Anti-Hierarchical Growth of Supermassive Black Holes and QSO lifetimes

Andrea Merloni

Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, D-85741, Garching, Germany

Abstract. I present a new method to unveil the history of cosmic accretion and the build-up of Supermassive Black Holes (SMBH) in the nuclei of galaxies, based on observations of the evolving radio and (hard) X-ray luminosity functions of AGN. The fundamental plane of black hole activity discovered by Merloni, Heinz & Di Matteo (2003) is used as a mass and accretion rate estimator. I adopt the local BH mass function as a boundary condition to integrate backwards in time the continuity equation for the SMBH evolution, neglecting the role of mergers. Under the most general assumption that accretion proceeds in a radiatively efficient way above a certain rate, and in a radiatively inefficient way below, the redshift evolution of the mass and accretion rate functions are calculated self-consistently. The only tunable parameters are the accretion efficiency and the critical ratio of the X-ray to Eddington luminosity at which the transition between accretion modes takes place. The evolution of the BH mass function between $z = 0$ and $z \sim 3$ shows clear signs of an anti-hierarchical behaviour: while the majority of the most massive objects ($M > 10^9$) were already in place at $z \sim 3$, lower mass ones mainly grew at progressively lower redshift. As an example, I will discuss the consequences of these results for the lifetimes of accreting black holes.

1 Introduction

It has been known for the last ten years that the cosmological evolution of massive galaxies shows signs of ‘down-sizing’ [1], i.e. of a progressive decrease of the typical mass of actively star forming galaxies. Many pieces of evidence, brought forward also during this meeting (see e.g. the contributions of Bender, Kauffmann and Danese to these Proceedings), suggest that the baryonic physics of star formation processes counterbalance the hierarchical (bottom-up) growth of dark matter structures, favouring the early formation and growth of the most massive (and dense) stellar aggregates.

The ubiquity of SMBH in galactic nuclei, and their tight relation with their hosts’ bulge properties [2] seem to indicate that the formation and growth of galaxies and of their resident black holes have proceeded in parallel, and probably influenced each other in the early stages of galaxy formation. As a matter of fact, the number of theoretical studies dedicated to AGN feedback in galaxy formation has flourished in the last five years (see e.g. Loeb’s contribution in this proceedings, and references therein). Furthermore, a recent comprehensive study of 23 000 local AGN carried out by the Sloan Digital Sky Survey (SDSS, [3]) have demonstrated, in a direct quantitative way, that accretion onto SMBH and formation of stars are tightly coupled even in the local universe.
Is it possible to learn more about the formation and growth of structures by just looking at the evolution of the AGN population? The aim of the work presented here is to show to what extent this is indeed possible, and to describe a robust, self-consistent way to unveil the history of cosmic accretion and the build-up of SMBH in the nuclei of galaxies, in the form of their evolving mass function. The methodology and the main results will be discussed in the next section, while in section 3 I will expand on the consequences of these results for the issue of QSO lifetimes. Section 4 will summarize my conclusions.

2 The Evolution of the SMBH Mass Function

Under the standard assumption that black holes grow mainly by accretion [4], the cosmic evolution of the SMBH accretion rate and its associated mass density can be calculated from the luminosity function of AGN: \( \phi(L_{\text{bol}}, z) = dN/dL_{\text{bol}} \), where \( L_{\text{bol}} = \epsilon_{\text{rad}} \dot{M} c^2 \) is the bolometric luminosity produced by a SMBH accreting at a rate of \( \dot{M} \) with a radiative efficiency \( \epsilon_{\text{rad}} \). In practice, the accreting black hole population is always selected through observations in specific wavebands. Crucial is therefore the knowledge of two factors: the completeness of any specific AGN survey, and the bolometric correction needed in order to estimate \( L_{\text{bol}} \) from the observed luminosity in any specific band. On both these issues, huge progress has been made in the last few years (see e.g. [5]).

In order to progress from the study of BH mass densities to that of BH mass functions, we need to break the degeneracy between mass and accretion rate of any given observed AGN. While in most semi-analytic works this is done by assuming a constant Eddington ratio for all sources, here I will propose an alternative, physically motivated, method. In a recent paper [6] it has been shown that the hard (2-10 keV) X-ray luminosity of an accreting black holes is related to its mass and its core radio (at 5GHz) luminosity by the following relation (the “fundamental plane” of black hole activity):

\[
\log L_R = (0.60^{+0.11}_{-0.11}) \log L_X + (0.78^{+0.11}_{-0.09}) \log M + 7.33^{+4.06}_{-4.07};
\]

which can be inverted to relate BH masses to observed nuclear radio and X-ray luminosities:

\[
\log M \simeq g(\log L_R, \log L_X).
\]

One of the consequences of this relation is that, in an ideal case, the conditional radio/X-ray luminosity function of active black holes, i.e. the number of sources per unit co-moving volume per unit logarithm of radio and X-ray luminosities, \( \Psi_{C}(L_R, L_X) \), could be used to reconstruct the mass function of the underlying black hole population. In fact, the current lack of the exact knowledge of \( \Psi_{C}(L_R, L_X) \) can be (at least partially) superseded, given the two separate radio, \( \phi_R(L_R, z) \), and X-ray, \( \phi_X(L_X, z) \), luminosity functions at redshift \( z \), and an independent estimate of the black hole mass function, \( \phi_M(M, z) \) at the same redshift. By taking into account the fundamental plane relationship, we have that, at any \( z \), the conditional luminosity function \( \Psi_C \) has to satisfy the following integral constraints:

\[
\phi_i(L_i) d\log L_i = \int_{L_{i,\text{min}}}^{\infty} \Psi_C(L_i, L_j) d\log L_j \quad (i, j) = (R, X)
\]
\[ \phi_M(M) d \log M = \int \int_{\log M < g < \log M + d \log M} \Psi_C(L_X, L_R) d \log L_R d \log L_X. \quad (2) \]

Given observational estimates of \( \phi_X, \phi_R \) and \( \phi_M \), we start with an initial guess for \( \Psi_C \), and proceed via successive iterations, minimizing the differences between the projections of the conditional luminosity function onto the X-ray and radio luminosity axes and the observed luminosity functions, until a conditional LF is obtained simultaneously satisfying eqs. 1 and 2. Once such an estimate of \( \Psi_C \) is found, it is possible to derive the local distribution of the X-ray to Eddington ratio, and from this, given an appropriate bolometric correction (i.e. a specific functional form \( L_X = L_X(M, \dot{m}) \)), the desired accretion rate function.

The redshift evolution of the SMBH population can then be computed integrating backwards the continuity equation that describes SMBH evolution driven by accretion only [7]:

\[ \frac{\partial \phi_M(M, t)}{\partial t} + \frac{\partial [\phi_M(M, t) \cdot \langle \dot{M}(M, t) \rangle]}{\partial M} = 0, \quad (3) \]

where the mean accretion rate as a function of black hole mass and time, \( \langle \dot{M} \rangle \) is calculated directly from the accretion rate distribution function at time \( t \). Starting from \( z = 0 \), the local BHMF, as determined independently from the galaxy velocity dispersion distribution and the \( M - \sigma \) relation, can be used as a boundary condition to integrate eq. 3 up to the redshift where hard X-rays and radio luminosity functions of AGN can be reliably estimated. The only parameters needed are the accretion efficiency \( \epsilon \), and the functional form \( L_X = L_X(M, \dot{m}) \).

Here I present the results obtained using the most recent determinations of the hard X-rays and radio LF [9,10], fixing \( \epsilon = 0.1 \), and assuming for the function \( L_X(\dot{m}) \) a simple broken power-law expression, with \( L_X \propto \dot{m}^2 \) at low accretion rates (radiatively inefficient regime) and \( L_X \propto \dot{m}^{0.8} \) at high luminosities (radiatively efficient regime, see [5,8] for details), with the transition being placed at \( x_{cr} = 10^{-3} [11] \).

The evolution of the black hole mass function is shown in the left panel of Figure 1. As opposed to the standard picture of hierarchical mass build up of dark matter halos in CDM cosmologies, supermassive black holes growing by accretion between \( z \sim 3 \) and now have a mass function which is more and more dominated by larger mass objects at higher redshift. Thus, most of the more massive black holes \( (M > 10^9) \) were already in place at \( z \sim 3 \), and as a result, the “typical” SMBH mass decreases with decreasing redshift. SMBH appear to be growing in anti-hierarchical fashion [5,12].

The right panel of Figure 1 shows instead the redshift evolution of the derived accretion rate function (expressed here as X-ray to Eddington ratio, \( L_X/L_{Edd} \)). While the number of sources accreting at low rates increases monotonically with decreasing redshift, the situation is different for rapidly accreting objects, that increase in number with increasing redshift. The cut-off redshift, above which the
number of sources declines again, is a function of the typical X-ray to Eddington ratio, being lower for lower accretion rate sources. Once again, it is clear that the “typical” X-ray to Eddington ratio, which can be approximately identified with the knee of the accretion rate functions of Fig.1, decreases with decreasing redshift, crossing the critical rate that separates radiatively inefficient from efficient regimes (here fixed at $10^{-3}$, vertical dashed line) around $z \sim 0.5$.

### 3 Lifetimes of Active Black Holes

In all models that derive the properties of the SMBH population from the observed QSO evolution, a key element is represented by the typical quasar lifetime or by the almost equivalent activity duty cycle. However, the significance of these parameters is limited to the standard case in which, on the basis of an observed luminosity function in a specific waveband, one tries to derive the distribution of either BH masses or accretion rates. Usually, a constant Eddington ratio is assumed in this case, which implies that QSO are considered as on-off switches. Then, the duty cycle is simply the fraction of black holes active at any time, and the lifetime is the integral of the duty cycle over the age of the universe (see e.g. [13] and references therein).

The picture discussed here is different, in that a broad distribution of Eddington rates is not only allowed, but actually calculated for the SMBH population at every redshift. When this is the case, a more meaningful definition of activity lifetime is needed. Let us first define the mean Eddington rate for object of mass $M_0$ at redshift $z = 0 \langle \dot{m}(M_0, z) \rangle$ and then introducing the mean accretion weighted lifetime of a SMBH with a given mass today: $\tau(M_0, z) = \int_{\infty}^{z} \langle \dot{m}(M_0, z') \rangle \frac{dz'}{\sigma_{\tau}}$. 

---

Fig. 1. Left Panel: Redshift evolution of the SMBH mass function (BHMF), from redshift 3 (lower curve) till redshift 0.1 (upper curve). Right Panel: Redshift evolution of the SMBH accretion rate function (expressed here in terms of X-ray to Eddington luminosity ratio), from redshift 3 till redshift 0.1; The vertical dashed line marks the adopted value of the critical accretion rate where a transition occurs between radiatively inefficient (below) and efficient (above) accretion.
Fig. 2. Partial mean accretion weighted lifetimes (in years) of SMBH with mass today $M_0$, calculated for three different redshift intervals: $0 < z < 1$ (solid line), $1 < z < 2$ (dashed line) and $2 < z < 3$ (dot-dashed line). The horizontal dotted line is the Salpeter time for accretion efficiency of 10%.

The ratio of $\tau(M_0, z)$ to the Salpeter time, $t_S = \epsilon Mc^2 / L_{\text{Edd}} = (\epsilon/0.1)4.5 \times 10^7$ yrs, gives the mean number of $e$-folds of mass growth for objects with mass $M_0$ up to redshift $z$. The ratio of $\tau(M_0, z)$ to the Hubble time $t_{\text{Hubble}}(z) = H(z)^{-1}$, instead, is a measure of the activity duty cycle of SMBH. It is also interesting here to calculate “partial” lifetimes in a given redshift interval $\Delta z = (z_i, z_f)$:

$$\Delta \tau(M_0, \Delta z) = \int_{z_i}^{z_f} \langle \dot{m}(M_0, z') \rangle \frac{dt}{dz'} dz'.$$

In Figure 2 I show $\Delta \tau(M_0, \Delta z)$ for three redshift intervals: $0 < z \leq 1$; $1 < z \leq 2$ and $2 < z \leq 3$. The accretion weighted lifetime for BH of any given mass between $0 < z < 3$ is of course just the sum of the three. The anti-hierarchical nature of mass build-up in actively accreting AGN and QSOs is again clearly illustrated by this plot. In fact, the major growth episode of a SMBH must coincide with the period when $\Delta \tau > t_S$. This happens at $z < 1$ for $M_0 < 10^{7.6}$, between redshift 1 and 2 for $10^{7.6} < M_0 < 10^{8.2}$, and at $2 < z < 3$ for $10^{8.2} < M_0 < 10^{8.4}$. Supermassive black holes with masses larger than $M_0 \sim 10^{8.5}$ today, must have experienced their major episodes of growth at redshift higher than 3. It also interesting to note that the objects that dominate the SMBH mass function today, i.e. those in the range of masses around $10^{7.5} M_\odot$, where $M_0 \phi_M(M_0, z = 0)$ peaks, mainly grew around $z \sim 1$, which is when most of the X-ray background light we see today was emitted [14].
4 Conclusion

I have presented a new method to study the growth of accreting supermassive black holes, based on the simultaneous evolution of the AGN radio and hard (2-10 keV) X-ray luminosity functions. The method is based on the locally observed trivariate correlation between black hole mass, X-ray and radio luminosity (the so-called fundamental plane of black hole activity, [6]). Thanks to this correlation, it is possible for the first time to break the degeneracy between luminosity, mass and accretion rate: QSO and AGN not only grow in mass during their evolution, but also accrete at different rates depending on their mass and age.

Qualitatively (i.e. independently on the values of the model parameters), the evolution of the black hole mass function between $z = 0$ and $z \sim 3$ shows clear signs of an anti-hierarchical behaviour: while the majority of the most massive objects ($M > 10^9$) were already in place at $z \sim 3$, lower mass ones mainly grew at progressively lower redshift, so that the average black hole mass increases with increasing redshift. At the same time, the typical accretion rate of SMBH decreases with decreasing redshift. Consequently, the lifetime of an actively growing BH, measured through the partial mean accretion weighted lifetime (see section 3), is a strong function of both redshift and black hole mass.

Broadly speaking, what is presented here is the SMBH analog of the downsizing of star forming galaxies. Future more direct and detailed comparisons between SMBH mass functions, such as those shown here, and galaxy luminosity functions, both at low and high redshifts, will hold the key of our understanding of the complex interplay between formation and growth of black holes and galaxies.

References

1. L. L. Cowie, A. Songaila, E. M. Hu, J. G. Cohen: AJ 112, 839 (1996)
2. J. Kormendy, D. Richstone: ARA&A 33, 581 (1995); J. Magorrian, et al.: AJ 115, 2285 (1998); L. Ferrarese, D. Merritt: ApJL 539, L9 (2000); K. Gebhardt, et al.: ApJL 539, L13 (2000); S. Tremaine, et al.: ApJ 574, 740 (2002); A. Marconi, L. K. Hunt: ApJL 589, L21 (2003)
3. T. M. Heckman, et al.: preprint astro-ph/0406218 (2004)
4. A. Soltan: MNRAS 200, 115 (1982); Q. Yu, S. Tremaine: MNRAS 335, 965 (2002)
5. A. Marconi, et al.: MNRAS 351, 169 (2004)
6. A. Merloni, S. Heinz, T. Di Matteo: MNRAS 345, 1057 (2003)
7. T. A. Small, R. D. Blandford: MNRAS 259, 725 (1992)
8. A. Merloni: MNRAS in press, astro-ph/0402495 (2004)
9. Y. Ueda, M. Akiyama, K. Ohta, T. Miyaji: ApJ 598, 886 (2003)
10. C. J. Willott, et al.: MNRAS 332, 536 (2001)
11. T. Maccarone, E. Gallo, R. P. Fender: MNRAS 345, L19 (2003)
12. G. L. Granato, et al.: ApJ 600, 580 (2004)
13. P. Martini: in Coevolution of Black Holes and Galaxies, from the Carnegie Observatories Centennial Symposia ed. by L. Ho (CUP, Cambridge 2004) p. 170
14. G. Hasinger: AIP Conf.Proc. 666, 227 (2003)