Carnegie Observatories Astrophysics Series, Vol. 1:
Coevolution of Black Holes and Galaxies
ed. L. C. Ho (Cambridge: Cambridge Univ. Press)

Supermassive Black Holes: Demographics and Implications

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Abstract

The central fact in the demographics of supermassive black holes is the correlation between black hole mass and the mass, luminosity or velocity dispersion of the bulge of the host galaxy. We are not aware of a "second parameter" or of any systematic departures (such as might be due to measurement technique) from these fundamental relationships. The cosmic density of supermassive black holes at zero redshift is $4.8 \times 10^5 h^2 M_\odot \mathrm{Mpc}^{-3}$ or $\Omega_\bullet = 1.7 \times 10^{-6}$. This is consistent with the quasar "background" light, which has an *emitted* energy density of about $1.3 \times 10^{-15} \mathrm{erg\,cm}^{-3}$.

The near equality of the cosmic supermassive black hole density with the quasar background energy (corrected by a suitable radiative efficiency) implies that the quasars are a by-product of the growth of black holes. We review a sampling of the wide variety of proposed theories for the growth of black holes and the coupling between black hole formation and galaxy bulge formation.

1.1 Introduction

The existence of this volume, reflecting a major meeting on supermassive black holes (BH), testifies to the rapid evolution of this subject. As recently as 15 years ago, skepticism about the existence of BH and their connection to active galactic nuclei (AGN) was respectable. At this point BH are the most conservative explanation for the dark mass concentrations in galactic centers. Elsewhere in this volume, my collaborators Kormendy and Gebhardt provide considerable information about the kinds of analysis that have been carried out, and the current state of our understanding of specific objects. In this chapter I focus on the inferences that can be drawn from these objects viewed together.

1.2 Correlations of BH Mass with Main Body Galaxy Properties

The central fact in discussions of BH demography is the relationship between BH mass and properties of the main body of the bulge of the host galaxy. Considerable attention has been drawn to the relationship between the BH mass and the bulge light (for example, in Kormendy & Richstone 1995, Kormendy & Gebhardt 2001), and the $M_\bullet - \sigma$ relation between the BH mass and rms velocities of bulge stars (Gebhardt *et al.* 2000, Ferrarese & Merritt 2000). We will rely heavily on the $M_\bullet - \sigma$ relation in this article. We illustrate both relationships in Figure 1. We note that other authors have argued that the galaxy luminosity profile also predicts the BH mass (see Erwin's and Graham's contributions to this volume). We will not comment on this.

Throughout this article, we use the BH masses tabulated in Tremaine *et al.* (2002) with the exception of the mass of the BH in the Galaxy, for which we adopt $M_\bullet = 3.5 \times 10^6$ from Ghez (this volume). In that paper, Tremaine *et al.* (2002) did a very careful review of the $M_\bullet - \sigma$ relation. We use his result

$$M_\bullet = 1.35 \times 10^8 \left(\frac{\sigma}{200 \text{ km s}^{-1}} \right)^{4.02} . \tag{1.1}$$

in what follows (see Figure 1). This result is consistent with the Gebhardt *et al.* (2000) original result and is about 1.5σ shallower than Merritt & Ferrarese's (2001b) shallowest published fit. Possible reasons for this disagreement are discussed in Tremaine *et al.* but at this writing we still do not fully understand it. The scatter about this relation is about 0.3 dex, noticeably less than the scatter in the relation between $M_\bullet$ and the bulge luminosity (see Figure 1).

Although the residuals from this fit are barely larger than the measurement errors, it is interesting is to investigate the residuals as a function of measurement method or as a function of galaxy type. In the first case, the BH masses are measured by stellar dynamics or by gas dynamics, and we would expect any systematic effects to have a different impact on the two methods. The residuals from the $M_\bullet - \sigma$ relation are are plotted for these two methods in figure 2. A t-test of sample means verifies that these distributions are insigificantly different. We conclude from this plot that any systematic methods either affect both methods in the same way, or are smaller than 0.1 dex (which would be detectable). Any systematic errors in these two different methods would have to conspire to create this agreement.

We have also investigated the residuals for evidence of an obvious second parameter in the BH – galaxy relation. We have not found a convincing second parameter. We were particularly interested in whether Hubble type might correlate with departures from this relation, and were unable to see any evidence of that in this data (see Figure 2).

1.3 Are they really BH?

We note three critical special cases. In the case of our own galaxy (see Ghez, this volume), M32 (van der Marel *et al.* 1998, see also Verome *et al.* 2002) and NGC 4258 (see Miyoshi *et al.* 1995), an unseen mass is measured in a volume sufficiently small that the enclosed mass density exceeds $10^9 M_\odot \text{pc}^{-3}$ ($10^8 M_\odot \text{pc}^{-3}$ for M32). At this mass and density a single mass will shine very brightly and evolve rapidly, while an aggregate of any *known* astrophysical object will either (i) evaporate and evolve rapidly or (ii) collapse to a black hole in a time much less than the probable ages of the stars in these galaxies (see Maoz 1995, 1998). We summarize Maoz' argument below. It has two strands. If we treat the aggregate as point masses, then two body relaxation sets an upper limit to the typical mass of the consituent particles. As this mass drops below the neutron star limit, the size of the objects is limited from below by ordinary electron degeneracy to the white dwarf mass-radius relation (in the solar mass range) or to the brown dwarf and planetary mass-radius relation (as one drops below $0.1 M_\odot$). These finite-sized objects collide in much less time than their likely age, regardless of their mass (at densities above the $10^9 M_\odot \text{pc}^{-3}$). Hence these objects are not long-lived dynamical equilibria. One is free to construct collections of dark matter for the purpose of evading these constraints, but not with *known* astrophysical objects except for BH of mass $\leq 0.2 M_\odot$.

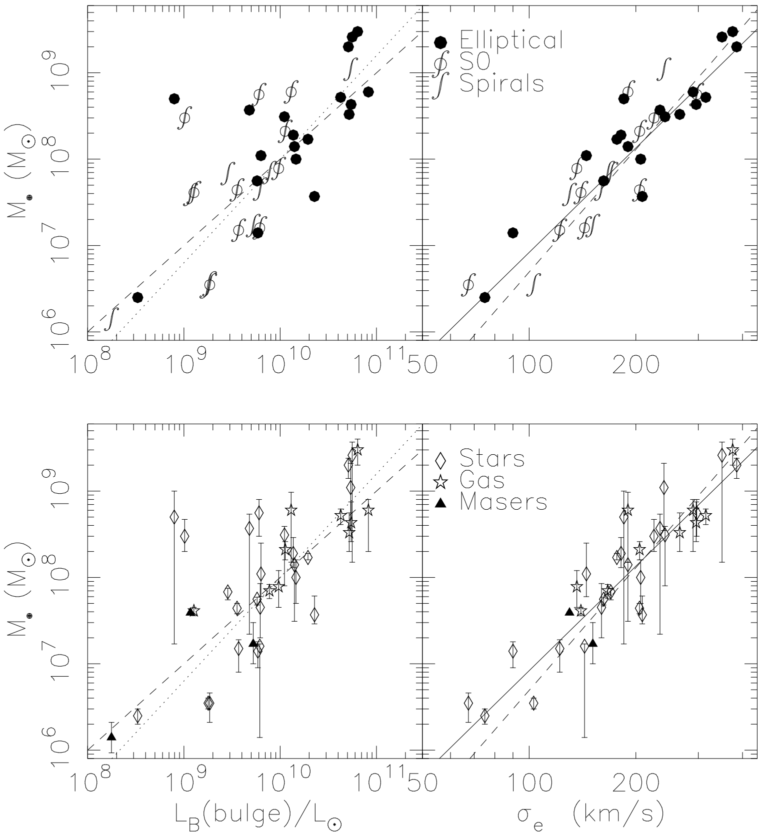

Fig. 1.1. Dynamically measured black hole masses from Tremaine *et al.* 2002 (except as noted in the text) are shown in the left-hand panels versus the host galaxy B band bulge luminosity L_B (from Kormendy & Gebhardt 2001), and, in the right-hand panels versus the slit-averaged bulge rms velocities out to half an effective radius (from the tabulation in Tremaine *et al*). In the top panels the points are marked by Hubble type, while in the lower panels they are designated by the method used to determine the BH mass. In the left-hand panel the dashed line represents $M_\bullet = 0.01 L_B$ and the dotted line represents $M_\bullet = 2.0 \times 10^{-3} \mathcal{M}_b$, where $\mathcal{M}_b$ is the bulge mass and we also assume that the bulge mass-to-light ratio is 5 at $L_B = 10^{10} L_\odot$ and that it varies as $\mathcal{M}/L = L^{0.2}$. In the right-hand panel the solid line represents the Tremaine *et al.* $M_\bullet - \sigma$ relation, and the dashed line represents the Merritt & Ferrarese 2001b relation.

1.4 The Density of BH and of the AGN Background

We can use the $M - \sigma$ relationship to compute the mass density of BH directly. Aller & Richstone (2002) do this by converting the galaxy luminosity function for different Hubble types, and the Faber-Jackson relation and its analog for bulges, to a "velocity dispersion function", and combine this with the $M - \sigma$ relation to get a black hole mass function from two different galaxy surveys (Marzke 1994a,b, and Madgwick 2002). The integrated density in BH mass at zero redshift is about

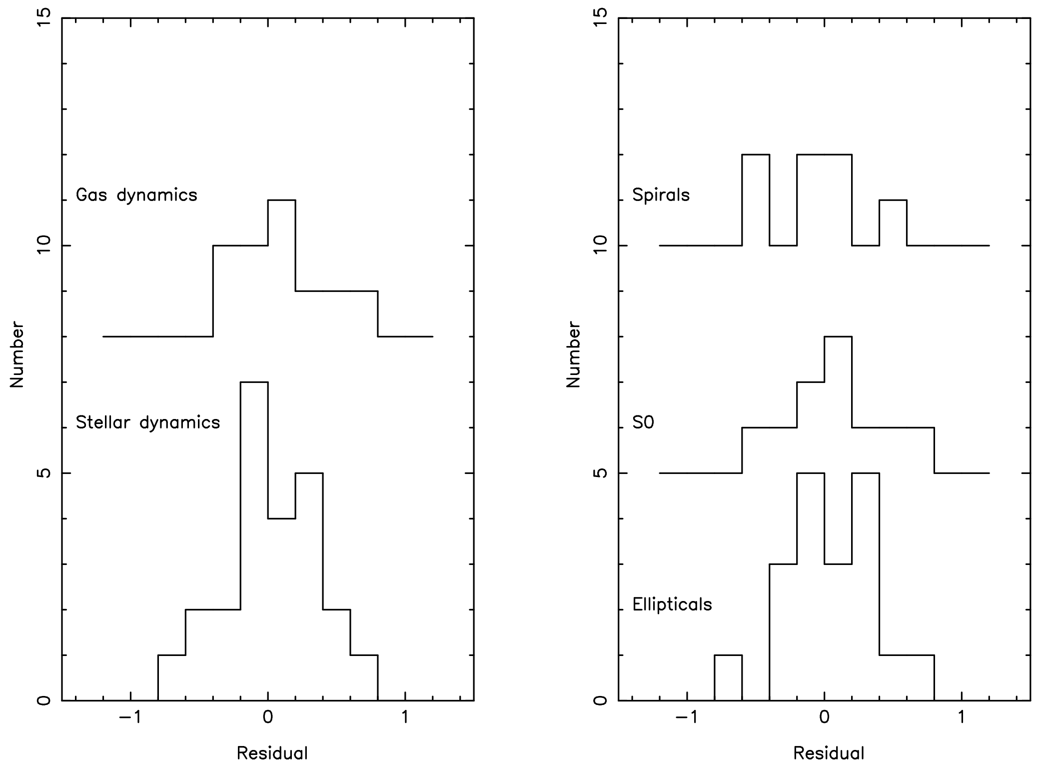

Fig. 1.2. Logarithmic residuals from the Tremaine *et al.* $M_\bullet - \sigma$ relation shown in Figure 1. In the left hand-panel the residuals have been sorted by the method used to dynamically determine the BH mass. In the right-hand panel they are segregated by Hubble type. We see no statistically significant difference among + either set of subsamples.

$$\rho_\bullet = 4.8 \times 10^5 h^2 M_\odot \mathrm{Mpc}^{-3}. \tag{1.2}$$

Yu and Tremaine 2002 used the SDSS result giving the number of galaxies as a function of velocity disperion (Bernardi *et al.* 2003) to also obtain

$$\rho_\bullet = 2.5 \pm 0.4 \times 10^5 M_\odot \mathrm{Mpc}^{-3}, \tag{1.3}$$

for $h = 0.65$. These two numbers are in excellent agreement. An earlier estimate obtained by Merritt & Ferrarese (2001a) using the $M_\bullet - \sigma$ relation to recalibrate an $M_\bullet - L_{bulge}$ relation gave $5 \times 10^5 M_\odot \mathrm{Mpc}^{-3}$ and was later adjusted downward to about $3 \times 10^5 M_\odot \mathrm{Mpc}^{-3}$ (Merritt & Ferrarese 2001c).

It is also useful to compare the cosmic black hole mass density at $z = 0$ from equation 2 or 3 to the luminous density of galaxies (this is a black hole mass to galaxy light ratio). Marzke *et al.* and Madgwick *et al.* both report a total luminous density in galaxies of

$$\rho_L = 2.0 \times 10^8 h L_\odot \mathrm{Mpc}^{-3}, \tag{1.4}$$

a value a factor of 2 larger than Loveday *et al.* 1992. Using eqn 2 and 4 we obtain the black hole mass density to galaxy light density of

$$\frac{\rho_\bullet}{\rho_L} = 2.4 \times 10^{-3} h L_\odot \mathrm{Mpc}^{-3}. \tag{1.5}$$

Note that this is about 4 times smaller than the mean BH mass to bulge light ratio Υ illustrated in Figure 1.1, which is about $\Upsilon = 10^{-2}$, consistent with the fact that about $1/4$ of the luminosity in galacties at $z = 0$ is in bulges or ellipticals. We can compute the fraction of the critical density carried by this BH mass,

$$\Omega_\bullet = 1.7 \times 10^{-6} \tag{1.6}$$

and the BH mass fraction of baryonic matter (taking $\Omega_{baryon} h^2 = 0.0224$ [Spergel *et al.* 2003])

$$\frac{\Omega_\bullet}{\Omega_{baryon}} = 0.76 \times 10^{-4} h^2. \tag{1.7}$$

This shows that the mass density in (supermassive) BH is small compared to the cosmic baryon density (or the critical density).

The cosmic density of BH can more interestingly be compared to the energy density in the radiation background due to quasars. Since quasars are thought to be accreting BH we expect that the cosmic BH density is at least as large as the quasars would predict. We believe that Soltan (1982) was the first to note the possibility of making this comparison and to use it to predict the masses of BH in galactic nuclei today. Chokshi & Turner (1992) reexamined that result and we follow their notation. They argue that the integrated comoving energy density in quasar light is

$$u_e = \int_0^\infty \int_0^\infty L\Phi(L|z) dL \frac{dt}{dz} dz = 1.3 \times 10^{-15} (C_B/16.5) \mathrm{erg\,cm}^{-3}. \tag{1.8}$$

This emitted energy density is related to the present day energy density u_0 by

$$u_0 = u_e \left(\overline{1+z}\right)^{-1} \sim 4.3 \times 10^{-16} (C_B/16.5) \mathrm{erg\,cm}^{-3}, \tag{1.9}$$

where $\bar{z}$ is the mean redshift of quasar emission, which we took to be $\bar{z} = 2$ for the estimate shown. The redshift dependence appears because, like the comoving mass density, the *comoving* photon density does not change with z, but the energy of any individual photon (and therefore the comoving radiation energy density) varies as $(1+z)^{-1}$ The local comoving energy density is, in principle, a direct observable given by $u_0 = 4\pi I/c$, where I is the frequency integrated surface brightness of quasar light on the sky, and the explicit integral is over solid angle.

We define the "Soltan number" S as the local mass density of the emitted quasar light corrected for the likely radiative efficiency of 10%. The next step in this procedure, using equation 8, is to relate u_e to the mass in BH.

$$S(QSO) = u_e \frac{1-\epsilon}{\epsilon c^2} = 2.2 \times 10^5 (1-\epsilon)\, \epsilon_{0.1}^{-1} (C_B/16.5) M_\odot \,\mathrm{Mpc}^{-3}, \tag{1.10}$$

where ϵ is the radiative efficiency of accretion (the ratio of luminosity to $\dot{m}c^2$ in the accretion flow), and $\epsilon_{0.1} = \epsilon/0.1$. We parameterize most of our results in terms of $\epsilon_{0.1}$ since $\epsilon = 0.1$ a fairly generic accretion efficiency for optically thick, geometrically thin accretion disks in Schwarzschild geometries (non-rotating BH).

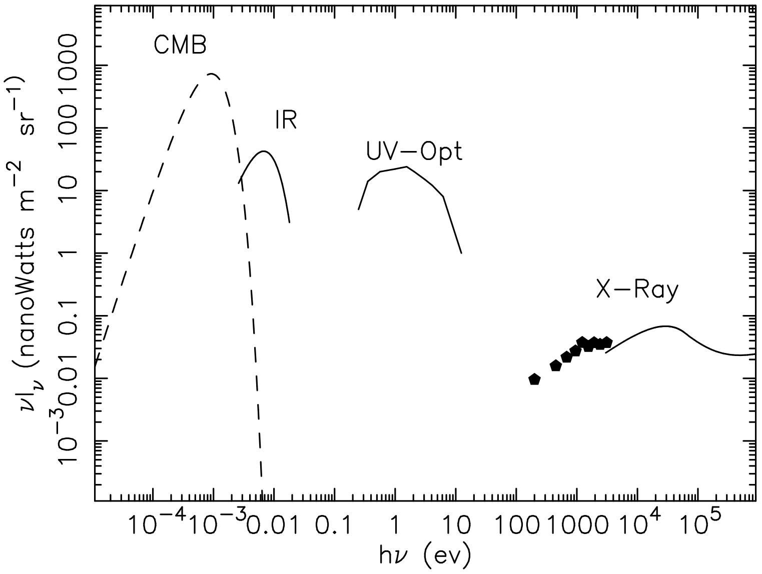

Fig. 1.3. The background radiation actually observed in the universe at redshift zero, adapted from Hauser & Dwek 2001.

Yu & Tremaine 2002 also use recent (Boyle *et al.* 2000) estimates of the quasar distribution in luminosity and redshift to revisit the Chokshi & Turner estimate of the Soltan number. They find

$$S = 2.1 \times 10^5 (C_B/11.8)[0.1(1-\epsilon)/\epsilon)]M_\odot \mathrm{Mpc}^{-3}, \tag{1.11}$$

in excellent agreement with Chokshi and Turner. However, Yu & Tremaine use a bolometric correction of 11.8 (reflected in eqn 11) based on work by Elvis *et al.* (1994).

The discussion above draws attention to the relationship of S to a background energy density for two reasons. First, it emphasizes that S is nearly independent of cosmological parameters like h, Ω or Λ. Second, it emphasizes the relationship of the QSO radiation background to the X-ray background. We emphasize, however, that the calculation, as usually performed, renders S critically dependent on an assumed bolometric correction and further corrections (often embodied in the bolometric correction) for obscured or undercounted objects.

It is widely believed that all of the X-ray background is produced by accretion onto BH. It is therefore of considerable interest to compare u_0 to the X-ray background. We illustrate backgrounds in many parts of the EM spectrum in figure 3 (Hauser and Dwek 2001).

We can compare the quasar energy from equation 4 with the X-ray background. The 4 indicated backgrounds are integrated over their wavelength range and given in Table 1. The energy density in the X-ray background is $u_o = 1.45 \times 10^{-16}$ ergs cm^{-3} — about a factor of 10 less than the emitted quasar energy in eqn 8.

Fabian & Iwasawa 1999, correcting for soft X-ray absorption and for completely buried X-ray emitters, derive a local energy density of the X-ray background of $u_0 = 1.3 \times 10^{-15}$erg cm^{-3}. Assuming a redshift distribution of unseen objects that is comparable to bright quasars they

Table 1.1. *Integrated intensities and energy densities of selected backgrounds*

Name	Intensity nanoWatts m^{-2} sr^{-1}	Energy Density ergs cm^{-3}
CMB	990	4.17×10^{-13}
IR	50.3	2.11×10^{-14}
UV-Opt	73.	3.1×10^{-14}
X-Ray	0.35	1.45×10^{-16}
Quasar		$u_0 = 4.3 \times 10^{-16}$

then obtain a rest frame co-moving energy density of $u_e = 4.1 \times 10^{-15}$erg cm^{-3}, about 3 times larger than the Chokshi & Turner estimate in eqn 8. This represents an extrapolation of a factor of 30 over the actual observed X-ray background. A factor of 10 came from estimates of the absorption of X-ray emission (or by fully obscurred sources) and a factor of 3 came from an assumption that much of the absorption came from $z \sim 2$ as in the case of the bright optical quasars. Fabian (this volume) discusses a downward revision of the X-ray background to an energy density corresponding to u_e in equation 8 above.

We note that the infrared background shown above exceeds the quasar "background" by about an order of magnitude. Bernstein, Freedman & Madore (2002 and references therein) have argued that consistency with the production of heavy elements requires that most of the infrared background be produced by stars and not quasars.

Supermassive black hole masses range from about $10^6 M_\odot$ to about $3 \times 10^9 M_\odot$ with a typical mass for L^* galaxies of about $10^8 M_\odot$. The Eddington luminosity (above which the outward radiation force on free electrons exceeds the gravitational attraction exerted on protons) is

$$L_E = 1.3 \times 10^{46} M_8 \,\mathrm{ergs/sec}, \tag{1.12}$$

comparable to the luminosity of bright quasars.

Since the mass density and the masses of the local BH population are consistent with the integrated quasar luminosity and the individual quasar luminosities, it is reasonable to suppose that the numbers of quasars are consistent with the numbers of BH locally. Small & Blandford 1992 suggest that this is not the case. Richstone *et al.* 1988 obtained a similar result by comparing the number of quasars — about 10^{-6}Mpc^{-3} — brighter than 6×10^{46}ergs/sec at the peak of the quasar epoch, to the number of bulges with BH of masses of at least $4 \times 10^8 M_\odot$. The brightest quasars are likely to be emitting near their Eddington limit, and hence their engines have BH of about $4 \times 10^8 M_\odot$. Bulges with BH this massive have a local density of 10^{-3}Mpc^{-3}. Why then, are there so few quasars? Since the number seen at any time is the duty-fraction η times the total number, it may simply be that the duty fraction is tiny. The Richstone *et al.* analysis imples $\eta = 10^{-3}$.

One possible problem raised by such a small duty fraction is that it suggests a lifetime of 10^6yr for the observed quasars. The ratio of this lifetime to the timescale for mass e-folding during Eddington-limited accretion (the "Salpeter time" t_S) —

$$t_S = M/\dot{M} = 4 \times 10^7 \epsilon_{0.1} \,\mathrm{yrs}. \tag{1.13}$$

is about 0.025, implying that BH acquire only a small fraction of their mass during the bright quasar phase. This would render the rough equality of the BH mass density and the Soltan number a coincidence. The Small and Blandford study is consistent with a less extreme duty fraction of about 10^{-2}, which weakens this argument considerably.

1.5 Supermassive Black Hole Formation and Evolution

1.5.1 Some general inferences

Setting aside the dilemma posed by the discrepancy between the number of the biggest BH and the number of the brightest quasars, the approximate equality of the Soltan number and the BH mass density leads to two important inferences: (i) supermassive black holes are the relics of the quasars (they have the correct cosmic density and individual masses); (ii) much of their mass was acquired during the quasar epoch and this accretion is electromagnetically visible. These two points suggest that the bulk of BH accretion is by accreting gas, not whole stars, dark matter or other black holes. Otherwise, the equality of the cosmic density of BH and the Soltan number is a coincidence.

The luminosity of bright quasars suggests that during the quasar epoch the BH are already massive, because the brightest are almost surely limited by their Eddington luminosity (equation 8) and require masses greater than $10^8 M_\odot$. Moreover, reaching this mass by Eddington limited accretion is a challenge (partly because of the duty-fraction dilemma, but also) because the age of an $\Omega_0 = 0.3, \lambda = 0.7$ universe at z = 5 (when the first quasars are known to exist) is 0.8Gyr $\sim 20 t_S$ (see Turner 1991 and Efstathiou & Rees 1988 for somewhat divergent views of this issue). It is conceivable that seed black holes of significantly lower mass formed well before z = 5.

Perhaps the most important inference concerns the connection between black hole growth and bulge formation. Because the velocity dispersion at R_e is closely related to the binding energy per unit mass of the bulge (which is, inside that radius, dominated by visible matter), and is set during bulge formation or subsequent mergers, and because the black holes have already formed by redshifts $z \sim 3$, the growth of the black hole and the formation of its host bulge are likely physically coupled.

1.5.2 A taxonomy of models for the $M_\bullet - \sigma$

It is interesting to consider how the $M_\bullet - \sigma$ relation might have been created. There are a wide array of theories relying on rather different physics. One can classify these theories in at least 3 dimensions. First, there is the question of what is accreted (gas, stars, other black holes, dark matter). Second, there is the question of whether BH formation (or, more correctly, most of the growth of the BH) precedes bulge formation or vice-versa, or whether the two are essentially synchronous. Finally, there is the question what physical process produces or regulates the $M_\bullet - \sigma$ relation.

One class of model depends on the competition between star formation and black hole accretion for gas in the protogalactic bulge (Burkert and Silk (2001)). They suggest that the mass accreted by a BH in a newly formed bulge is limited by competion with star formation, and that both processes procede on a dynamical time (for different reasons). They argue that the mass accreted by the BH therefore scales as $M \propto f_g \sigma^3 (1+z)^{-3/2}$, where f_g is the gas mass fraction in the bulge. This model eventually leads to $M_\bullet \propto \sigma^3$, somewhat shallower than observed. The virtues of models of this sort are (i) inevitability — competition between

BH accretion and star formation for gas in the bulge seems unavoidable (although it may not be regulated in a manner conceived by the authors); (ii) connection to quasars (most BH growth is due to gas accretion and will therefore produce the required radiation, and is likely to occur during the epoch of bulge formation — which probably corresponds to the epoch of BH formation); (iii) connection to popular views of galaxy formation — the model offers a possible physical mechanism to produce the initial $M-\sigma$ assumed in the semi-analytic model of Haehnelt & Kaufman (2000).

Silk & Rees (1998) and Blandford (1999) have suggested that the mechanical force exerted on the gas by the quasar (perhaps through its jet) limits its growth by accretion. This is an energy-limited accretion process. This has many of the same virtues of the Burkert & Silk model, but predicts a steeper relationship in the form of an inequality $M_\bullet \le (f_g/f_w)\sigma^5$, where f_w is the fraction of the quasar luminosity output as mechanical energy. Another energy-limiting model due to Ciotti & Ostriker (1997, 2001) regulates the accretion rate of the BH by heating the accreting gas.

Direct infall from a cold mass distribution with $\rho \propto r^{-2}$ and constant angular velocity onto a seed black hole (Adams, Graff, Richstone 2001, 2003) can also produce a BH from either non-interacting or baryonic matter (so long as it is cold). The mass not captured by the BH forms the bulge in this model. An important limitation of this model is its fragility against modification of the initial conditions as it depends very sensitively on the angular momentum distribution in the protogalactic (or galactic) material.

Two other models provide very interesting foils. Ostriker (2000) has proposed a model in which self-interacting dark matter is accreted by a seed black hole following the Bondi formula, and shows that the model leads to $M \propto \sigma^4$ provided the BH is in the center of a spherical singular isothermal mass distribution ($\rho \propto r^{-2}$).

A second interesting foil is one in which two-body relaxation drives the bulge to core collapse and creates a supermassive black hole via the merger of degenerate or collapsed objects. In globular clusters, the binding energy of a single contact nondegenerate binary star is comparable to the entire binding energy of the cluster, so the extraction of energy from hard binaries can halt the collapse. Bulge masses are much greater, so binary formation will not necessarily halt their collapse. A model of bulge core collapse has been proposed by Ebisuzaki *et al.* 2001. An important feature of relaxation is conservation of energy. As long as the core collapse and BH formation is driven by conservative two-body relaxation, the flow of energy procedes from the most tightly bound part of the cluster to the evaporating stars, which carry away very little energy. In order to make a BH, energy of the order of $M_\bullet c^2$ must be extracted from the stars that will form the BH and deposited in the rest of the mass reservoir, which cannot absorb much more than its binding energy $M_t\sigma^2$. Hence,

$$\frac{M_\bullet}{M_t} \le \frac{\sigma^2}{c^2} \sim 0.5 \times 10^{-6} \tag{1.14}$$

where the numerical result is for a bulge of dispersion 200 km s^{-1}. Ebisuzaki *et al.* extract some of the energy in their model by gravitational radiation, but in order to reach $M_\bullet/M_t \sim 10^{-3}$ (see equation 7), they need to rely almost entirely on gravitational radiation or some other form of dissipation.

The Ostriker and Ebisuzaki models have the property that the accretion is electromagnetcially invisible. Hence if these processes dominate the growth of black holes we need to seek an alternate source for the energy radiated by quasars, and the approximate equality of the Soltan number and the cosmic density of BH is a false clue to the dominant accretion mechanism.

1.5.3 Coevolution of galaxies and BH

Once produced, the supermassive BH co-evolve with their host galaxies. The galaxy controls any further the fueling of the BH. However there are (at least) 3 ways that the BH can influence the galaxy (Richstone 2002).

First, the luminosity of an accreting BH can be compared to the stars in the galaxy by

$$\frac{L(bh)}{L(stars)} = 3 \times 10^4 \left(\frac{M_\bullet}{M_b}\right) \Upsilon_b = 30\, \Upsilon_b \tag{1.15}$$

where the Υ_b is the usual bulge mass-to-light ratio. Thus, during the quasar epoch, the luminous output of the quasar can dominate the starlight in the galaxy (especially in X-rays) and thereby dominate the heat input to the ISM. Second, the BH dominates the mass and gravitational field in the inner few parsecs of the galaxy, and may (or may not) destroy triaxial structure (see Holley-Bockelman *et al.* 2001, Poon & Merritt 2001 and references therein). Finally, the BH can play a major role during galactic and protogalactic mergers. During these mergers, the BH can scatter stars, altering the stellar distribution function and reducing the density of stars near the center. See, for example, Milosavljevic *et al.* 2002 and in this volume.

1.6 Acknowledgements

I thank Rebecca Bernstein and Kelly Holley-Bockelmann for helpful comments and Michael Hauser and Eli Dwek for helping me to adapt Figure 3 from their review. I've enjoyed valuable conversations with the Nuker team for 15 years. I thank the editor of these proceedings, Luis Ho, for gently and persistently getting me to write this review.

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