The formation and evolution of supermassive black holes and their host galaxies *

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Abstract. We discuss constraints on the assembly history of supermassive black holes from the observed remnant black holes in nearby galaxies and from the emission caused by accretion onto these black holes. We also summarize the results of a specific model for the evolution of galaxies and their central black holes which traces their hierarchical build-up in CDM-like cosmogonies. The model assumes (i) that black holes, ellipticals and starbursts form during major mergers of galaxies (ii) that the gas fraction in galaxies decreases with decreasing redshift (iii) that the optical bright phase of a QSO lasts for about 10^7 years. The model successfully reproduces the evolution of cold gas as traced by damped Lyα systems, the evolution of optically bright QSOs, the remnant black hole mass distribution and the host galaxy luminosities of QSOs.

1 Introduction

The evidence for the existence of supermassive black holes has been steadily increasing over the last years. For the two most convincing cases our own galactic centre and NGC4258 [1,2,3], the evidence is now beyond reasonable doubt. The evidence that most nearby galaxies contain supermassive black holes is also compelling. Early suggestions of a linear relation between the black hole mass and the bulge mass have been corroborated by larger samples [4,5]. It is generally believed that we observe a significant fraction if not all the material falling into supermassive black holes by the radiation emitted by active galactic nuclei. A supermassive black hole therefore seems to “know” in which galaxy it will end up at the present day. This and the fact that supermassive black holes contain as much as 0.2 to 0.6 percent of the baryonic mass of the galaxy [5,6], suggests that the formation of stars in the bulges of galaxies and the assembly of supermassive black holes at their centre are closely linked [4]. On the other hand, there is strong evidence that structures in the Universe form hierarchically, i.e. larger structures build up by merging of smaller structures. This is a generic feature of a wide class of structure formation scenarios, the so called cold dark matter (CDM) cosmogonies. Both galaxies and AGN activity have been succesfully modelled within such hierarchical cosmogonies [7,8,9,10,11,12,13,14,15]. Here we first review observational

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constraints on the accretion history of supermassive black holes and discuss some clues for the formation mechanism. We then summarize the results of a specific model that describes the joint evolution of galaxies and supermassive black holes within a hierarchical cosmogony (see Kauffmann & Haehnelt 1998 for more details [16]). We assume here \( \Omega_{\text{mat}} = 0.3, \Omega_{\Lambda} = 0.7, h = 0.65 \) and \( \sigma_8 = 1 \).

2 The formation and evolution of supermassive black holes

2.1 Black hole mass densities

We can get some information on the assembly history of supermassive black holes in nearby galaxies by comparing the mass density of remnant black holes to that required to produce the radiation emitted during the accretion process [17]. The mass density in remnant black holes can be inferred from the total mass density in bulges and the mass ratio of black hole mass to bulge mass,

\[
\rho_{\text{BH}} = 7.2 \times 10^5 \left( \frac{M_{\text{bh}}}{M_{\text{bulge}}} \right) \left( \frac{\Omega_{\text{bulge}}}{0.003} \right) M_\odot \text{Mpc}^{-3}.
\]

The total mass density in bulges has been estimated by Fugukita Hogan and Peebles to be \( 0.001 h^{-1} \leq \Omega_{\text{bulge}} \leq 0.003 h^{-1} \) [18]. The normalization of the bulge to black hole mass correlation is still a matter of debate. Magorrian et al claim a value of 0.6 percent while van der Marel argues that a value of 0.2 percent is more realistic [5,6]. We will adopt the latter value in the rest of the paper.

The integrated emission by optically bright QSOs due to accretion onto supermassive black holes can also be used to infer the corresponding mass density in supermassive black holes if an efficiency for the transformation of accreted rest mass into optical light is assumed [19,20],

\[
\rho_{\text{opt}} = 1.4 \times 10^5 \left( \frac{f_B \epsilon}{0.01} \right)^{-1} M_\odot \text{Mpc}^{-3}.
\]

Here \( \epsilon \) is the overall efficiency of transforming accreted rest mass energy into radiation and \( f_B \) is the fraction emitted in the B-band. Similarly we can estimate the black hole mass density which results from the emission of hard X-rays [21],

\[
\rho_{\text{X-ray}} = 3.8 \times 10^5 \left( \frac{f_{\text{X-ray}} \epsilon}{0.01} \right)^{-1} M_\odot \text{Mpc}^{-3},
\]

where we have assumed a total hard X-ray flux of 140 keV s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\). The sources producing the hard X-ray background are generally assumed
to be a class of AGN different to optically bright QSOs that has not yet been identified. We adopt an effective emission redshift $z_{em} = 1.5$ for these unidentified sources.

Part of the IR-background should also be produced by AGN, although it has been argued that their contribution should not exceed 30 percent [22]. If 30 percent of the IR background were indeed emitted by AGN [23], then

$$\rho_{IR} = 7.5 \times 10^5 \left( \frac{f_{IR}}{0.1} \right)^{-1} M_\odot \text{Mpc}^{-3},$$

where we have assumed a total IR flux of $15 \text{nW} \text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1}$ and again $z_{em} = 1.5$. There has been some debate if the mass density inferred from the optical emission is large enough to explain the mass density in remnant black holes alone. Even for the low value of black hole to bulge mass ratio of 0.2 percent adopted here, there is still a discrepancy of a factor of about five. This suggests (i) that there is either a significant contribution to the black hole mass density by accretion other than that traced by optical bright QSOs or (ii) that the efficiency for producing optical light during the accretion is lower than usually assumed or (iii) that the black hole to bulge mass ratio is lower than 0.2 percent [24,25]. The possible additional accretion may well explain the hard X-ray background and part of the infrared background. It may or may not trace the evolution of optical bright quasars.

### 2.2 Possible assembly histories of supermassive black holes

There is still a rather wide range of possible assembly histories for the supermassive black holes in nearby galaxies (see Haehnelt, Natarajan & Rees for a more detailed discussion [25]). In Fig. 1 we sketch three possible options out of this range. In the left panel most of the mass is assembled in supermassive black holes during the epoch of optically bright QSOs around $z \sim 2.5$. In the middle panel only 20% of the mass is assembled in supermassive black holes.

![Fig. 1. A sketch of possible assembly histories of supermassive black holes in nearby galaxies. Plotted is the overall black hole mass density relative to its present-day value. For further description see text.](image-url)
holes during the epoch of optically bright QSO. The rest is accreted at low redshift, possibly in the form of hot gas in an advection dominated accretion flow. In the right panel most of the mass is assembled into small supermassive black holes at very high redshift. Present-day supermassive black holes form predominantly by merging of smaller black holes. Accretion of gas during the epoch of bright QSOs or at an later epoch does not change the mass density much.

2.3 Clues for the formation mechanism of the typical supermassive black hole

A variety of physical mechanisms for assembling mass into supermassive black holes have been suggested (see Rees 1984 [26] and Rees these proceedings for a review),

- the dynamical evolution of a dense cluster of stellar objects,
- the build-up of a supermassive black hole by merging of smaller black holes,
- the viscous evolution and/or merger-driven collapse of a self-gravitating gaseous object.

All of these processes certainly occur and can lead to the formation of supermassive black holes. The last option seems, however, the most attractive way of explaining the observed black hole bulge mass relation. The main reason is the high formation efficiency inferred from the large black hole to bulge mass ratios. It is hard to see how as much as one percent of all available cold gas could end up in a supermassive black hole of $10^9 M_\odot$ if an intermediate state of a dense stellar cluster is involved. Initially relaxation times in such a cluster would be long and a considerable fraction of stars would evaporate before the cluster becomes dense enough to evolve rapidly [27]. It is also problematic to build up supermassive black holes predominantly by merging of smaller black holes that have formed well before the epoch of optically bright QSOs. This would require large black hole formation efficiencies in shallow potential wells with $v_c < 100 \text{km s}^{-1}$. It seems more plausible that black holes should form less efficiently in smaller potential wells due to the feedback of the energy released both by accretion onto the (forming) supermassive black hole and due to supernovae. It is also unclear whether supermassive black holes in galaxies merge efficiently or whether sling-shot ejection plays a role [28,29]. We therefore consider the assembly history in the right panel of Fig. 1 to be rather improbable.

In the next section we will discuss a specific model for the evolution of galaxies and their supermassive black holes within a hierarchical cosmogony. This model assumes that the optical bright QSOs do trace the accretion history of supermassive black holes well (as in the left panel of Fig.1), but it could easily be altered to accommodate other accretion modes.
3 Modelling the assembly of supermassive black holes and their host galaxies

3.1 Merging galaxies, starbursts and AGN

In CDM-like cosmogonies, galaxies build up by hierarchical merging. The formation and evolution of galaxies in such cosmologies has been studied extensively using Monte-Carlo realizations of the hierarchical build-up of galaxies which include simple prescriptions to describe gas cooling, star formation, supernova feedback and merging rates of galaxies. These models reproduce many observed properties of galaxies both at low and at high redshifts [11,13,14,15]. In the models, the quiescent accretion of gas from the halo results in the formation of a disk. If two galaxies of comparable mass merge, a spheroid is formed and the remaining gas undergoes a starburst. We assume here that such major mergers are also responsible for the growth and fuelling of black holes in galactic nuclei. If two galaxies of comparable mass merge, the central black holes of the progenitors coalesce and a few percent of the gas in the merger remnant is accreted by the new black hole. We have made the following assumptions in our model:

- The fraction of cold gas that forms stars over one dynamical time increases with decreasing redshift.
- A fraction $\frac{0.01}{1 + (280/v_c)^2}$ of the cold gas in the merging galaxies is accreted by the black hole, where $v_c$ is the circular velocity of their combined dark matter halo.
- The accretion timescale of the gas scales with the dynamical time, $t_{acc} = 2.5 \times 10^7 [0.7 + 0.3(1 + z)^3]^{-0.5}$ yr.

![Fig. 2. The cosmological mass density in cold gas in galaxies as a function of redshift. The data is taken from Storrie-Lombardi [29].](image-url)
Fig. 3. The correlation between the logarithm of the mass of the central black hole expressed in units of $10^9 M_\odot$ and the absolute V-band magnitude of the bulge. The dots are an absolute V-band magnitude limited sample of bulges in our model. The thick solid line is the $M_V$(bulge) vs. $M_{BH}$ relation obtained by Magorrian et al. [5] for nearby normal galaxies. The dashed lines give an indication of the $1\sigma$ scatter in the observations. The right panels is the prediction for young ellipticals.

- A fixed fraction of the accreted rest mass energy is radiated away in the optical. The luminosity cannot exceed the Eddington limit.

Our assumptions result in a strong decrease of the gas fraction in galaxies with redshift, from about 75 percent at $z = 3$ to 10 percent at $z = 0$. Our model also fits the strong decrease of the overall density of cool gas in the universe as inferred from the incidence rate of damped Ly$\alpha$ absorbers (Fig 2.). Because of this change in gas fraction with redshift, the gas fraction in major mergers that produce bulges is systematically higher for fainter bulges, which form on average at higher redshift. This might explain the systematic differences in the the slope of the stellar density distribution in the cores of high-luminosity and low-luminosity ellipticals [30].

3.2 Remnant black holes in nearby galaxies

Fig. 3 shows scatterplots of black hole mass versus bulge luminosity drawn from absolute magnitude-limited catalogues of bulges produced from our models. The thick solid line shows the relation derived by Magorrian et al. [5] and the dashed lines show the $1\sigma$ scatter of their observational data around this relation. Both the slope and the scatter predicted by our models agree
3.3 Evolution of optically bright QSOs

One of the striking features of the QSO population is their rapid evolution. The observed rapid decline of the space density at low redshift is not trivial to understand. An important clue is probably the similar rapid drop of the overall amount of cool gas in the Universe inferred from the rate of incidence of damped Lyα systems. The solid curve in Fig. 4 shows the model prediction for the evolution of the QSOs with $M_B < -24$ compared to observational data compiled by Grazian et al. 35. The agreement is reasonably good. In our model the strong decrease in quasar activity at low redshift results from a combination of three factors i) a decrease in the merging rates of
intermediate mass galaxies at late times, ii) a decrease in the gas fraction of galaxies with decreasing redshift iii) the assumption that black holes accrete gas more slowly at late times.

3.4 QSO host galaxies

In Fig. 5 we show scatterplots of host galaxy luminosity versus quasar luminosity at a series of different redshifts. For reference, the horizontal line in each plot shows present-day value of $L_*$ for galaxies. At low redshift,
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Quasars with magnitudes brighter than $M_B = -23$ reside mostly in galaxies more luminous than $L_*$. Our results at low redshift agree remarkably well with a compilation of ground-based and HST observations of quasar hosts by Mcleod, Rieke & Storrie-Lombardi [36]. The triangle in Fig. 5 marks the region spanned by their observational data points. At high redshifts, our models predict that the quasars should be found in progressively less luminous host galaxies. This is not surprising because in hierarchical models, the massive galaxies that host luminous quasars at the present epoch are predicted to have assembled recently [13]. The luminosities of quasars hosted by galaxies at different epochs depends, however, on the redshift scaling of $t_{\text{acc}}$. Recently there have been a number of detection of hosts of high redshift QSOs [37,38,39]. Typically these seem to have $\sim L_*$ luminosity, suggesting that our assumed $t_{\text{acc}}$ and its scaling with redshift is indeed correct.

4 Conclusions

There is agreement to within a factor of a few between the black hole mass density inferred from black holes in nearby galaxies and that inferred from the radiation emitted by optically bright QSOs. This is consistent with the possibility that optical bright quasars trace the assembly history of supermassive holes well, but significant accretion in a different accretion mode with a different redshift evolution is also viable.

The large black hole to bulge mass ratio in nearby galaxies argues for a formation mechanism that avoids the intermediate step of a dense stellar cluster. A scenario in which supermassive black holes are assembled by mergers of smaller black holes which formed well before the epoch of optically bright QSOs would require high formation efficiencies (about 10%) in shallow potential wells. The most plausible mechanism by which the mass in a typical present-day supermassive black hole is assembled, is the collapse and accretion of cold gas plus some additional accretion of hot gas and merging of black holes at late times.

It is possible to built a unified model for the evolution of galaxies their central black holes and AGN activity by assuming that black holes and bulges of galaxies form together during the frequent (major) mergers predicted by hierarchical cosmogonies. Such a model can reproduce the observed rapid evolution of the space density of bright QSO with redshift, the mass distribution of remnant black holes in nearby galaxies and the luminosity of QSO host galaxies.

Interesting implications of our model are the following. The typical duration of the optically bright QSO phase should be $10^7$ yr. Young ellipticals should harbour black holes with smaller masses than the spheroid population as a whole. QSO hosts are typically brighter than $L_*$ at low redshift and should become fainter with increasing redshift. Important for the rapid decline of the space density of bright QSOs and the cosmological density of cold
gas, is that the gas fraction in galaxies decreases with decreasing redshift. As a consequence, fainter ellipticals have formed in more gas-rich mergers than bright ellipticals. Supermassive binaries and merging of supermassive binaries should occur frequently in hierachical cosmogonies. The latter is good news for space-borne gravitational wave experiments like LISA [40, 41].

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