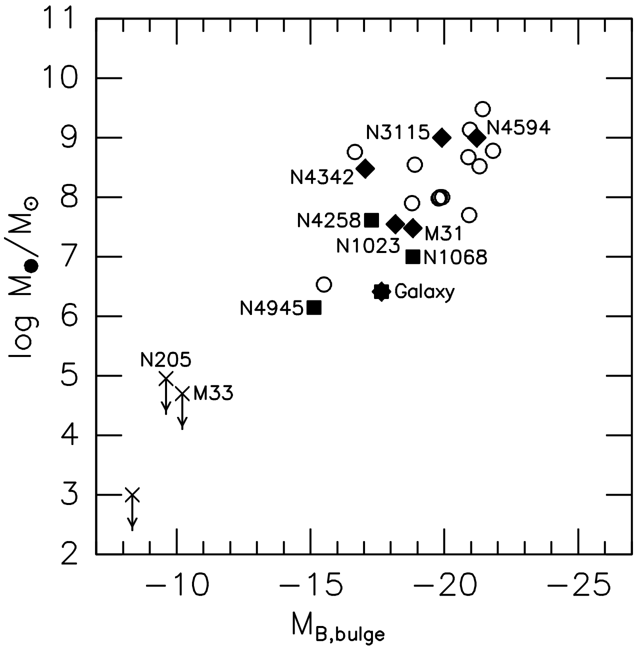

Fig. 5 The $M_\bullet - M_{B,\mathrm{bulge}}$ correlation for elliptical galaxies (open circles), traditional bulges (diamonds) and pseudobulges (squares). The central parts of our Galaxy are more pseudobulge-like than bulge-like, but it may be a transition case, so it is plotted as both a square and a diamond.

So there is growing evidence that the "bulges" whose luminosities I used in the $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation diagrams are two different kinds of objects. Classical bulges are thought to form like small ellipticals, via a dissipative collapse, possibly triggered by a merger. Pseudobulges are thought to form by secular evolution of the disk. Material flows inward in both cases. Potentially, both formation processes may include BH feeding. One way to explore this is to ask whether bulges and pseudobulges have the same BH content.

This question is addressed in Fig. 5. Here I distinguish between bulges and pseudobulges as well as I can with present data. It is plausible that pseudobulges have lower luminosities than classical bulges if they are made from disks. But for their low luminosities, pseudobulges appear to have normal BH masses. This conclusion is based on only 3 – 4 pseudobulges, and their mass-to-light ratios may be abnormally small (§ 5.2). Therefore it needs to be checked. However, it is consistent with the hypothesis that (pseudo)bulge formation and BH feeding are closely connected. To first order, present data do not show any dependence of $M_\bullet$ on the details of whether BH feeding happens rapidly during a collapse or slowly via secular evolution of the disk.

5. $M_\bullet$ FROM DYNAMICAL MODELING VERSUS $M_\bullet$ FROM REVERBERATION MAPPING

One subject of current concern is the apparent discrepancy between $M_\bullet$ from dynamical modeling and $M_\bullet$ from reverberation mapping. Dynamical models are based on stellar or gas motions at $\sim 10^4$ to 10^5 r_s, where r_s is the Schwarzschild radius. The stellar mass interior to this is taken into account, although BH detections are not convincing unless this stellar mass is $\ll M_\bullet$. In reverberation mapping (Blandford & McKee 1982; Netzer & Peterson 1997), we interpret the time delay between brightness variations in the continuum and in the broad emission lines as a light travel time and hence estimate the radius r of the broad-line region. This is combined with a velocity V derived from the FWHM of the emission lines to measure a mass $M_\bullet = V^2 r/G$, where G is the gravitational constant. The broad-line region is $\gtrsim 10^2$ times closer to the BH than the stars or gas used in the more detailed dynamical studies. Having two such different techniques to measure $M_\bullet$ is a great potential advantage. Also, reverberation mapping works in active galaxies, while spatially resolved dynamics are easiest to study in inactive galaxies. Therefore the techniques are complementary.

The problem is that they do not agree. Many authors point out that reverberation mapping gives smaller BH masses. In some cases, the difference is overestimated, because the authors use BH masses from Magorrian *et nuk.* (1998). These are based on two-integral models applied to low-resolution data that were not taken for the BH search; they provided a larger sample than the high-resolution data used for published BH detections. Magorrian *et nuk.* (1998) was a sanity check on those detections, and it took a first look at the question of whether BHs exist in most galaxies. The results were reassuring (they confirmed the $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation) and interesting (they were consistent with ubiquitous BHs), but the BH masses derived were slightly too high.

Ho (1999) finds that dynamical models applied to high-resolution, spatially resolved kinematic data give BH masses that are a factor of ~ 5 larger than those derived from reverberation mapping. It is important that this discrepancy be resolved for the purposes of BH astrophysics. But there is also a more immediate issue: Does the discrepancy signal a fundamental problem with one of the measurement techniques? Like Ho (1999), I argue that the answer is probably "no." It appears likely that the discrepancy is the cumulative effect of a number of technical problems that are (with one exception!) probably not fundamental:

5.1. *Weak Points in the Stellar Dynamical $M_\bullet$ Measurements*

(1) Model limitations were once a concern but are now under control. The current state of the art is to use Schwarzschild's method (Schwarzschild 1979; Richstone & Tremaine 1988) to construct three-integral models that include galaxy flattening and velocity anisotropy (van der Marel *et al.* 1998; Gebhardt *et nuk.* 2000). When such models are fitted to HST data, the errors on $M_\bullet$ are adequately small. However, for many galaxies in Table 1, this has not yet happened. Therefore some $M_\bullet$ values are likely to decrease by factors of $\lesssim 2$.

(2) Selection effects: Early BH detections were biased toward objects with unusually high $M_\bullet$. We are still recovering. That is, stellar-dynamical BH masses are still biased toward high values.

(3) The astrophysically important issue is this: Do galaxies contain central concentrations of ordinary dark matter (e. g., clusters of stellar remnants) in addition to BHs? This question is prompted by the fact that there is substantial room between the radii that we resolve with HST spectroscopy and the broad line regions that are used in reverberation mapping. Dark clusters have been excluded in only two galaxies (see § 2).

5.2. *Weak Points in the Reverberation Mapping $M_\bullet$ Measurements*

(1) Geometry: If the broad-line region is disky rather than spherical, then $M_\bullet$ increases by factors of 2 – 3. More generally, it is not obvious what fraction of FWHM we should use to calculate $M_\bullet = V^2 r/G$.

(2) AGNs are commonly associated with pseudobulges. But some pseudobulges are actively forming stars. Then $M_\bullet$ can look too small in the $M_\bullet - M_{B,\mathrm{bulge}}$ correlation, for the following reason. We plot $M_\bullet$ versus blue luminosity. But the physical correlation is presumably with (pseudo)bulge mass. Star formation can easily reduce M/L_B by a factor of 2 – 4 compared to its value in real bulges that are made of old stars. In a plot of $M_\bullet$ versus blue luminosity, the galaxy will then be too far to the right compared to where it would be in a plot of $M_\bullet$ versus (pseudo)bulge mass. There can be compensating factors, like internal absorption. Also, this is clearly not the only explanation for the $M_\bullet$ discrepancy – an offset is not seen in Fig. 5. But it is likely to be important for some objects.

(3) Selection effects may restrict the BH masses that are measureable by reverberation mapping. E. g., if higher-mass BHs have longer variation timescales, then they may be harder to measure over the limited time that reverberation mapping has been in progress.

(4) In contrast to the above effects which may cause us to underestimate $M_\bullet$, it is important to note that non-gravitational effects on the velocities in the broad-line region would cause us to overestimate $M_\bullet$.

The $M_\bullet$ discrepancy needs to be resolved, but enough possible reasons for it can be identified so that it does not necessarily point to a fundamental problem. Still, it may contain physics. The obvious possibility is that some galactic centers may contain dark clusters as well as BHs. The safest way to resolve the discrepancy is to measure as many galaxies as possible using both techniques. Observing programs to do this are in progress.

6. COMPARISON OF $M_\bullet$ WITH PREDICTIONS BASED ON QUASAR ENERGETICS

Richstone *et nuk.* (1998) compare observed BH masses with predictions based on quasar energetics. The result is that we already see enough BH mass to account for active galactic nuclei. In fact, we see slightly too much mass. The discrepancy is a little less than an order of magnitude if mass is converted to energy with an efficiency of $\epsilon = 0.1$. This may be a hint that $\epsilon < 0.1$. Also, more quasar energy than we know about may be shrouded in dust and missing from our AGN census. Within the rather large errors in both quantities, it appears that AGN energetics and detected BH masses are broadly consistent.

7. CONCLUSION

As we continue the search with HST, we continue to find BHs in virtually every bulge observed. This ubiquity and especially the correlation between BH mass and bulge mass suggest a strong connection between the amount of BH feeding and the total amount of matter that makes up the stars in the bulge (or bulge-like) part of the galaxy. These results are increasingly consistent with the hypothesis (e. g., Sanders *et al.* 1988a, b) that the major event that forms a giant elliptical and the major AGN phase of the BH are the same event.

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