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Supermassive Black Holes in Galactic Nuclei

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Abstract. As an example of how the *Hubble Space Telescope* (HST) has strengthened dynamical arguments for supermassive black holes (BHs), we review the case of M 31. The $M_\bullet \simeq 3 \times 10^7\ M_\odot$ central massive dark object (MDO), discovered using spectra of $1''$ resolution, has been observed at 10 times better resolution with the Space Telescope Imaging Spectrograph (STIS). The observations show that the MDO is located in a blue cluster of A-type stars embedded in P2, one of the two nuclei of M 31. The cluster's tiny size and large velocity dispersion, $\sigma \gtrsim 800$ km s^{-1}, suggest that $M_\bullet$ is confined to a radius $r \lesssim 0\farcs06 = 0.22$ pc. If this is confirmed, then M 31 is the third galaxy (after NGC 4258 and our Galaxy) in which dark clusters of brown dwarfs or dead stars can be excluded on astrophysical grounds. This strengthens the inference that dynamically detected MDOs in other galaxies are supermassive black holes also.

The demographics of 38 BH detections lead to these conclusions: (1) BH mass correlates with the luminosity of the bulge component of the host galaxy, albeit with considerable scatter. The median BH mass fraction is 0.13 % of the mass of the bulge. (2) BH mass correlates with the mean velocity dispersion of the bulge inside its effective radius, i. e., with how strongly the bulge stars are gravitationally bound to each other. (3) BH mass does not correlate with the luminosity of galaxy disks. If pure disks contain BHs, then $M_\bullet \ll 0.13\,\%$ of the mass of the disk. (4) To first order, BH mass does not depend on whether the high-density central component in disk galaxies is a bulge (a mini-elliptical, believed to form via a merger-induced dissipative collapse and starburst) or a "pseudobulge" (believed to form secularly by inward transport of disk gas). Thus present observations show no dependence of BH mass on the details of whether BH feeding happens rapidly during a collapse or slowly via secular evolution of the disk. The results also support the hypothesis that the major events that form a bulge or elliptical galaxy and the main growth phases of its BH, when it shone as a quasar, were the same events.

1. Introduction

Progress on supermassive BHs is now rapid, as STIS spectroscopy reveals MDOs in the centers of many galaxies (see Kormendy & Gebhardt 2001 for a review). Ongoing surveys assume that the BH paradigm is correct and address demographic questions. This approach has produced fundamental results, such as the correlation between BH mass and bulge velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et nuk. 2000), the realization that BHs correlate with bulges but not disks (§§ 3 – 4), and a growing interdependence of our understanding of galaxy evolution and AGN physics (see Kormendy 2000 for a review). That's the good news. The bad news is this: the evidence that MDOs are BHs is not overwhelming. Only in NGC 4258 and in our Galaxy is the MDO known to live inside a small enough radius so that physical arguments rule out the most plausible BH alternatives, dark clusters of brown dwarf stars or stellar remnants (Maoz 1995, 1998). Both galaxies are atypical of MDO detections: they contain pseudobulges thought to be made by secular evolution out of disk material (§ 5). The AGN paradigm depends critically on the assumption that MDOs are BHs. Even one more test in a normal bulge would add a great deal of confidence. M 31 contains a normal bulge and is poised to provide this test (§ 2).

The oral version of this review summarized the search for BHs and the implications of the demographics of the 38 detections available in mid-2001. Detailed written versions have been published in Kormendy & Richstone (1995) for ground-based detections and in Kormendy & Gebhardt (2001, hereafter KG) for HST detections. Sections 3 – 5 provide a brief update.

2. The $M_\bullet \simeq 3 \times 10^7\ M_\odot$ BH in M 31

M 31 was the second galaxy (after M 32 – Tonry 1984) in which kinematic observations revealed the presence of an MDO (Kormendy 1987, 1988; Dressler & Richstone 1988). Its mass, $M_\bullet \simeq 3 \times 10^7\,M_\odot$, is known to only a factor of 2 because of uncertainties introduced by the asymmetry in the stellar cluster or "nucleus" in which it is embedded (Light et al. 1974). Observed with HST, the nucleus proved to be double (Lauer at al. 1993, 1998). Also, integral-field spectroscopy showed that the velocity field is asymmetric: the brightest and hottest points are displaced from the rotation center by similar amounts in opposite directions (Bacon et al. 1994, 2001). This is surprising. At the projected separation of the nuclei, $2r = 0\farcs49 = 1.7$ pc, a relative velocity of 200 km s^{-1} implies a circular orbit period of 50,000 yr. If the two nuclei were star clusters in orbit around each other, dynamical friction would make them merge within a few orbits. The simplest explanation – that the double nucleus is a merger in progress – is implausible. Figure 1 illustrates the above properties.

Tremaine (1995) proposed that both nuclei are parts of the same eccentric disk of stars. The brighter nucleus, P1, is farther from the barycenter and results from the lingering of stars near apocenter. The fainter nucleus, P2, results from the disk's increase in density toward the center. A BH is required near P2 to make the potential almost Keplerian; only then can the alignment of orbits be maintained by modest restoring forces such as the disk's self-gravity. Tremaine showed that the asymmetries of the nucleus could be explained by this model.

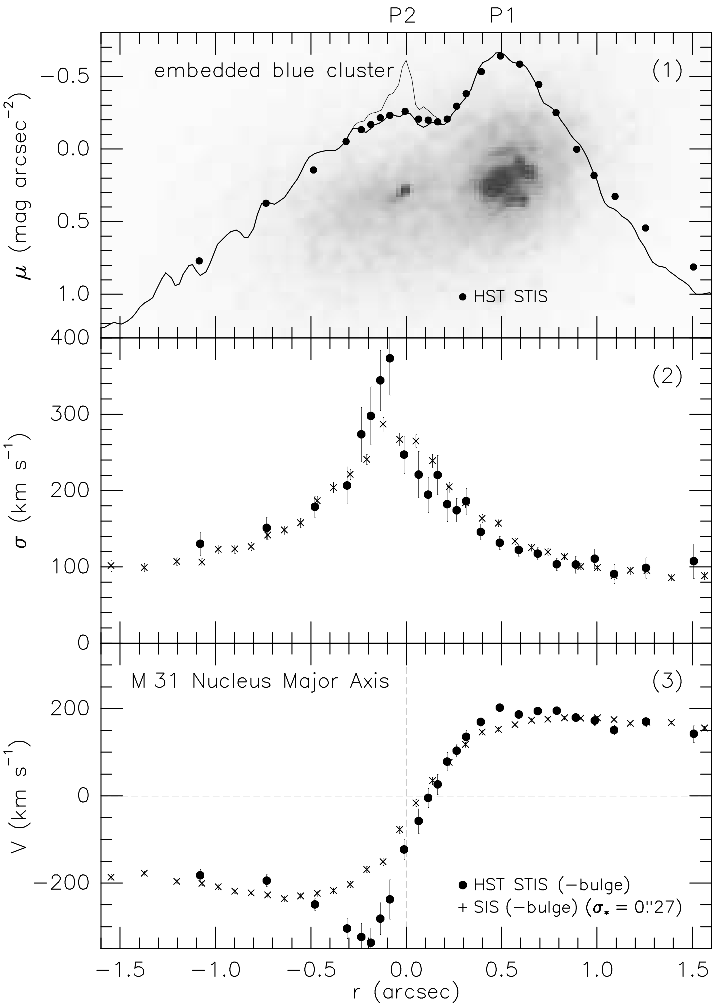

Figure 1 – Panel 1 shows the double nucleus discovered by Lauer et al. (1993); this image is a V + 3000 Å composite adapted from Kormendy & Bender (1999). Brightness peak P1 is brighter than P2 in the optical. Embedded in P2 is a tiny cluster of blue stars that is invisible in I but brighter than P1 in the ultraviolet. Panel 1 includes an I-band brightness cut along the P1 − P2 axis (lower curve) and a V-band cut through the blue cluster (upper curve). Radius $r = 0$ is at the center of the blue cluster. The center of the bulge is at $r = +0\farcs07$. P1 and the blue cluster are on opposite sides of the bulge center and displaced from it by just the right amount so that a $M_\bullet \simeq 3 \times 10^7\ M_\odot$ MDO in the blue cluster balances the asymmetry of the stellar mass distribution toward P1 and puts the combined center of mass at the center of the galaxy. Panels 2 and 3 show velocity dispersions and rotation velocities along the P1 − P2 axis after subtraction of the bulge. The ground-based points are from the Subarcsecond Imaging Spectrograph ("SIS") and the Canada-France-Hawaii Telescope (Kormendy & Bender 1999). The STIS data and this figure are from Bender et al. (2002). The points in panel 1 are the brightness profile in the STIS spectrum; they are used to register the kinematics with the photometry in radius. Bacon et al. (2001) have made an independent reduction of the STIS spectra; it is consistent with ours.

Kormendy & Bender (1999) show that the nucleus has the signature of Tremaine's eccentric disk model and suggest that the BH is in the blue cluster. The most direct confirmation of the model is the asymmetry in $V(r)$ and $\sigma(r)$. This is even more compelling now at the spatial resolution of the STIS spectra. Eccentric disk stars linger at apocenter in P1; V and σ are relatively small there. They pass pericenter in P2, slighly on the anti-P1 side of the BH, and, indeed, the velocity amplitude is high at $r \simeq -0\farcs2$. Because the PSF and slit average over stars seen at different radii and viewing geometries, the apparent velocity dispersion should have a sharp peak slightly on the anti-P1 side of the BH. Figure 1 shows that σ has a sharp peak slightly on the anti-P1 side of the blue cluster. On the other side of the BH and near it if the eccentric disk has a central hole, there should be no P1 stars; consistent with this, the dispersion in P2 drops sharply at and to the right of the blue cluster. These observations and the above center-of-mass argument update Kormendy & Bender's main reasons for suggesting that the BH is in the blue cluster.

The foregoing arguments are based on spectra at the Ca II infrared triplet. They see only the stars in the eccentric disk. They are completely blind to the blue cluster, which contributes essentially no light at wavelengths $\lambda \simeq 8500$ Å. Based on broad-band colors, Lauer et al. (1998) and Brown et al. (1998) suggest that the blue cluster consists of A-type stars. We have obtained a one-orbit (2040 s) integration at $\lambda\lambda \simeq 3500$ to 5000 Å. At this wavelength, the blue cluster is visible. Its spectrum is shown in Figure 2. Balmer lines are very strong, confirming that the nucleus is made mostly of A stars.

The very different stellar populations of the blue cluster and double nucleus allow a clean test of the hypothesis that the BH is in the blue cluster. It is easy to subtract the spectrum of the P2 stars. We get a clean dynamical probe of the central $0\farcs2$, without line-of-sight integration through uninteresting foreground and background stars. Dwarf and giant A0 standard stars consistently imply that $\sigma \simeq 790 \pm 150$ km s^{-1} (Figure 2). However, the Pickles (1998) standard star spectral library which we used has an instrumental dispersion of 520 km s^{-1}. Since the intrinsic width of the lines is not zero, we will be conservative and conclude only that the true dispersion of the blue cluster is 800 to 950 km s^{-1}.

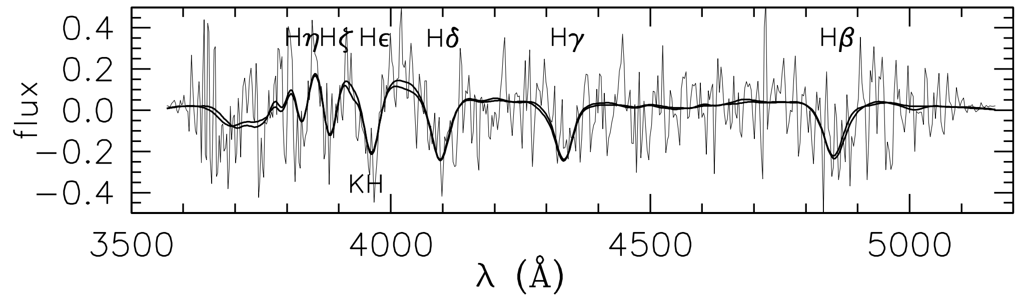

Figure 2 – Spectrum (thin line) of the central $0\farcs2$ of the blue cluster. The adjacent spectrum of the stars in the bulge and nucleus has been subtracted. The spectrum is continuum-subtracted and normalized for the Fourier correlation quotient program (Bender 1990). Flux is in arbitrary linear units. Heavy lines show the spectra of an A0 V star and an A0 III star broadened to have the line-of-sight velocity distribution that best fits the cluster spectrum. Balmer lines and Ca II H + K are identified. This figure is from Bender et al. (2002).

This value is much larger than the velocity dispersion in the surrounding part of P2. It confirms that the MDO is in the blue cluster. In fact, it shows that the MDO is so small that dark cluster alternatives to a supermassive BH are implausible:

The half-light radius of the blue cluster is $r_e \simeq 0\farcs06$ (Lauer et al. 1998). If all of $M_\bullet = 3 \times 10^7$ M$_\odot$ is interior to r_e, then the circular rotation velocity at r_e is 760 km s^{-1} and the corresponding local dispersion is $\sigma \sim 540$ km s^{-1}. We get a higher dispersion for the blue cluster, implying that it has a high central light concentration. We plan dynamical models to explore how extended the dark mass can be and still be consistent with the observations after PSF convolution. However, the high dispersion already implies that essentially all of the dark mass is interior to $0\farcs06$. We assume that the MDO is a Plummer model and that 80 % of the mass $M_\bullet$ is interior to $r = 0\farcs06$. The corresponding half-mass radius of the MDO is $r_h = 0.114$ pc.

Then the question is: Can we stuff $M_\bullet = 3 \times 10^7$ M$_\odot$ of brown dwarfs or stellar remnants into the above volume without getting into trouble? The answer is "no", as follows. The first part of our argument follows Maoz (1995, 1998). We calculate collision timescales for MDOs made of brown dwarfs and evaporation times for MDOs made of stellar remnants. The resulting timescales are shown in Figure 3.

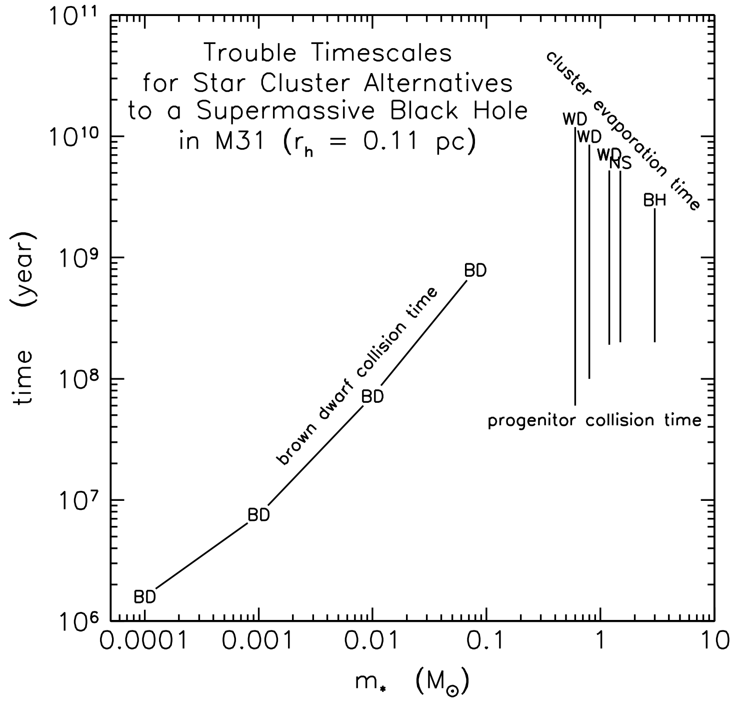

Figure 3 – Timescales on which dark cluster alternatives to a BH get into trouble in M 31. The stellar mass is m_*. For an MDO made of brown dwarfs (BD), the left curve shows the timescales on which every typical star suffers a physical collision with another star. Points WD, NS, and BH show the times in which MDOs made of white dwarfs, neutron stars, or stellar-mass black holes would evaporate. Vertical lines point from these evaporation times down to the timescales on which the corresponding progenitor stars would collide.

The problem with brown dwarfs is that they collide with each other, merge, and become visible stars. Collisions are slow enough even in the present case so that the stars merge with little mass loss. The timescales are so short that, unless the MDO is implausibly young, there has been plenty of time to make it visible. Brown dwarfs are strongly excluded.

Stellar remnants are too small to collide. Instead, relaxation gives positive energies to a steady trickle of stars that are lost to the system. In $\lesssim 300$ half-mass relaxation times, the cluster evaporates. Figure 3 shows the evaporation times for MDOs made of 0.55 $M_\odot$ white dwarfs, 0.8 $M_\odot$ white dwarfs, 1.2 $M_\odot$ white dwarfs, 1.5 $M_\odot$ neutron stars, and 3 $M_\odot$ black holes (left to right, symbols WD, WD, WD, NS, and BH). For BH remnants and neutron stars, the evaporation times are a few billion years. This is implausibly short. Lighter remnants have longer evaporation times and are not excluded by this argument.

However, we can add a new argument. An MDO made of stellar remnants is viable only if its progenitor stars can safely live their lives and deliver their remnants at suitable radii. We do not ask how a cluster of progenitors can form; we do not understand star formation well enough to base arguments on it. But main sequence stars are well understood, and we know progenitor star masses well enough for the present purposes. It turns out that progenitor clusters get into trouble because the stars are so close together that they collide.

The argument is summarized as follows. The progenitor cluster must be approximately as small as the MDO cluster, because dynamical friction is too slow to deliver remnants from much larger radii. We get into less trouble with collisions if fewer progenitors are resident at one time. That is, if the MDO was made in time T, and if the progenitor star lifetime is T_*, the safest strategy is to have T/T_* successive generations of progenitors. We assume that $T = 10^{10}$ yr. We then calculate the timescale on which any one progenitor star collides with another as a function of generation number. The longest such timescales are shown in Figure 3. For all but the highest-mass white dwarfs, progenitors collide at least once during their lifetimes. Colliding stars merge and become progenitors of high-mass remnants. The resulting MDO would have a short evaporation time. Also, stellar mergers increase the mass range and shorten the evolution times.

Therefore astrophysically plausible alternatives to a supermassive BH are likely to fail. This conclusion is preliminary, because neither the signal-to-noise of the blue spectrum nor the consequent spatial resolution after 4 STIS rows have been averaged are the best that HST can deliver. Higher resolution spectroscopy is planned. Dynamical models to better constrain r_h are also planned. However, it already appears that M 31 is the third galaxy in which astrophysical arguments favor the conclusion that a dynamically detected MDO is a BH. This increases our confidence that all dynamically detected MDOs are BHs.

3. The $M_\bullet - M_{B,\mathrm{bulge}}$ and $M_\bullet - \sigma_e$ Correlations

The rest of this paper uses BH demographics to address a variety of astrophysical questions (see KG for a more detailed review). Two correlations have emerged. Figure 4 (left) shows the correlation between BH mass and the luminosity of the "bulge" part of the host galaxy (Kormendy 1993a, Kormendy & Richstone 1995; Magorrian et nuk. 1998) brought up to date with new detections. A least-squares fit gives

$$M_\bullet = 0.78 \times 10^8\ M_\odot \left(\frac{L_{B,\mathrm{bulge}}}{10^{10}\ L_{B\odot}}\right)^{1.08}. \tag{1}$$

Since $M/L \propto L^{0.2}$, equation 1 implies that BH mass is proportional to bulge mass, $M_\bullet \propto M_{\mathrm{bulge}}^{0.90}$. The canonical BH is $\sim 0.13\,\%$ of the mass of the bulge.

Figure 4 (right) is the correlation between $M_\bullet$ and the luminosity-weighted velocity dispersion σ_e within the effective radius r_e (Gebhardt et nuk. 2000; Ferrarese & Merritt 2000). A least-squares fit to the galaxies with most reliable $M_\bullet$ measurements (Gebhardt et nuk. 2000; KG) gives

$$M_\bullet = 1.3 \times 10^8\ M_\odot \left(\frac{\sigma_e}{200\ \mathrm{km\ s^{-1}}}\right)^{3.65}. \tag{2}$$

The scatter in the $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation is large, and there are two exceptions with unusually high BH masses. The more extreme case, NGC 4486B (Kormendy et nuk. 1997; Green et al. 2001), is still based on two-integral models. Three-integral models may give a smaller BH mass. Despite the scatter, the correlation is robust. We conclude that the $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation is real and not just the upper envelope of a distribution that extends to smaller BH masses. Ongoing searches find BHs in essentially every bulge observed and in most cases would have done so even if the galaxies were significantly farther away.

In contrast, the scatter in the $M_\bullet$ – σ_e correlation is small, and the galaxies that were discrepant above are not discrepant here. Gebhardt et nuk. (2000) find that the scatter is consistent with the measurement errors for the galaxies with the most reliable $M_\bullet$ measurements. So the $M_\bullet$ – σ_e correlation is more fundamental than the $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation. What does this mean?

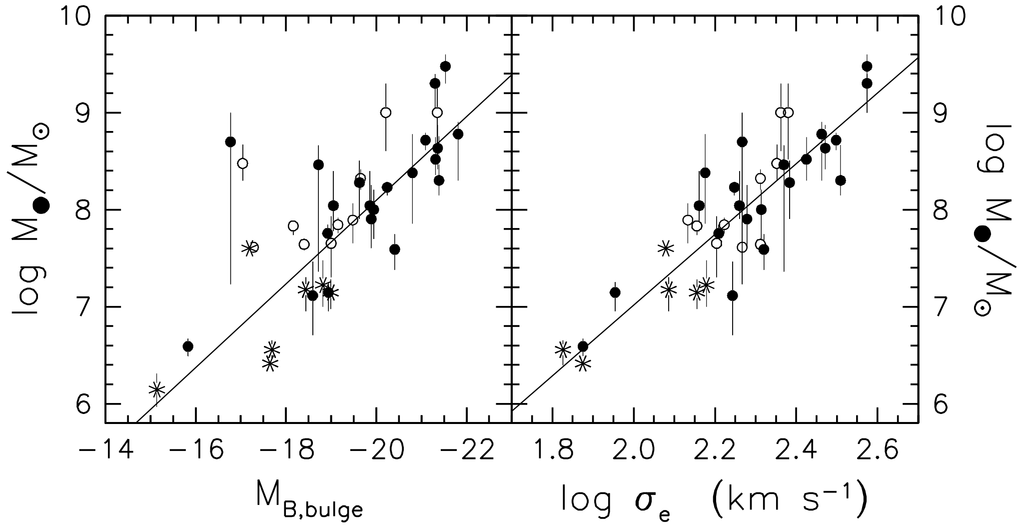

Figure 4 – Correlation of BH mass with (left) the absolute magnitude of the bulge component of the host galaxy and (right) the luminosity-weighted mean velocity dispersion inside the effective radius of the bulge. Filled circles represent elliptical galaxies, open circles represent classical (elliptical-galaxy-like) bulges of disk galaxies, and stars represent pseudobulges. The lines are equations 1 and 2.

The correlations imply that BH growth and galaxy formation are connected. BH mass is partly determined by the amount of fuel available; this tends to be larger in larger galaxies. But Figure 4 suggests that more is involved than the amount of fuel. Exceptions to the $M_\bullet - M_{B,\mathrm{bulge}}$ correlation satisfy the $M_\bullet - \sigma_e$ correlation. That is, when a BH is unusually high in mass for a given luminosity, it is also high in σ_e for that luminosity. This could happen if the mass-to-light ratio of the stars is unusually high. This proves not to be the biggest effect. Rather, ellipticals with unusually high dispersions for their luminosities are unusually compact: they have unusually high surface brightnesses and small effective radii for their luminosities. Similarly, cold galaxies are fluffy: they have low effective surface brightnesses and large effective radii for their luminosities. Therefore, when a galaxy is hotter than average, it underwent more dissipation than average and shrunk inside its dark halo to a smaller size and higher density than average. That is, it collapsed more than the average galaxy.

We can see this quantitatively by noting that the $M_\bullet - M_{B,\mathrm{bulge}}$ and $M_\bullet - \sigma_e$ relations are almost equivalent. The left panel in Figure 4 is almost a correlation of $M_\bullet$ with the mass of the bulge, because mass-to-light ratios vary only slowly with luminosity. Bulge mass is proportional to $\sigma_e^2 r_e/G$. So a black hole that satisfies the $M_\bullet - \sigma_e$ correlation will look discrepant in the $M_\bullet - \sigma_e^2 r_e$ correlation if r_e is smaller or larger than normal. We conclude that BH mass is directly connected with the details of how bulges form.

What is the connection? There are three generic possibilities. (1) BHs could have grown to essentially their present masses before galaxies formed and then regulated the amount of galaxy that grew around them (Silk & Rees 1998). (2) Seed BHs that were already present at the start of galaxy formation or that formed early could have grown to their present masses as part of bulge formation. (3) Most BH mass may have been accreted after galaxy formation from ambient gas in the bulge. The problem is that the $M_\bullet$ correlations do not tell us which alternative is most correct. This is a very active area of current research. All three alternatives have proponents even on the Nuker team.

However, a variety of evidence favors alternative (2) for most of the BH growth. That is, the merger and dissipative collapse events that made a bulge or elliptical galaxy were the same events that made quasars shine. Ultraluminous infrared galaxies (ULIGs) are nearby examples of the formation of giant ellipticals (see Sanders & Mirabel 1996 for a review). Sanders et al. (1988a, b) have suggested that ULIGs are quasars in formation. More than 10 years of debate followed about whether ULIGs are powered by starbursts or by AGNs (Filippenko 1992; Sanders & Mirabel 1996; Joseph 1999; Sanders 1999). The observations now suggest that 2/3 of the energy comes from starbursts and 1/3 comes from nuclear activity (Genzel et al. 1998; Lutz et al. 1998). This is consistent with the present picture: we need a dissipative collapse and starburst to make the observed high densities of bulges (Kormendy 1989, Kormendy & Sanders 1992). Submillimeter observations are finding high-redshift versions of ULIGs from the quasar era (Ivison et al. 2000). Many are AGNs. Further evidence for a connection between ULIGs and AGN activity is reviewed in Veilleux (2000). ULIG properties strongly suggest that bulge formation, BH growth, and quasar activity all happen together.

4. The $M_\bullet - M_{B,\mathrm{total}}$ Correlation: BHs Do Not Know About Disks

Figure 5 shows that BH mass correlates better with bulge luminosity than it does with bulge plus disk luminosity. The four galaxies that have strong $M_\bullet$ limits but no bulges demonstrate expecially clearly that disks do not contain BHs with the same mass fraction as do bulges. The bulgeless galaxy M 33 has the strongest limit, $M_\bullet \lesssim 1500\ M_\odot$ (Gebhardt et al. 2001). If M 33's disk contained a BH with the same mass fraction as in bulges, then we would expect $M_\bullet \sim 3 \times 10^7\ M_\odot$. We conclude that BHs do not "know about" galaxy disks. They correlate only with the high-density, bulge-like component in galaxies.

These results do not preclude BHs in pure disk galaxies as long as they are small. Filippenko & Ho (2001) emphasize that some pure disks are Seyfert galaxies. They probably contain BHs. An extreme example is NGC 4395, the lowest-luminosity Seyfert known (Figure 5). However, if its BH were radiating at the Eddington rate, then its mass would be only $M_\bullet \sim 100\ M_\odot$ (Filippenko & Ho 2001). So pure disks may contain small BHs.

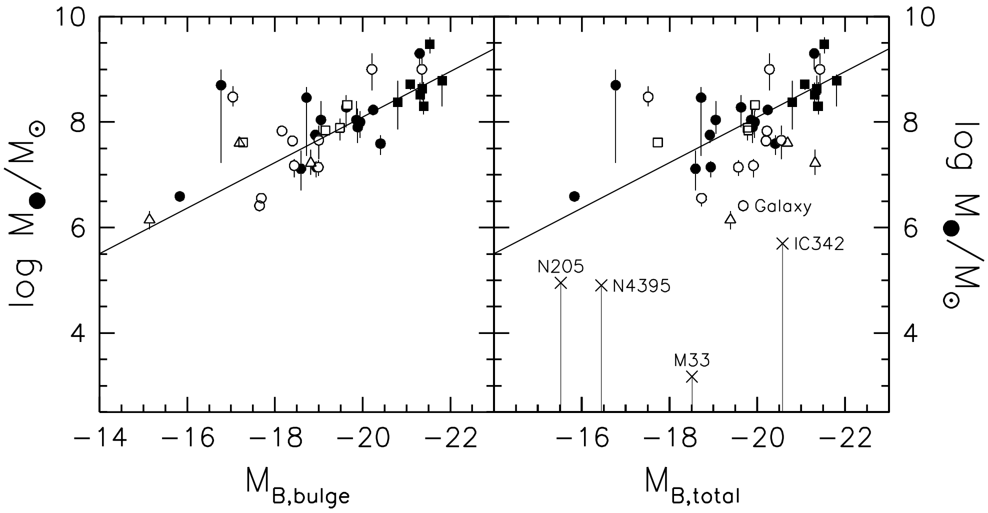

Figure 5 – (left) $M_\bullet - M_{B,\mathrm{bulge}}$ correlation from Figure 4. (right) Plot of $M_\bullet$ against the total absolute magnitude of the host galaxy. Filled symbols denote elliptical galaxies, open symbols denote bulges of disk galaxies. Crosses denote galaxies that do not contain a bulge: M 33 is from Gebhardt et al. (2001); IC 342 is from Böker et al. (1999), and NGC 4395 is from Filippenko & Ho (2001).

5. Black Hole Mass Correlations. II. Bulges Versus Pseudobulges

So far, we 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 $M_\bullet - M_{B,\mathrm{bulge}}$ and $M_\bullet - \sigma_e$ correlations. But a variety of observational and theoretical results show that there are two different kinds of high-density central components in disk galaxies. Both have steep surface brightness profiles. But, while classical bulges in (mostly) early-type galaxies are like little ellipticals living in the middle of a disk, the "pseudobulges" of (mostly) late-type galaxies are physically unrelated to ellipticals.

Pseudobulges are reviewed in Kormendy (1993b) and in KG. Observational evidence for disklike properties includes (i) rapid rotation V that implies V/σ values above the "oblate line" describing rotationally flattened, isotropic spheroids in the V/σ – ellipticity diagram, (ii) velocity dispersions σ that are smaller than those predicted by the Faber-Jackson (1976) $\sigma - M_B$ correlation, (iii) dense central concentrations of molecular gas (Regan et al. (2001), and (iv) spiral structure that dominates the pseudobulge part of the galaxy. The spiral structure is especially prominent in HST images (Carollo et al. 1997, 1998a, b). Many pseudobulges have brightness distributions that are closer to exponentials than to $r^{1/4}$ laws (Andredakis & Sanders 1994; Andredakis, Peletier, & Balcells 1995; Courteau, de Jong, & Broeils 1996). Such observations and n-body simulations suggest that high-density central components can form out of disk gas that is transported toward the center by bars and oval distortions (e.g., Kormendy 1993b; Courteau et al. 1996; Carollo et al. 1997, 1998a, b).

Pseudobulges are an extension of the properties of galaxy disks discussed in Freeman (1970). With > 1000 citations, this is by far Ken's most cited paper. In it, Ken discusses pure and "Type II" exponentials; near the center, the latter drop below the inward exptrapolation of an exponential fitted to the outer parts. We suggest that the construction of pseudobulges produces – at least initially, before internal heating – disk profiles that rise above the inward extrapolation of an exponential fitted to the outer disk (see Kormendy 1993b, Figure 9).

The construction of pseudobulges by secular evolution in barred galaxies is extensively discussed by Pfenniger & Norman (1990, 1991), Hasan, Pfenniger, & Norman (1993), Norman, Sellwood, & Hasan (1996), and Sellwood & Moore (1999). Norman and collaborators emphasize that the evolution does not just produce a high-density central disk; dynamical heating occurs that thickens the disk and makes it look more like a bulge. One such heating process is the scattering of stars off of bars. The buildup of the central mass concentration makes it more difficult for bar-sustaining orbits of different radii to precess together; as a result, the bar can dissolve. In addition, unbarred but oval disks also transport gas efficiently toward the center. Therefore, lack of a bar is no sign that pseudobulge formation cannot have occurred in the past or be going on now. Norman et al. (1996) conclude that "barred Sc galaxies with sufficient central mass concentrations should be building [pseudo]bulges now." The observations imply that most early-type galaxies contain bulges, that later-type galaxies tend to contain pseudobulges, and that only pseudobulges are seen in Sc – Sm galaxies.

So there is growing evidence that the "bulges" in Figure 4 are two different kinds of objects. Classical bulges are thought to form like ellipticals, in a dissipative collapse triggered by a merger. Pseudobulges are thought to form by secular evolution in disks. In both cases, gas flows inward and may feed BHs.

Do these very different processes produce similar-mass BHs? Preliminary evidence suggests that they do (Figure 4). Pseudobulges have low luminosities, consistent with the assumption that they are made from disks. But for their low luminosities, they have normal BH masses. The indentification of pseudobulges is somewhat uncertain, and only a few have been observed. It will be important to check our result with a larger sample. However, it is consistent with the hypothesis that (pseudo)bulge formation and BH feeding are connected. Present data show no dependence of $M_\bullet$ on the details of whether BH feeding happens rapidly during a collapse or slowly via secular evolution of the disk. If disks contain only small BHs while the pseudobulges that form from disks contain standard BHs with 0.13 % of the pseudobulge mass, then we suggest that these BHs grew to their present masses during pseudobulge formation.

6. Conclusion: Black Holes and Galaxy Formation

Conclusions about galaxy formation are less secure than the observational results discussed above. However: *The observations suggest that the major events that form a bulge and the major growth phases of its BH – when it shone as an AGN – were the same events.* The likely formation processes are either a series of dissipative mergers that fuel starbursts and AGN activity (Sanders et al. 1988a, b) or secular inward flow of gas in disks that builds pseudobulges and simultaneously feeds their BHs (Kormendy et nuk. 2001).

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