Formation and Evolution of Supermassive Black Holes

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Summary. The correlation between the mass of supermassive black holes in galaxy nuclei and the mass of the galaxy spheroids or bulges (or more precisely their central velocity dispersion), suggests a common formation scenario for galaxies and their central black holes. The growth of bulges and black holes can commonly proceed through external gas accretion or hierarchical mergers, and are both related to starbursts. Internal dynamical processes control and regulate the rate of mass accretion. Self-regulation and feedback are the key of the correlation. It is possible that the growth of one component, either BH or bulge, takes over, breaking the correlation, as in Narrow Line Seyfert 1 objects. The formation of supermassive black holes can begin early in the universe, from the collapse of Population III, and then through gas accretion. The active black holes can then play a significant role in the re-ionization of the universe. The nuclear activity is now frequently invoked as a feedback to star formation in galaxies, and even more spectacularly in cooling flows. The growth of SMBH is certainly there self-regulated. SMBHs perturb their local environment, and the mergers of binary SMBHs help to heat and destroy central stellar cusps. The interpretation of the X-ray background yields important constraints on the history of AGN activity and obscuration, and the census of AGN at low and at high redshifts reveals the downsizing effect, already observed for star formation. History appears quite different for bright QSO and low-luminosity AGN: the first grow rapidly at high $z$, and their number density decreases then sharply, while the density of low-luminosity objects peaks more recently, and then decreases smoothly.

1 Introduction

It is now well established that all nearby galaxies possessing a spheroidal stellar component or bulge possess a central black hole (BH), with a BH mass proportional to the bulge mass, with a proportionality factor which is now renormalised around $2 \times 10^{-3}$ (Magorrian et al 1998, Gebhardt et al 2000, Merritt & Ferrarese 2001, Shields et al 2003). It soon appeared that the relation is more precise and with less scatter, between the BH mass and the central velocity dispersion (or dispersion inside the effective radius of the bulge $\sigma_e$), as shown in Figure[1]. The BH-mass grows then close to the 4th power of the central velocity dispersion.

The determination of this relation has been carried out by various methods:
- stellar proper motions for the Galactic center BH (Schödel et al. 2003, Ghez et al. 2003),
- stellar absorption lines, to obtain the stellar kinematics,
- ionized gas emission lines (less reliable, since affected by outflows, inflows), and also masing gas emission lines,
- reverberation mapping, exploiting time delays between variations of AGN continuum, and broad line emission, giving the size of the emitting gas region, combined with the gas Doppler velocity to give the virial mass (Peterson & Wandel, 2000)
- ionization models: method based on the correlation between quasar luminosity and the size of the Broad Line Region (BLR, Rokaki et al. 1992).

The relation has recently been somewhat extended to lower masses, in dwarf Seyfert 1 nuclei, which are more difficult to measure (Barth et al. 2004, 2005). Some progress has also been made in the search of intermediate mass black holes (IMBH), for example in the globular clusters M15 in our Galaxy and G1 in M31: in M15, the mass of the central object is lower than $10^3 M_\odot$ and could be stellar remnants (van der Marel 2003), while in G1, a BH of $2 \times 10^4 M_\odot$ is identified, and obeys the $M_{BH} - \sigma$ relation (Gebhardt et al. 2002). A $1000 M_\odot$ IMBH has also been estimated as member of a binary, at the origin of the ULX source M82 X-1 in the starburst galaxy M82 (Portegies Zwart et al. 2004a).

![Fig. 1. The relation between BH mass and the velocity dispersion $\sigma$ inside the effective radius of the bulge. Filled circles indicate BH mass measurement from stellar dynamics, squares from ionized gas, triangles on maser lines, crosses are from reverberation mapping, and “plus signs” from ionization models (from Kormendy & Gebhardt 2001). The relation is close to a power-law of slope 4.](image-url)
The demography of SMBH, statistics on their activity frequency, and their observed mass functions, constrain the possible AGN life-time and growth rate. It was already suspected that AGN were active during a short duty cycle of $\sim 4 \times 10^7$ yr, and that many galaxies today should host a starving black hole (Haehnelt & Rees 1993). The observed $M_{bh} - \sigma$ relation now strongly constrains the duty cycle time-scale. Also the cosmic background radiation detected at many wavelengths constrains the formation history. The volumic density of massive black holes today is derived, from the observed density of bulges, and the proportionality factor $M_{bh} = 0.002 M_{bulge}$. And independently, the light that should have been radiated at the formation of these BHs can be computed, redshifted and compared to the observed cosmic background radiation: in the optical, we see only 10% of the expected flux, but 30% in X-rays, and 80% in the infra-red. The accretion radiation does not get out in optical light, probably due to the extinction.

2 BH growth

Powerful QSOs are observed early in the universe, at $z>6$, with luminosities indicating very high BH masses, meaning that masses as high as $10^8$-$10^9 M_\odot$ can grow in less than one Gyr. However, the time-scale to grow a black hole from a stellar mass of $10 M_\odot$ to the Hills limit, $M_c$ ($M_c = 3 \times 10^8 M_\odot$), above which stars are swallowed by the black hole without any gas radiation, is of the order of 1.6 Gyr, if the gas accretion occurs at the Eddington limit, and the efficiency is $\epsilon \sim 0.1 - 0.2$ (Hills 1975). The problem is therefore to accelerate the growth rate, or begin from a higher initial mass.

2.1 Quantifying the problem

To have an order of magnitude, and simple dimensional relations, let us assume spherical accretion, from an accretion radius $R_{acc} = 0.3 M_6/v_2^2$ pc, where $M_6$ is the mass of the BH in $10^6 M_\odot$, and $v_2$ the velocity in 100 km/s (corresponding to the effective stellar velocity inside the galaxy nucleus, related to the bulge mass). The canonical Bondi accretion rate is then:

$$dM/dt = 4\pi R^2 v \rho = 10^{-4} M_\odot/yr M_6^2/v_2^3 \rho$$

where $\rho$ is the local density in $M_\odot/pc^3$.

Since $dM/dt \propto M^2$, then the accretion time is $\propto 1/M$, $t_{acc} \sim 10^{-10}$ yr/M_6 v_2^2/\rho; for very low mass BH, this takes much larger than the Hubble time. Therefore the formation of SMBH requires a large seed, mergers of BH, or very large densities, like that characteristic of the Milky Way nucleus, $10^7 M_\odot/pc^3$.

If these conditions are fulfilled, the growth of massive BH can then be accretion-dominated, i.e. $t_{growth} = t_{acc}$. This phase could correspond to moderate AGN, like Seyferts, and the luminosity is increasing as $L \propto dM/dt \propto M^2$. At some point, the luminosity will reach the Eddington luminosity, since $L_{edd} \propto M_{bh}^2$...
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M. The Eddington ratio increases as \( L/L_{edd} \propto M \), the BH growth slows down when approaching \( L_{edd} \), corresponding to a QSO phase. The time-scale of this powerful AGN phase is \( t_{edd} = M/(dM/dt)_{edd} = 4.5 \times 10^7 \text{ yr } (0.1/\epsilon) \) (where \( \epsilon \) is the usual radiation efficiency). Equating \( t_{acc} = t_{edd} \), this occurs for \( M = 2 \times 10^8 M_\odot \). Wang et al. (2000) propose that tidal perturbations help to grow a SMBH from a small seed, by boosting the accretion, and then lead to the \( M_{bh} - \sigma \) relation.

2.2 Formation of the first massive black holes, in the early universe

One solution to the growth problem could be that massive BH form very early at high redshift, as the remnants of Pop III stars. In the CDM scenario of hierarchical structure formation, it is generally thought that the first stars are expected to form in dark matter minihalos of mass \( 10^6 M_\odot \), at redshifts around 20. Their virial temperature is too small for atomic hydrogen cooling to be efficient, but the molecular hydrogen cooling is fast enough (Tegmark et al 1997). Without metals and dust, the \( \text{H}_2 \) molecules form through \( \text{H}^- \) with the electrons as catalysts. The minimum halo mass at a given redshift, in which the baryons are able to cool and form stars is obtained through the condition that the cooling time is smaller than the dynamical time, and is confirmed to be \( 10^6 M_\odot \), at \( z \approx 20-30 \) (Fuller & Couchman 2000). Both semi-analytical estimations, and full 3D numerical simulations concur to find very massive first stars, with \( M^* > 100 M_\odot \) (e.g. Abel et al 2002, Bromm & Larson 2004). Fragmentation is quite inefficient for these first condensations, due to the low metallicity and negligible radiative losses. The mass spectrum of these first stars is still not well known, but according to the cosmology, it is expected that the most massive structures are significantly clustered.

Above \( 260 M_\odot \), the formed objects could collapse to a BH directly (Bond et al 1984, Madau & Rees 2001, Schneider et al. 2002). After the first subhaloes have merged in larger entities, and formed dwarf galaxies, there could exist \( 10^5 M_\odot \) IMBH in each center, formed by the merging of these seeds.

The total mass in these first black holes can be quite important. If every halo corresponding to a 3 sigma peak (or higher) at \( z=24 \) forms a \( 260 M_\odot \) BH, then the density per comoving volume is estimated at \( \rho_* = 2.910^5 M_\odot/\text{Mpc}^3 \), already half of the present SMBH density (Islam et al 2004). It will then be sufficient to add some gas accretion to grow the BH along their lives, and to ensure the merging of all seeds. The problem at this stage is however the low efficiency of dynamical friction for objects that are still not massive enough. The consequence is that many BH will keep orbiting around subhaloes, instead of sinking to the main center. Semi-analytical merger-tree calculations have been carried out, taking into account dynamical friction, tidal disruption and encounters with the galactic disk, to determine the abundance and distribution of MBHs in present-day haloes of various masses (Islam et al 2004): the result is that it is difficult to reproduce the observed mass distribution of SMBH with only merging of the initial seeds, and that further gas accretion is required. Also the formation of binaries at the center of structures require gas accretion in order for the binary
BH to merge before a triple is formed and some BH are lost in intergalactic space.

The consequence of low merging efficiency of the seed BH is the predicted large abundance of these intermediate mass BH in a given galactic halo (cf Figure 2): typically a thousand or more should exist in the Milky Way. Coming from rare high density peaks, they are expected to cluster in the bulges and spheroids; when they accrete gas, they could account for ultra-luminous X-ray sources (ULX) which are offset from the galaxy centers. In particular, masses typical of large IMBH, i.e. $10^5 M_\odot$, should reach the number of $\sim 10$ in the Galaxy. Also, it is found that hierarchical merging can only be responsible of 10\% of the total mass of present SMBH, and that gas accretion should be responsible for the rest. Taking into account the progressive gas accretion along the BH growth leads to a present SMBH density comparable to what is observed (Volonteri et al 2003a), and also to a large number of wandering IMBHs.

Numerical simulations show that the $M_{\text{bh}}-\sigma$ relation can indeed be conserved through several successive mergers, provided that gas dissipation and star formation is included at each merger (Kazantzidis et al 2005); collisionless mergers could cause some scatter in the relation.

2.3 Mini-quasars and reionization

An intense UV background is expected from the first stars. These stars are so massive that they create an HII region around them, able to blow away all the gas from the mini-halo where they are seated (Whalen et al 2004). The UV photons in the Lyman-Werner bands are able to photo-dissociate the fragile H$_2$ molecules in the neighbourhood, preventing the gas to cool down. Star formation will be inhibited in a large region, until accumulation of gas creates dense regions able to be shielded.

At the death of the first stars, the massive black holes created from merging of the seeds, could accrete gas and become mini-quasars, able to produce a harder radiation background, including hard and soft X-rays. It has been argued that these X-rays could have a positive feedback on the formation of the H$_2$ molecules in producing electrons, and compensate for the negative feedback of the UV background (Haiman et al 2000). However, 3D detailed simulations, find that the positive feedback is barely sufficient (Machacek et al 2003).

A fundamental question is to know precisely at which epoch the inter-galactic hydrogen has been completely re-ionized, ending the dark age, and whether this has been done essentially through stellar radiation of from mini-quasars. The discovery of the Gunn-Peterson trough in some $z>6$ quasars of the Sloan Survey (Becker et al 2001) suggests that reionization is occurring near $z=6$, while the WMAP result of a high electron scattering optical depth implies that ionizing sources were present up to $z=15$, suggesting a long reionization period, may be in two steps (very massive stars at $z=15$, and after a feedback epoch, much less massive stars at $z=6$). The possibility of mini-quasars as the source of reionization has been studied by Dijkstra et al (2004), in view of the X-ray background
2.4 The case of IMBH

Does the $M_{bh} - \sigma$ relation extrapolates to low masses? At least below $10^6 M_\odot$, the extrapolation appears straightforward (Barth et al. 2005), however, it is difficult to bridge the gap towards the low end of intermediate mass black holes (of $10^3 M_\odot$); their observation is very difficult, both by the kinematics, since their gravitational influence is small, and from their possible AGN activity, since the expected luminosity is weak. According to the extrapolation of the $M_{bh} - \sigma$ relation, these IMBH should be searched as AGN in dwarf galaxies: among the good candidates are NGC 4395 (Filippenko & Ho 2003), where the BH mass is likely to be $10^4$-$10^5 M_\odot$ (radiating much below the Eddington limit), or Pox 52,
with $\sim 210^5 M_\odot$ (Barth et al 2004). The problem of this search is that dwarf galaxies frequently host nuclear star clusters of $\sim 10^6 M_\odot$, hiding the weak AGN. They are best observed in the Local Group; a famous example, M33, does not host any BH more massive than $10^3 M_\odot$, which is already 10 times below the value expected from the $M_{bh} - \sigma$ relation (cf figure 3).

![Diagram](image)

Fig. 3. Extension of the $M_{bh} - \sigma$ relation to IMBH (from Barth et al. 2005). Points in the upper right are black holes with dynamical mass measurements compiled by Tremaine et al (2002). Open circles represent stellar-dynamical measurements, filled triangles are gas-dynamical detections, and crosses are from H$_2$O maser observations. In the middle of the diagram, filled circles are the SDSS Seyfert 1 galaxies studied by Barth et al (2005). The low mass points are indexed by their galaxy name. Note the upper limit for any black hole mass in M33 by Gebhardt et al (2001).

One of the main features of lower mass IMBH is that they are no longer unique objects at the very center of the galaxies, but could be found in large numbers, spread out in galaxy haloes. The dynamical friction is no longer efficient enough, and their formation mechanism, through mergers of lower mass black holes through binary coalescence could provide them randomly large velocities (Ebisuzaki et al 2001).
X-ray observations have revealed in nearby galaxies a class of extranuclear point sources with X-ray luminosities of $10^{39}$-$10^{41}$ ergs/s, exceeding the Eddington luminosity for stellar mass objects. These ultraluminous X-ray sources (ULXs) may be powered by intermediate-mass black holes of a few thousand $M_\odot$ or stellar mass black holes with special radiation processes.

Liu & Bregman (2005) find a strong association between ULXs and star formation sites, ULXs are preferentially observed in late-type galaxies, in spiral arms, and in some cases associated with supernovae. However a few ULXs are observed in old globular clusters, and Colbert et al (2004) find them associated with population II stars, in particular in elliptical galaxies.

These ULX sources could be due to intermediate black holes resulting from the mergers of massive BH seeds, formed out of Population III objects in the early universe (Volonteri & Perna 2005). The large number of BH formed can merge in galaxies, through binary coalescence, but the possibility of a triple association, followed by the ejection of one of the BH, and recoil of the binary, leads to the predicton of many IMBHs wandering through the haloes. To be observed radiating at the high end of X-ray luminosity, these sources must be associated to baryons, and the most probable locations are in the disk of late-type galaxies (Volonteri & Perna 2005).

There are however observational problems in the interpretation of ULXs in terms of IMBH (Makishima et al 2000). In most of them, the inner disk temperature is observed around 2kev, too high to be compatible with the high black hole mass, as required with the IMBH hypothesis, radiating at Eddington luminosity. They might be a mixed-bag class of objects, some could result from beamed emission during a short phase of common X-ray binaries, and they could be related to micro-quasars. This would explain their relation to star formation region. (e.g. King et al 2001). Some could represent the intermediate mass black hole, expected in the continuity of SMBHs. An interesting case is the ULX source right at the nucleus of M33 which nature is still debated (Dubus & Rutledge 2002). The central source corresponds to radiosources expected for micro-quasars (Trejo et al 2004).

Evidence for an IMBH could come from the Milky Way nucleus: Hansen & Milosavljevic (2003) propose its existence to explain the observation of bright stars orbiting within 0.1pc, which are are young massive main-sequence stars, in spite of an environment hostile to star-formation. Alternative solutions could be star mergers, or exotic objects (Ghez et al. 2003). In the IMBH scenario, stars were formed in a star cluster outside the central pc, and then dragged in by a BH of $10^3$-$10^4$ $M_\odot$. The decay time-scale by dynamical friction for normal stars is too large (much longer than the massive stars life-time), but for the IMBH, this time-scale is 1-10 Myr. Stars may be dragged inwards even after the star cluster has been disrupted.

Such a system SMBH-IMBH and a gas disk may reveal interesting dynamics; it is similar to a protosolar system, with the Sun-Jupiter couple, resonant effects like planetary migration are expected (Gould & Rix 2000).
2.5 NLS1 and black hole growth

The $M_{bh} - \sigma$ relation has been established locally, and it is not yet known whether the relation was already there in the primordial structures, and then was maintained during the evolution by a feedback process, or was obtained progressively, without maintaining a permanent relation.

There might be phases in the life of a galaxy, where the star formation has some advance with respect to the black hole growth, according to the various feedback and regulating mechanisms, and we should be able to recognize a subclass of AGN where the BH-mass is somewhat below the standard relation. This has been proposed by Mathur (2000) for Narrow Line Seyfert 1 galaxies (NLS1). Grupe & Mathur (2004) investigated the BBR relation for a sample of broad-line Seyfert 1 galaxies (BLS1s) and narrow-line Seyfert 1 galaxies (NLS1s), and confirm that NLS1s lie below the BBR relation of BLS1s. As a consequence, black holes grow by accretion in well-formed bulges, possibly after a major merger. As they grow, they get closer to the BBR relation for normal galaxies (Mathur & Grupe 2005). The accretion is highest in the beginning and then decreases with time. There is no AGN feedback for the control of bulge growth there.

Kawaguchi et al (2004) estimate that the NLS1 phase is characterized by very efficient accretion, at a super-Eddington rate; given the high frequency of these objects (10 of all AGN), and the average duty cycle for an average AGN phase ($10^7 - 10^8$ yrs), the essential of the BH growth is occurring during this phase: the BH grows by up to 1-2 orders of magnitude, while in the BLR phase (the most frequent and common phase) at sub-Eddington rate, the BH will only multiply its mass by about 2.

When the accretion rate is much larger than Eddington, the accretion is occurring not through a "thin" but a "slim" disk, with a cooling time larger than the viscous time, so that energy is advected towards the BH before being radiated. The luminosity can then saturate, and never be larger than a few Eddington luminosity. According to the type of BH, the accretion rate can range from 60 (Schwarzschild BH) to 300 Eddington accretion rate (Kerr BH). Whatever these accretion rates, and whatever the mass of the BH, the luminosity is always no more than 10 Eddington luminosities, as shown in Figure 4 and the accretion rate a few M$c$/yr (Collin & Kawaguchi 2004). This is a strong indication of a mass-limited supply, with an external mechanism to regulate the accretion.

2.6 Down sizing, and life-time of activity

It is now well known that the physics of baryons, both the star formation, and gas accretion by black holes, act to compensate the hierarchical formation of dark matter haloes, which grow larger and larger with time: the most massive star-forming galaxies and the most massive SMBH are forming at high redshift, early in the universe, while only smaller masses are assembling now (Cowie et al 1996). Semi-analytic follow up of these processes have succeeded to reproduce the down sizing, and taking into account the constraints of luminosity functions.
Fig. 4. The Eddington luminosity ratio $R_{\text{edd}}$ as a function of $\dot{m}$, the accretion rate in Eddington units, $\dot{m} = \dot{M}c^2/L_{\text{edd}}$, for the NLS1 sample of Grupe & Mathur (2004). The luminosities are computed with the standard disc (open squares) and the self-gravitating disc (filled squares). The two curves correspond to the slim disc model, and respectively a Schwarzschild and a Kerr BH (from Collin & Kawaguchi 2004).

of galaxies and AGN at all redshifts can teach us more on the formation of the objects, and for instance on the duty-cycles or life-time of activity.

Using the observed correlations between X-ray and radio luminosities of quasars and their black hole mass, Merloni (2004) has computed the past history of SMBH, assuming their growth is only due to gas accretion. The accretion rate, and radiative regime (Eddington or not) is not fixed, but derived by the model. The results show a clear anti-hierarchical growth of the black holes, as shown in Figure 5. The most massive SMBH are in place at high redshift, while at low redshift only smaller mass black holes are accreting, so that the average BH mass of observable AGN is increasing with redshift. The life time of activity is also varying with redshift, being shorter at early times. The mean life time is defined by the average over the activity of the time, weighted by the accretion rate. It is not imposed to be the doubling time of the mass at the Eddington rate, i.e. the Salpeter time $t_s = \epsilon Mc^2/L_{\text{Edd}} = 4.510^7$ yrs. The life time ranges from $10^7$ yrs to assemble $10^9M_\odot$ at $z=3$, up to $10^8$ yrs to assemble $10^7M_\odot$ at $z=0$ (Merloni 2004).
2.7 Quasar life times

The quasar life time can be estimated from the observations of the AGN demography, through the statistical argument that the fraction of active nuclei among the whole number of SMBH present in every early-type galaxy is a measure of the time spent in the active phase. The observation of the proximity effect (presence of an ionized region around the quasar host) puts already a lower limit to the life time of $10^4$ yrs. The life time is defined as the total active time of a quasar, i.e. if the same quasar experiences episodic activity, the life time is the sum of the duration of the active phases. The minimum life-time of $10^4$ yrs is for one episode only. The various methods to estimate the quasar life time have been reviewed by Martini (2004), and results in values between $10^7$ and $10^8$ yrs, quite close to the Salpeter time, or mass doubling time, assuming Eddington luminosity, and with efficiency $\epsilon = 0.1$. One of the longest duration of an episode may be derived by the observed length of radio jets, about $t_Q \sim 10^8$ yrs. Through the measurement of the AGN-galaxy cross-correlation length, Adelberger & Steidel (2005) conclude that high and low luminosity AGN are both found in haloes of similar masses, and therefore the higher observed frequency of faint AGN must imply that their duty cycle is much longer than for bright AGN, of a few Gyr.

All these estimations are compatible to the hypothesis that the active phases of bright AGN are triggered by a major merger between two gas rich galaxies, that removes angular momentum and drives the gas towards the center (Barnes & Hernquist 1992). This hypothesis is supported by the frequent association between quasars and interactions (e.g. Hutchings & Neff 1992). However, it is possible that the observed quasar life-time is biased in the observations, if the active phase, where the BH grows and radiation is emitted, is partially obscured by dust, as expected when a lot of gas is driven towards the galaxy centers, in the beginning of the activity. Hopkins et al (2005) have estimated the importance of this obscuration phase in numerical simulations, and find that the quasar life time is then reduced from an intrinsic value of 100 Myr, to an observable value of 10-20 Myr.
3 Interpretation of the $M_{bh} - \sigma$ relation

Several models have been proposed to account for the relation, all involving a simultaneous formation of bulges and SMBH, and constraining the feedback processes.

3.1 Radiative feedback

Although the radiative feedback is not the most efficient, it can play an important role at the end of the feeding of a giant black hole in an elliptical galaxy, which by definition does not possess much gas. Sazonov et al (2004) have computed the equilibrium temperature $T_{eq}$ of the gas around a quasar, heated by Compton scattering and photoionization, and cooled by continuum and line emission. When $T_{eq}$, which is proportional to $L/(nr^2)$ becomes larger to the virial temperature of the galaxy, proportional to the velocity dispersion $\sigma^2$, the gas is expelled, and the fueling is stopped. This occurs when the density $n$ becomes lower than a critical density, $n_{crit} \propto L/(r^2\sigma^2)$. Assuming that the gas distribution follows the stellar distribution, which is isothermal, with an $r^{-2}$ radial profile, then the equilibrium temperature is constant with radius, and inversely proportional to $\sigma^2$. At the critical regime, when $T_{eq} = T_{vir}$, the maximum BH-mass is then proportional to $\sigma^4$, and its growth is stopped. The radiative feedback then could explain the $M_{bh} - \sigma$ relation, for massive ellipticals, with very low gas mass content (Sazonov et al 2005).

3.2 Feedback due to QSO outflows

QSO and stars main cosmic formation epoch coincide (e.g. Shaver et al. 1996). Their common formation could be regulated by each other, and the QSO outflows prevent star formation (Silk & Rees 1998). The condition for the wind to be powerful enough to give escape velocity to the gas constrains the BH mass to $M_{bh} \propto \sigma^5$, which from the Faber-Jackson relation, gives $M_{bh} \propto M_{bulge}$. But the phenomenon is assumed spherical, in reality jets are collimated, the gas is clumpy, and compressed to form stars.

The mass of the SMBH in a Galaxy is quite negligible, lower than $10^{-3}$ in general, and the distance to which the gravitational action is significant is quite small, less than 100pc even for the more massive BH. But the energy that the SMBH can radiate or expel as jets, winds or outflows, is relatively large, in comparison to the binding energy of the gas component in the Galaxy, and therefore, the energy output of the AGN could have some significant feedback action, in stopping the gas inflow favoring the accretion (Wyithe & Loeb 2002). Let us note that the binding energy of the gas, rotating at circular velocity $v_c$ in the galaxy, is of the order of $(v_c/c)^2 \sim 10^{-6}$ of its rest mass, while the energy output of the AGN could be much larger, around 10% of the rest mass energy, so that the accretion of only a fraction $10^{-5}$ of the gas mass will be sufficient to release its binding energy.
This could explain the relation between the mass of the black hole and the central velocity dispersion, as a self-regulation mechanism. If the binding energy of the system of mass $M$ is of the order $M \sigma^2$, and its dynamical time $r/\sigma$, the typical energy per dynamical time is $M \sigma^3/r$. Eliminating the mass through the virial relation $M \sim \sigma^2 r/G$, the typical energy rate or luminosity is $\sigma^5/G$. This can be considered as the maximum luminosity of the black hole before unbinding the system hosting it. Equating this to the Eddington luminosity, relates the mass of the black hole to $\sigma^5$ with an order of magnitude quite comparable to the $M_{bh} - \sigma$ relation observed (Silk & Rees 1998, Ciotti & Ostriker 2001). The proportionality factor takes into account the low coupling of the energy of the quasar (wind, outflows) to the galaxy gas. About 5-10% of the energy of the quasar must be absorbed by the galaxy to explain the self-regulation. Also the self-regulation might account for the maximum mass observed for SMBHs, which are never more massive than a few $10^9 M_\odot$.

The principle of the self-regulation is welcome to account for the very short duty cycle of nuclear activity in galaxies. The statistics of the number of AGN with respect to the quiescent SMBH in all galaxies leads to a duty cycle as short as $10^7$ to $10^8$ yrs, according to the strength of the AGN. The duty cycle is of the same order as the dynamical time of the gas feeding the AGN.
3.3 Models based on self-regulation growth

The detailed computation has been done by several groups, with different assumptions. The main lines are that the BH grows as long as the energy released in the galaxy is lower than the binding energy. If the heated gas can cool with a sufficiently short time-scale, more energy is required for the feedback, by a factor up to $c/\sigma$, and the resulting relation is then $M_{\text{bh}} \propto \sigma^4$. The mass function of quasars is obtained, assuming that the BH grows in galaxy mergers (Kauffmann & Haehnelt 2000), both by the merging of the BH, and also by gas accretion falling during the interaction. The quasars are assumed to radiate at Eddington luminosity during their duty cycle, which is comparable to the dynamical time of the feeding system. The peak in the quasar luminosity function at $z \sim 2$ is obtained through the merging history, since it coincides to the peak of the formation of massive ellipticals, while the galaxy clusters are forming. The maximum BH masses correspond to the maximum galaxy masses, obtained at these epochs. The models then should cut off the gas infall in haloes with velocity larger than 500 km/s typically (cf Figure 5). These systems correspond to small clusters of galaxies, where the hot gas cannot cool to fuel a central SMBH. The duty cycle of quasars of $3 \times 10^7$ yrs corresponds also to the peak of quasar luminosity at $z \sim 2$, but this time scale must be shorter at high redshifts.

The main conclusions of these models is that 80-90% of the SMBH mass has been already accreted at $z \sim 1.5$ (Wyithe & Loeb 2003). The total light in galaxies can be also modelled according to the same ideas, assuming that star formation is regulated by feedback, and ceases when an energy comparable to the binding energy is released (Dekel & Woo 2003). However, the dependence in redshift of the efficiencies to accrete mass for black holes and star formation is not the same, and therefore the $M_{\text{bh}} - \sigma$ relation should be $z$-dependent. Only the $M_{\text{bh}} - \sigma$ relation should be constant. Indeed for a given dark halo mass, the dependence of the stellar mass is in $(1 + z)^5/2$, and the ratio is $\sim (1 + z)^{3/2}$. The BH mass is larger with respect to the stellar mass at high redshift, with the same $M_{\text{bh}} - \sigma$ relation, since stellar systems are more centrally condensed at high $z$.

The influence of AGN feedback due to energetic winds can be studied through numerical simulations, adopting simple recipes for the accretion of gas by the growing black holes, and energy release through winds in the interstellar medium. Di Matteo et al (2005) have then compared major mergers between two spiral galaxies with and without the presence of BH, and shown the dramatic difference between the star formation rate, and the presence of gas in the remnant. A series of such simulations, where the star formation rate and BH accretion rate are self-regulated, can yield at the end the $M_{\text{bh}} - \sigma$ relation in the present remnants.

3.4 AGN feedback and cooling flows

The self-regulation between accretion and feedback appears to be at work in elliptical galaxies, where the cooling of the gas is only intermittent, and at larger scale in galaxy clusters, where huge cooling flows are impeded through re-heating
by the central AGN. Ciotti et al (1991) and Binney & Tabor (1995) developed the regulating mechanism, based on the two opposed sources: mass loss from evolving stars fuels the galaxy in gas, and the heating by Type Ia supernovae keeps it far from the cold phase, but with a faster declining efficiency. Since the heating by supernovae cannot compensate for the mass drop out, there must occur a cooling catastrophe, fueling the central black hole now known to be present in every elliptical galaxy. The energy release during the short active phase reheats efficiently the gas, which is then the source of X-ray radiation. The intermittent AGN phases are schematically shown in Figure 7, revealing relaxation oscillations.

At larger scales, it has become evident in recent years, thanks to the progress of X-ray observations by Chandra and XMM-Newton, that cooling flows in galaxy clusters are completely different from the stationary, symmetrical and abundant phenomenon expected by simple theoretical ideas. The X-ray observations have constrained the amount of cool gas observed, and the cooling rates have been reduced by at least one order of magnitude; the old view of quiet and regular, quasi-spherical cooling has given place to partial and intermittent cooling, perturbed by re-heating and feedback processes due to the central AGN. The compensation of cooling and heating could even be used to measure the
power of the AGN (Churazov et al 2002). A spectacular illustration of this perturbed cooling is the Chandra image of the cooling flow in Perseus, with bubbles, shocks, gas streaming up and down from the center, and ripples looking like emitted sound waves (Fabian et al. 2003). In the same time, cold gas in the form of CO molecules were observed in dozens of cooling flows (Edge 2001, Salomé & Combes 2003), and the amount of cold gas corresponds to the order of magnitude expected by the revised cooling rates. High spatial resolution observations show that the cold gas is associated to the dense X-ray gas, compressed by the AGN lobes, and is present around the cavity created by the lobes (cf Figure 8). In these dense regions, star formation occurs, and HII regions are observed.

All these new observations concord to draw a picture where the cooling flows are intermittent, and the AGN feedback is self-regulating both the growth of the central black hole mass, but also the amounts of star formation in the central galaxy.

Fig. 8. Cold gas associated to the Abell 1795 cooling flow: Left CO(2-1) map obtained with the IRAM interferometer, from Salomé & Combes (2004). The AGN is indicated by the white ring. Right Hα+[NII] line emission (grey scale), with 6cm contours from van Breugel et al. (1984).

3.5 Hierarchical models of galaxy formation

The mass assembly of supermassive black holes in galaxies, simultaneous to the build-up of their stars can well be integrated in the CDM scenario of hierarchical formation, and the \( M_{bh} - \sigma \) relation follows (Haehnelt & Kauffmann 2000). The main hypotheses of the model are that black holes are essentially assembled in galaxy major mergers, which simultaneously form starbursts, elliptical galaxies, and fuel a QSO phase. An additional assumption is that the fraction of gas transformed into stars per dynamical time increases along the Hubble time, while the available gas fraction in galaxies decreases, as does the rate of gas accretion by galaxies. The required gas fraction accreted by the black hole grows
with the mass of the halo, and the accretion time scales with the dynamical time.

In this model, the scatter in the $M_{\text{bh}} - \sigma$ relation is due to:

- $M_{\text{gas}}$ of the bulge progenitor depends on $\sigma$, but not on the formation epoch of the bulge, while $M_*$ depends on both;
- mergers move the galaxies on the $M_{\text{bh}} - \sigma$ relation, even at the end, when there is only BH mergers, and not enough gas left to grow the black hole.

The gas fraction in galaxies falls from 75% at $z=3$ to 10% at $z=0$. The gas fraction in major mergers is higher in fainter spheroids that form at high $z$, which are more concentrated. Elliptical/spheroids forming recently have smaller BH.

Typically a seed BH of $10^6 M_\odot$ forms at $5 < z < 10$ and then gas is accreted. For a typical SMBH, about 30 black holes are merged. Today black holes in big ellipticals accrete only by merging with small galaxies, but in the past gas accretion was dominant.

Both the number density of quasars as a function of redshift, and the evolution of gas abundance are found compatible with observations. The required duration of a QSO phase is $10^7$ yrs (Haehnelt & Kauffmann 2000).

### 3.6 Feedback through bars in spiral galaxies

If quasars, which are the high luminosity end of the AGN population, are clearly associated with interactions and mergers (Hutchings & Morris 1995), it is difficult to trace evidence of dynamical triggering mechanisms for milder AGN, like Seyfert or LINERS in spiral galaxies (e.g. Combes 2003).

The accretion rates required are of course very different, of the order of a few $10 M_\odot$/yr for quasars, and more than two orders of magnitude less for nearby Seyferts, so that the dynamical processes are much less violent, for Low Luminosity AGN (LLAGN). However, most SMBH in galaxies today have been built by gas accretion, since the successive mergers of BH from the primordial ones are far insufficient (Islam et al 2004), so it is of prime importance to understand the dynamical processes responsible for gas accretion in the nearby LLAGN, that can be studied in details.

Non-axisymmetries, and essentially bars, are the main providers of gravity torques, that will make the gas lose its angular momentum, and infall towards the center. This is the main mechanism both for isolated galaxies with spontaneous bar instabilities, and also during galaxy interactions, that favor bar instability: bars are then the way to propagate tidal interactions in the inner parts of galaxies (e.g. Barnes & Hernquist 1992).

The feedback mechanism due to the energy released by the AGN, such that studied for cooling flows in elliptical galaxies (Ciotti et al 2001) might not be efficient here, because of the low luminosity of LLAGN, and also the low coupling with the gas in a disk. Instead, other intrinsic feedback mechanisms exist, related to the dynamical mechanisms themselves that drive the gas to the center. In these cases, the $M_{\text{bh}} - \sigma$ relation could be explained only with the feedback mechanisms
related to bars, that both can be responsible for bulge and BH formation (e.g. review in Combes 2001).

The demographics of nearby AGN reveals that LLAGN exist in about 40% of all galaxies, and they tend to lie in early-type galaxies (Terlevich et al 1987, Moles et al 1995). In an optical spectroscopic survey of 486 nearby galaxies, Ho et al (1997) detected 420 emission-lines nuclei (86% detection rate). Half of these objects can be classified as HII or star-forming nuclei, and half as some kind of AGN: Seyfert, LINERs and transition objects LINER/HII. A signature of Broad Line Region is found in 20% of the AGN, while Seyfert nuclei reside in about 10% of all galaxies. AGNs are found predominantly in luminous, early-type galaxies, while HII nuclei are in less luminous late-type objects, which is compatible with the \( M_{bh} - \sigma \) relation.

Bars are present in roughly two thirds of spiral galaxies. The frequency of bars and non-axisymmetries has recently been quantified in details from near-infrared surveys (Block et al 2002, Laurikainen et al 2004), and the fraction of bars does not seem to vary with redshift (e.g. Jogee et al 2004). Since bars are observed to have a suicidal behaviour in spiral galaxies with gas (e.g. Hasan et al 1993, Friedli & Benz 1995), bars must be reformed to explain their frequency (Bournaud & Combes 2002). The bar is destroyed by two main mechanisms: first the central mass concentration built after the gas inflow, destroys the orbital structure sustaining the bar, scatters stellar particles and pushes them on chaotic orbits (Hozumi & Hernquist 1999; Shen & Sellwood 2004). Second, the gas inflow itself weakens the bar, since the gas loses its angular momentum to the stars forming the bar (Bournaud & Combes 2005). This increases the angular momentum of the bar wave, in decreasing the eccentricity of the orbits.

This bar destruction is reversible, and other bar episodes are driven by external gas accretion, replenishing the gas disk (cf Figure 4). A typical spiral galaxy is in continuous evolution, and must accrete gas all along its life, both to maintain its star formation rate, and its spiral and bar structure. The amount of gas required is able to double the galaxy mass in about 10 Gyr. This gas cannot be provided by accretion of gas-rich dwarf galaxies, since the interaction with companions would heat and destroy the disk. Instead, cold gas from cosmic filaments must inflow to replenish the galaxy disk; this can decrease temporarily the bulge-to-disk ratio, making the disk more self-gravitating, and triggering another bar instability. Several bar episodes can succeed each other in a Hubble time, through this dynamical feedback. At each bar episode, both bulge and BH grow in a similar manner, which explains the \( M_{bh} - \sigma \) relation.

It is then more easy to understand the lack of correlation between the presence of bars and nuclear activity in spiral galaxies. The gas is driven to the very center only intermittently, through the action of a secondary nuclear bar, or even viscous torques, once the primary bar has been dissolved by the main gas flow (García-Burillo et al 2005). The first gas flow is frequently stalled at the inner Lindblad resonance, responsible for a nuclear starburst. Only when the bar has dissolved, can the gas fuel the nucleus. The activity of the nucleus can occur in short episodes, which time scales are much shorter than the bar formation and dissolution time scales, which are of the order of 1 Gyr.

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There are however some components, like resonant rings in galaxy disks, which are the remnants of the presence of bars in galaxies: once the bar has dissolved, the rings survive for some more time, from stars formed in the previously gaseous rings (e.g. Buta & Combes 1996). Unbarred galaxies observed with three resonant rings can be considered as good evidence for the bar dissolution phenomenon. The presence of outer rings has been found to be predominant in Seyfert galaxies (Hunt & Malkan, 1999, and Figure 10).

3.7 Other mechanisms

Since the relation between BH and bulge mass does not include the disk, ideas to involve only a spheroidal system in the required angular momentum transfer, led to the radiation drag from the bulge stars. The relativistic drag force by the radiation from bulge stars is exerted on the dusty gas distributed spheroidally in the bulge. In practice, the radiation drag saturates in case of optical thickness, but the optically thin envelope of interstellar clouds is stripped, loses angular momentum, and is accreted by the center (Umemura 2001). The $M_{bh}/M_{bulge}$ is then an universal constant depending only on the energy conversion efficiency for nuclear fusion of hydrogen to helium. The efficiency of nuclear reactions in stars is $\epsilon = 0.007$, which would predict a too important ratio between BH and bulge mass. The efficiency falls as $1/\tau^2$, with $\tau$ the optical depth of the gas. Also the radiation drag could be strongly subject to geometrical dilution.

The global scenario relates the ultra-luminous infra-red starburst phase and the formation of a quasar. During the first phase, a large number of stars are formed, while the black hole is still growing. In this phase, the BH-to-bulge mass ratio is well below the present relation (such as has been proposed for
Fig. 10. Fraction of inner and outer rings in galaxies as a function of their activity class. Rings are thought to be formed at resonances with bars, near the corotation, for the inner rings, and the OLR (Outer Lindblad Resonance) for the outer rings. Only objects with $v < 5000 \text{km/s}$ are shown (from Hunt & Malkan 1999).

NLS1, Mathur 2000). Then at the end of the starburst phase, the black hole has grown, and radiates at maximum luminosity, in its QSO phase, while the optical thickness of the interstellar medium decreases. Then the black hole ends up its growing phase, with the well-known ratio between BH and bulge mass. Today this mechanism is no longer inefficient, since elliptical galaxies and bulges have no gas. The mechanism has been quantified, with the radiative transfer in a clumpy medium by Kawakatu & Umemura (2002). This idea has the advantage to explain why the BH mass is not proportional also to the disk mass, where radiation drag loses its efficiency due to dilution and optical thickness (Kawakatu & Umemura 2004).

Also related to the formation of a starburst in a first phase, is the formation of Super Star Clusters (SSC) in the centers of galaxies (e.g. de Grijs et al 2001). Sinking of these Super Star Clusters in their dark halo, due to dynamical friction, has been proposed to form cuspy stellar bulges (Fu et al. 2003); the merging of small BH associated to clusters would provide a mass ratio $M_{bh}/M_{bulge} = 10^{-4}$ only, slightly below what is observed. Some intermediate mass black holes (IMBH) of masses 800-3000 $M_{\odot}$ would form easily in dense and young star clusters (Portegies Zwart et al 2004b).
4 Stellar cusps and cores and binary black-holes

The supermassive black hole present in every spheroid, has a gravitational influence on its stellar environment. It can form a cusp, through gravitational attraction, or a hole by swallowing the low angular momentum stars in the neighbourhood, or flatten a core, through interaction with another merging black hole. The observation of the stellar profile in galaxy centers can then teach us the formation history of the SMBH (e.g. Merritt 2004).

Observed is a well known dichotomy between massive and small ellipticals (e.g. Lauer et al 1995):

- Cusps (steep power-law in stellar central density profile) are characteristic of low-mass ellipticals, with disky isophotes and weak rotation;
- Cores (flat central density profile) are found in high-mass galaxies, with boxy isophotes and no rotation.

4.1 Formation of a cusp of stars around the black hole

The density profile in the stellar component around a massive black hole depends on the relative value of the 2-body relaxation time scale with respect to the Hubble time, or more precisely with respect to the formation time of the black hole.

The relaxation time can be expressed by

\[ T_{\text{rel}} = \frac{V^3}{8\pi G^2 m \rho(r) \log(\Lambda)} \]

where \( V \) is the mean relative speed between the stars, \( m \) the mean stellar mass, and \( \rho(r) \) the volumic density in the nucleus (\( \log(\Lambda) \) is the Coulomb parameter). It is well known that globally in a galaxy, the relaxation time is much longer than the Hubble time, it varies approximately as \( 0.2(N/\log N) t_c \), if \( N \) is the total number of stars in the system, and \( t_c = R/V \) is the crossing time. However, the relaxation time becomes shorter than the Hubble time in dense systems like globular clusters, and the nuclear stellar clusters may also approach these conditions (small \( N \)). For the galactic center, with a volumic density of stars of \( 10^7 M_\odot/pc^3 \), \( <V^2>^{1/2} = 225 \text{ km/s} \), this relaxation time is \( 3 \times 10^8 \text{ yr} \).

Young (1980) has computed the adiabatic growth of a black hole inside a nuclear stellar cluster: the growth rate is assumed to be longer than the cluster dynamical time scale but shorter than the relaxation time scale. Then a stellar cusp forms, stars being attracted by the black hole. The power-law profile has a slope larger then 2, up to 2.5. Two regimes can be distinguished, according to the initial mass of the black hole, the slope being larger for more massive black holes (Cipollina & Bertin, 1994).

If 2-body relaxation can take place among the stars, then the cusp is less pronounced, and the slope is 1.75 \((7/4)\) (Bahcall & Wolf 1976). N-body simulations can retrieve asymptotically this result, cf Preto et al (2004) and Figure 11.

The black hole can grow by swallowing the nearby stars, that have an angular momentum lower than \( J = (2GMm_b r_t)^{1/2} \), with \( r_t \) being the tidal radius, beyond which a star is disrupted by the black hole. After a dynamical time, if 2-body
relaxation does not refill these particles in the loss-cone, the black hole will starve. In fact, the angular momentum can diffuse faster than the energy (faster than the stellar relaxation time $T_{\text{rel}}$), and the low angular momentum stars are replenished faster, which increases the accretion rate to $T_{\text{rel}} (1-e^2)$, with $e$ the excentricity of the orbits (Frank & Rees 1976, Lightman & Shapiro 1977). It is possible that black holes less massive than $10^7 M_\odot$ can be formed only through stellar accretion.

**Fig. 11.** Evolution of the mass density profile around a massive black hole: **Left:** density from $N$-body simulations, at times $t/T_{\text{rel}} = 0.07, 0.13, 0.2, 0.25, 0.33, 1$. **Right:** Densities predicted from the Fokker-Planck equation at the same times. The curves progressing from bottom to top, are bracketed by the lower dashed curves at $t = 0$ and the upper dashed curves showing $\rho \propto r^{-7/4}$, the asymptotic solution to the Fokker-Planck equation (from Preto et al 2004).

### 4.2 Wandering of the black hole

A massive compact object, like a black hole, embedded in a dense stellar system, experiences a multitude of gravitational encounters; the total action on this body is composed of a slowly varying force, deriving from the smooth stellar system potential, and a rapidly fluctuating stochastic force due to discrete encounters with individual stars. The motion of the black hole is then similar to that of a random walk (Chatterjee et al 2002, 2003), and this Brownian motion has been invoked to counter the effect of the empty loss-cone, and provide new stars to
interact with. It is expected that equipartition of energy is reached, so that the velocity acquired by the black hole is small, even if the black hole interacts with particles with high velocity dispersion. Numerical simulations over-estimate this effect, since the number of particles is far smaller than the realistic number.

The effect of wandering might be even more interesting on a binary black hole (see next section). When interacting with a third body, the binary can eject stars at large velocity. Also the dynamical friction on a binary is less than on a single black hole. Finally, when a black hole binary merges, the gravitational waves emitted take away some momentum, producing a recoil of the merged object. This hardly ejects it out of the galaxy (except may be at high redshift, when the potential wells are not deep enough), but can produce a large wandering of the black hole, and a flattening of the cusp into a core (Merritt et al 2004).

4.3 Binary black holes

![Density profiles obtained through N-body simulations of the spiral-in of a massive BH, from Nakano & Makino (1999). The falling BH mass is 4% of the galaxy mass. The BH has initially only a tangential velocity $v_{t,0}$, function of the Kepler velocity $v_K$, as indicated on the figure.](image-url)
The formation of binary black holes in the centers of galaxies is a natural prediction of the hierarchical scenario, given the presence of a massive black hole in nearly every galaxy. The successive physical processes able to brake the two black holes in their relative orbit have been considered by Begelman et al. (1980). Each black hole sinks first toward the merger remnant center through dynamical friction onto stars. A binary is formed; but the life-time of such a binary can be much larger than a Hubble time, if there is not enough stars to replenish the loss cone, where stars are able to interact with the binary. Once a loss cone is created, it is replenished only through the 2-body relaxation between stars, and this can be very long ($T_{rel}$). If the binary life-time is too long, another merger with another galaxy will bring a third black-hole. Since a three-body system is unstable, one of the three black-holes will be ejected by the gravitational slingshot effect (Saslaw et al. 1974).

Numerical simulations have brought more precision in the determination of the life-time of the binary, although numerical artifacts have given rise to debates. Ebisuzaki et al. (1991) claimed that the life-time of the binary should be much shorter if its orbit is eccentric, since then the binary can interact with more stars and release the loss cone problem. The first numerical simulations tended to show that orbit eccentricity should grow quickly through dynamical friction (Fukushige et al. 1992). Mikkola & Valtonen (1992) and others found that the eccentricity in fact grows only very slowly (Quinlan 1996).

Numerical simulations suffer from a restricted number of bodies $N$, and consequently of a large random velocity of the binary (that should decrease in $N^{-1/2}$). The binary then wanders in or even out of the loss cone, and the effect of the loss cone depletion does not occur (Makino et al. 1993). Also the 2-body relaxation time is shorter than in the real system, contributing to replenish the cone.

More recent simulations, with increased number of particles, have indeed shown that the hardening of the binary depends of the relaxation time-scale, proportional to the number of particles (Makino & Funato 2004), and therefore another mechanism is required to merge the binary, such as gas accretion.

The ejection out of the core of stars interacting with the binary weakens the stellar cusp, while the binary hardens. In addition, a sinking black hole during a merger, contributes also to form a core (Nakano & Makino 1999, Figure 12). Gas dissipation, and star formation in the central concentration formed, can restore the cusp. This might explain the existence of cores in the center of giant ellipticals, having experienced multiple mergers, while small-mass systems have still a cusp. The computation of the deficit of stars in the central profiles, and the formation of cores, appear in agreement with observations (Graham 2004, Volonteri et al. 2003b).

5 History of accretion onto SMBH: X-ray constraints

It is possible to relate the amount of energy produced in Active Galactic Nuclei, per comoving volume, to the mass density accreted by black holes, and therefore to their growth history, given an accretion efficiency $\epsilon$ (e.g. Soltan 1982). From
the $M_{bh}$-$M_{\text{bul}}$ relation, the density of black hole can be estimated to:

$$\rho_{bh} = 1.1 \times 10^6 \left( \frac{M_{bh}}{M_{\text{bul}}}/0.002 \right) \left( \frac{\Omega_{\text{bul}}}{0.002} h^{-1} \right) M_\odot/Mpc^3$$

as a function of the mass density $\Omega_{\text{bul}}$ in stellar spheroids.

The efficiency of conversion of mass into energy is generally adopted to be around $\epsilon = 0.1$ for quasars, this value being an average between two extremes: for a Schwarzschild black hole, without rotation, this value is low ($\epsilon = 0.054$), and for a Kerr black hole, with maximum rotation, it can reach $\epsilon = 0.37$ (Thorne 1974). It is possible to estimate the present growth of black holes by the optical QSO luminosity function, which yields an accreted mass density of

$$\rho_{\text{accr}} = 2 \times 10^5 \frac{0.1}{\epsilon} M_\odot/Mpc^3$$

(Yu & Tremaine 2002). This is however a lower limit, since most AGN light is absorbed at optical wavelengths. The estimation from the far-infrared, assuming a contribution of AGN to the FIR of 30%, is:

$$\rho_{\text{accr}} = 7.5 \times 10^5 \frac{0.1}{\epsilon} M_\odot/Mpc^3$$

which confirms that the accretion radiation mainly does not get out in optical light, but is re-radiated by dust.

It has been shown that the optically selected AGN correspond only to one third of the X-ray background (Barger et al 2003), which is now essentially Fig. 13. Density of luminous QSO as a function of redshift, from soft X-ray selected sources (empty circles), and optically selected ones (dash lines and triangles), from Hasinger (2004). The $z < 2$ dash curve for optically selected QSO ($M_{\text{bul}} < -26$) is from a combination of 2dF and 6dF surveys (Croom et al 2004). The triangles at $z > 2.7$ have been renormalised from Schmidt et al (1995) and Fan et al (2001).
resolved in individual sources, at least at energy lower than 2-5 kev (Worsley et al 2005). The accretion density estimated from the X-ray background has been estimated as high as $3 \times 10^5 M_\odot/Mpc^3$ (Salucci et al 1999) and $6-9 \times 10^5 M_\odot/Mpc^3$ (Fabian & Iwasawa 1999). These estimations have now been updated to lower values. Taking into account the hard X-ray selected AGN, and their total corrected bolometric luminosity, Barger et al (2005) find a strong evolution with redshift of the AGN production rate, in $(1+z)^{\alpha}$, with $\alpha = 3.2$ between $z=0$ and $z=1$. At higher redshifts the production decreases again (with $\alpha = -1$), but the global integrated production is dominated by the $z=1$ objects. The deduced accretion density at $z=0$ is

$$\rho_{\text{accr}} = 4 \times 10^5 \frac{0.1}{\epsilon} M_\odot/Mpc^3$$

and about 40% of this accretion density is due to the Broad-Line AGN, that are also the most powerful AGN (Steffen et al 2003). The redshift evolution of the accretion rate is remarkably similar to the star formation history. Both histories reveal a downsizing effect, in the sense that the most active objects assemble mass in the early universe, and are no longer active now, while the remaining activity occurs now in the small-mass objects. Indeed, the most powerful and massive AGN observed at high redshifts have disappeared now, at the benefit of less powerful objects. This is also true for starbursts and ultra-luminous objects.

When compared with the density of black hole mass now in galaxies, estimated from the velocity dispersion of early-type galaxies determined from the Sloan Survey and the BH-mass to dispersion relation (Yu & Tremaine 2002) or other estimations based on the mass density in the local universe and the $M_h - \sigma$ relation (Aller & Richstone 2002, Marconi et al 2004), there is a good concordance with the mass expected from accretion luminosity, if the efficiency of accretion is $\epsilon = 0.1$. If the efficiency is higher, then there must exist obscured AGN, not counted in the above balance.

With deep X-ray surveys, it is now possible to draw quite precise conclusions on the AGN redshift evolution, and luminosity functions (Hasinger 2004). There is a clear evolution of luminosity functions versus redshift, which results from both number density evolution, and luminosity evolution. The evolution with $z$ depends strongly on luminosity. For low-luminosity AGN, the amplitude of number density evolution is less pronounced, and the maximum occurs at low redshift, while bright quasars reveal a factor 100 increase in density, and the peak occurs at higher $z$. For $L_X = 10^{42}-10^{43}$ erg/s, the peak is at $z \sim 0.5-0.7$, while it is at $z\sim 2$ for $L_X = 10^{45}-10^{46}$ erg/s. This points towards a downsizing effect: rare and bright QSO form very early in the universe, and then decline by two orders of magnitude, while the more frequent low-luminosity AGN form later, and decline by only a factor 10 in number.

A clear decline at higher redshifts is now detected. The comparison between the X-ray selected and optically-selected AGN is illustrated in Figure 13. The comparison is to be taken with caution, since the precise shape of the number density evolution depends highly on luminosity.
6 Conclusion

The BH masses measured in local spheroids and spiral galaxies with bulges, are tightly correlated to the central velocity dispersion, and with more scatter to the bulge luminosity or mass. This has been interpreted as a concomitant formation of stars in the bulge and growth of the black hole at the center. The BH growth occurs by a combination of external gas accretion, and coalescence of binary BHs, during galaxy mergers. From the measured density of BH in the local universe, it is possible to deduce how many active galaxy nuclei have radiated in the past, while accreting and growing these black holes. The comparison of the optical, far-infra-red or X-rays outputs, either in the form of point sources, or unresolved in the background, with the local BH density constrains the radiating efficiency of the AGN; the efficiency should be around $\epsilon \sim 0.1$, in between that expected from Schwarzschild and Kerr black holes.

The discovery of high redshift ($z > 6$) bright QSOs has posed the problem of their formation in a short time-scale. This problem appears related to the anti-hierarchical evolution observed: the brighter AGN form earlier, in a shorter time-scale, while the low- luminosity AGN takes more time to form, and reveals less evolution amplitude. Their peak number density occurs at lower redshift than for bright QSO. This behaviour might be explained by the much higher gas density at high $z$, the higher merging rate and the shorter dynamical time-scale.

The most massive black holes are confined in galaxy nuclei. But there must exist an intermediate mass category for BH, between the stellar-mass BHs and the supermassive ones. Those IMBHs with masses around $10^4 - 10^5 M_\odot$, are not found particularly in nuclei, since they have not been braked by dynamical friction. There appears now some evidence of the existence of these IMBHs, but it is not yet clear whether they might prolonge the $M_\text{bh} - \sigma$ relation, at low masses.

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Through the study of AGN demographics and several clues like their cross-correlation length, the quasar lifetimes are determined to be around a few $10^7$ yrs; this is understood as the sum of all activity phases in a single object, if there exist episodic recurrent activity. This life time is luminosity dependent, being much longer for low luminosity AGN.

The relation between BH mass and bulge luminosity breaks down for a certain category of AGN, the NLS1 which appear to have formed their stars in the past at a higher rate than growing their black hole. Evidence is found that nuclei in these objects are now accreting mass much above the Eddington rate, although they are barely radiating around the Eddington rate. Gas accretion towards a starburst or a BH are then not exactly concomitant, there could be time delays between the two processes.

Can we trace back the formation of supermassive black holes back to the early universe? Small BH can form very early by the collapse of Population III stars, around $z \sim 20$, with masses of a few hundred solar masses. But the low efficiency of dynamical friction on these small masses, make the BH growth through merging unlikely. Most of the BH growth must then be due to gas accretion. There must exist a large range in mass distribution of black holes wandering
all across galaxies; when accreting gas, these mini-quasars can contribute to the reionization of the universe.

Different kinds of feedback processes have been invoked to account for the $M_{bh} - \sigma$ relation, and in particular the energy released in AGN activity, QSO outflows, radiation, that could self-regulate the gas accretion. Such processes are particularly conspicuous in the center of cooling flow clusters, where gas reheating regulate the cooling flow. Episodically, the cooling gas fuels the central AGN, triggering a new activity phase. For low luminosity AGN, dynamical instabilities in galaxy disks, like spirals and bars, are invoked to fuel the central nucleus, and also self-regulate the gas accretion. Bars are destroyed through gas inflow, and this could explain the apparent lack of correlation between nuclear activity and the presence of strong bars.

The existence of binary black holes are a natural consequence of the hierarchical scenario of galaxy formation, if there exists a supermassive black hole dormant in each nucleus. The coalescence of the binaries should occur relatively rapidly, to avoid the loss of SMBH through 3-body interactions. Since dynamical friction on bulge stars is not sufficient, the coalescence must be due to gas accretion by the nucleus. During the hardening of the binary, energy is given to the central stellar population, and any cuspy density distribution can be flattened into a core, by this dynamical heating. A cuspy stellar distribution can later reform around the resulting single black hole.

In spite of large progress in massive black hole formation in the recent years, many questions remain open, such as the evolution of the $M_{bh} - \sigma$ relation with redshift, the local exceptions to the relation (for instance galaxies like M33), the radiative efficiency of the nucleus for a given accretion, etc..

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