A synthetic view of AGN evolution and supermassive black holes growth

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Abstract.
I will describe the constraints available from a study of AGN evolution synthesis models on the growth of the supermassive black holes (SMBH) population in the two main 'modes' observed (kinetic- and radiatively-dominated, respectively). I'll show how SMBH mass function evolves anti-hierarchically, i.e. the most massive holes grew earlier and faster than less massive ones, and I will also derive tight constraints on the average radiative efficiency of AGN. An outlook on the redshift evolution of the AGN kinetic luminosity function will also be discussed, thus providing a robust physical framework for phenomenological models of AGN feedback within structure formation. Finally, I will present new constraints on the evolution of the black hole-galaxy scaling relation at $1 < z < 2$ derived by exploiting the full multi-wavelength coverage of the COSMOS survey on a complete sample of 90 type 1 AGN.

1. Introduction

In the past decade three seminal discoveries have revealed tight links and feedback loops between the growth of nuclear super-massive black holes and galaxy evolution, promoting a true shift of paradigm in our view of astrophysical black holes, which have moved from the role of exotic tracers of cosmic structures to that of fundamental ingredients of them.

First of all, the search for the local QSO relics via the study of their dynamical influence on the surrounding stars and gas led to the discovery of SMBH in the center of most nearby bulge-dominated galaxies. The steep and tight correlations between their masses and bulge properties (so-called scaling relations; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Haring & Rix 2004) represented the first and fundamental piece of evidence in favor of a connection between galaxy evolution and central black holes. The second one stems from the fact that SMBH growth is now known to be due to radiatively efficient accretion over cosmological times, taking place during “active” phases (Marconi et al. 2004; Merloni & Heinz 2008, hereafter MH08). If most galaxies host a SMBH today, they should have experienced such a phase of strong nuclear activity in the past. Finally, extensive programs of optical and NIR follow-up observations of X-ray selected AGN in the Chandra and XMM-Newton era put on solid grounds the evolution of accretion luminosity over a significant fraction of cosmic time. We have thus discovered that lower luminosity AGN peak at a lower redshift than luminous QSOs (see e.g. Hasinger et al. 2005). Such a behavior is analogous to that observed for star formation (usually referred to
as “cosmic downsizing”) lending further support to the idea that the formation and evolution of SMBHs and their host galaxies might be closely related.

In this brief review, I will try to summarize observational evidences for AGN downsizing, on the basis of a simple theoretical framework according to which supermassive black holes evolution is dominated by accretion, and governed by a continuity equation, that we can solve numerically between \( z = 0 \) and \( z \sim 4 \). I will then show the implication for these specific trends for the AGN energy release in kinetic form. Finally, I will present some recent observational results on the evolution of the scaling relations, and briefly discuss their implication for feedback models.

2. Dissecting AGN downsizing

The term downsizing was first used by Cowie et al. (1996) to describe their finding that actively star-forming galaxies at low redshift have smaller masses than actively star-forming galaxies at \( z \sim 1 \). In the current cosmology jargon, this term has come to identify a variety of possibly distinct phenomena, not just related to the epoch of star formation, but also to that of star formation quenching, or galaxy assembly (see the discussion in Faber et al. 2007, and references therein). Given the growing body of observational evidence for galaxy downsizing, it is legitimate to ask whether black holes and AGN do also show a similar trend. The first hints of a positive answer came from the study of the evolution of the X-ray selected AGN luminosity function. In the last decade, we have learned that more luminous AGN were more common in the past, with the X-ray luminosity function (XLF) following a so-called Luminosity Dependent Density Evolution (Ueda et al. 2003; Hasinger et al. 2005), a direct phenomenological manifestation of AGN downsizing. How can we use this (and other analogous) results on the XLF evolution to gain further insights on the physical evolution of the black hole population?

As opposed to the case of galaxies, where the direct relationship between the evolving mass functions of the various morphological types and the distribution of star forming galaxies is not straightforward due to the never-ending morphological and photometric transformation of the different populations, the situation in the case of SMBH is much simpler. For the latter case, we can assume their evolution is governed by a continuity equation (MH08, and references therein), where the mass function of SMBH at any given time can be used to predict that at any other time, provided the distribution of accretion rates as a function of black hole mass is known. Such equation can be written as:

\[
\frac{\partial \psi(\mu, t)}{\partial t} + \frac{\partial}{\partial \mu} \left( \psi(\mu, t) \langle \dot{M}(\mu, t) \rangle \right) = 0
\]  

(1)

where \( \mu = \log M \) (\( M \) is the black hole mass in solar units), \( \psi(\mu, t) \) is the SMBH mass function at time \( t \), and \( \langle \dot{M}(\mu, t) \rangle \) is the average accretion rate of SMBH of mass \( M \) at time \( t \), and can be defined through a “fueling” function, \( F(\dot{\mu}, \mu, t) \), describing the distribution of accretion rates for objects of mass \( M \) at time \( t \): \( \langle \dot{M}(M, z) \rangle = \int \dot{M} F(\dot{\mu}, \mu, z) d\mu \). Such a fueling function is not a priori known, and observational determinations thereof have been able so far to probe robustly only the extremes of the overall population. However, the AGN fueling function
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Figure 1. **Left**: Average Growth time of Supermassive Black Holes (in years) as a function of redshift for different black hole mass ranges. The dashed line marks the age of the Universe; only black holes with instantaneous growth time smaller than the age of the Universe at any particular redshift can be said to be effectively growing. **Right**: the fraction of the final black hole mass accumulated as a function of redshift and final (i.e. at $z=0$) mass is plotted as contours.

can be derived by inverting the integral equation that relates the luminosity function of the population in question with its mass function. Indeed we can write:

$$
\phi(\ell, t) = \int F(\ell - \zeta, \mu, t)\psi(\mu, t) \, d\mu
$$

(2)

where I have called $\ell = \log L_{\text{bol}}$ and $\zeta = \log (\epsilon_{\text{rad}} c^2)$, with $\epsilon_{\text{rad}}$ the radiative efficiency, here assumed to be constant. This is the approach followed in MH08, were the inversion was performed numerically, based on a minimization scheme that used both the X-ray and radio AGN luminosity functions as constraints, complemented by recipes to relate observed (and intrinsic) X-ray and radio (core) luminosities to $L_{\text{bol}}$ (see MH08 for details).

Using this approach, we have integrated eq (1) starting from $z = 0$, where we have simultaneous knowledge of both mass, $\psi(\mu)$, and luminosity, $\phi(\ell)$, functions, evolving the SMBH mass function backwards in time, up to where reliable estimates of the AGN luminosity functions are available (currently this means $z \simeq 4$). The adopted hard X-ray luminosity function is supplemented with luminosity-dependent bolometric corrections of Marconi et al. (2004) and absorbing column density distributions consistent with the X-ray background constraints, following the most recent XRB synthesis model (Gilli et al. 2007). Similar results can of course be obtained using directly bolometric luminosity functions (see e.g. Hopkins et al. 2007).

In this way, we can estimate the specific instantaneous ratio of black hole mass to accretion rate as a function of SMBH mass and its cosmological evolution. Such a ratio defines a timescale, the so-called growth time, or mass
doubling time (Figure 1 left). The redshift evolution of the growth time distribution can be used to identify the epochs when black holes of different sizes grew the largest fraction of their mass: black holes with growth times longer than the age of the Universe are not experiencing a major growth phase, which must have necessarily happened at earlier times. Figure 1 then shows that, while at \( z \approx 1 \) only black holes with masses smaller than \( 10^7 M_\odot \) are experiencing significant growth, as we approach the peak of the black hole accretion rate density (\( z \sim 1.5 - 2 \)), we witness the rapid growth of the entire SMBH population. Better constraints on both bolometric luminosity and mass functions evolution are however needed to paint a clearer picture at higher \( z \). A strikingly similar behaviour has indeed been observed for the whole of the star-forming galaxy population (Perez-Gonzalez et al. 2008).

Solutions of the continuity equation allow also to trace the growth of black holes of a given final (i.e. at \( z = 0 \)) mass. The right hand side panel of Fig. 1 shows that, for the most massive black holes (> \( 10^9 M_\odot \)) half of the mass was already in place at \( z \sim 2 \), while those with \( M(z = 0) < 10^8 M_\odot \) had to wait until \( z \sim 1 \) to accumulate the same fraction of their final mass.

3. Kinetic energy output of AGN

The phenomenological investigation presented here, however, leaves open the fundamental question about the physical origin of such a clear, parallel differential growth of both the black holes and the galaxy population. Some clues may come from attempts to trace the evolution of the feedback energy released by growing black holes as a function of black hole mass and redshift. In this section, we describe in some detail how such an inventory can be made.

Direct evidence of AGN feedback in action has been found in the X-ray observations of galaxy clusters, showing how black holes may deposit large amounts of energy into their environment. From studies of the cavities, bubbles and weak shocks generated by the radio emitting jets in the intra-cluster medium (ICM) it appears that AGN are energetically able to balance radiative losses from the ICM in the majority of cases (Best et al. 2006; Rafferty et al. 2006).

On the other hand, numerical simulations of AGN-induced feedback have shown that mechanical feedback from black holes may be responsible for halting star formation in massive ellipticals, explaining the bimodality in the color distribution of local galaxies (Springel et al. 2005), as well as the size of the most massive ones. At a global level, these models hinge on the unknown efficiency with which growing black holes convert accreted rest mass into kinetic and/or radiative power. Constraints on these efficiency factors are therefore vital for the theory. Recent works of ours (Merloni & Heinz 2007) showed that the output of low-luminosity AGN is dominated by kinetic energy rather than by radiation and have allowed estimates of the kinetic luminosity function of AGN based on the observed radio emission of their jets (either core, MH08, or extended, Cattaneo & Best 2009).

As opposed to the mass growth evolution, the kinetic luminosity function so derived is not very tightly constrained due to poor observational information on the true (intrinsic) radio core/extended luminosity functions and to the large uncertainties in the calibration of the empirical relations between total
kinetic power and radio luminosity. Nevertheless, we can constrain the local $(z = 0)$ AGN kinetic power density, $\rho_{\text{kin}}$, between $1$ and $10 \times 10^{39}$ erg s$^{-1}$ Mpc$^{-3}$, comparable with the total kinetic power density from type II Supernovae ($\rho_{\text{SNII}} \simeq 4 \times 10^{39}$ erg s$^{-1}$ Mpc$^{-3}$, Hopkins & Beacom 2006), with the total AGN radiative density being about $\rho_{\text{rad}}(z = 0) \simeq 1.6 \times 10^{40}$ erg s$^{-1}$ Mpc$^{-3}$.

Integrating over redshift, we are able to measure the overall efficiency of SMBH in converting accreted rest mass energy into kinetic power, the “kinetic efficiency” $\epsilon_{\text{kin}} \equiv \frac{L_{\text{kin}}}{(\dot{M} c^2)}$, which ranges between $3$ and $8 \times 10^{-3}$ (MH08), depending on the choice of the radio core luminosity function, or between $1$ and $10 \times 10^{-3}$ (Cattaneo & Best 2009), depending on the exact choice of the $L_{\text{kin}}$-$L_{\text{radio}}$ relation. This is to be compared to the radiative efficiency, $\epsilon_{\text{rad}}$, approximately constrained to be between $0.07$ and $0.16$, depending on the choice of the local BH mass function, bolometric and obscuration corrections (see e.g. Marconi et al. 2004; Merloni & Heinz 2008; Yu & Lu 2008). As mentioned before, this implies that the overall growth of SMBH happens “radiatively”, with mechanical power output representing a small, albeit significant, fraction of the energy release.

The possibility to resolve the mass and accretion rate distribution functions with the continuity equation approach allows us to separate the evolution of both growth rate and kinetic energy density into different mass bins and into the various modes of accretion. We found that the kinetic power density at low redshift is dominated by low luminosity AGN, while the contribution from radio loud QSOs becomes significant at $z \sim 2$ (see left panel in Fig. 2). The measured $\epsilon_{\text{kin}}$ varies strongly with SMBH mass and redshift, being maximal for
very massive holes at late times, a property in agreement with what required for the AGN feedback by many recent galaxy formation models (right panel of Fig. 2).

4. The evolution of scaling relations

In the two previous sections, we have described methods to extract information from observations at various wavelengths about the differential growth of supermassive black holes and the corresponding mechanical energy output. However, direct evidence that AGN feedback may be responsible for the observed downsizing of galaxies is still missing. Observational clues could be hidden in the cosmological evolution of the scaling relations between SMBH and hosts, and, indeed, modern multiwavelength surveys are increasingly designed to allow measurements of the physical properties of AGN hosts.

Within the COSMOS survey (Scoville et al. 2007), we have recently studied the hosts of 89 broad line (type–1) Active Galactic Nuclei (AGN) detected in the zCOSMOS survey in the redshift range $1 < z < 2.2$ (for all the details, see Merloni et al. 2009). The unprecedented multi-wavelength coverage of the survey field allowed us to disentangle the emission of the host galaxy from that of the nuclear black hole in their Spectral Energy Distributions (SED). We derive an estimate of black hole masses through the analysis of the broad MgII emission lines observed in the medium-resolution spectra taken with VIMOS/VLT as part of the zCOSMOS project. Then, we estimated rest frame K-band luminosity
and total stellar mass (and their corresponding uncertainties) of the AGN hosts through an extensive SED fitting procedure, based on large databases of both phenomenological and theoretical galaxy spectra.

We found that, as compared to the local value, the average black hole to host galaxy mass ratio appears to evolve positively with redshift, with a best fit evolution of the form \((1 + z)^{0.68 \pm 0.12^{+0.6}_{-0.3}}\) (see Fig. 3), where the large asymmetric systematic errors stem from the uncertainties in the choice of IMF, in the calibration of the virial relation used to estimate BH masses and in the mean QSO SED adopted. A thorough analysis of observational biases induced by intrinsic scatter in the scaling relations reinforces the conclusion that an evolution of the \(M_{\text{BH}} - M_*\) relation must ensue for actively growing black holes at early times: either its overall normalization, or its intrinsic scatter (or both) appear to increase with redshift.

4.1. Implications for theoretical models

Such an evolution is at odds with the predictions of essentially all feedback models in which the black hole energy injection is very fast (explosive). Indeed, the first published predictions of merger-induced AGN activity models (Robertson et al. 2006) indicated that, if strong QSO feedback is responsible for rapidly terminating star formation in the bulge, as in the models of Di Matteo et al. (2005), then very little evolution, as well as very little scatter, is expected for the scaling relations. However, later works within the same theoretical framework (Hopkins et al. 2009) have analyzed in greater depths the role of dissipation in major mergers at different redshift. Under the assumption that black hole and spheroids obey a universal “black hole fundamental plane”, where \(M_{\text{BH}} \propto M_* \sigma_*^2\), they show how, in gas-richer environments (at higher redshift), dissipation effects may deepen the potential well around the black hole, allowing it to grow above the local \(M_{\text{BH}} - M_*\) relation, to a degree marginally consistent with our results. Another, related effect was discussed in Croton (2006). There it was assumed that major mergers can trigger both star formation in a bulge as well as black hole growth, in a fixed proportion. However, bulges can also acquire mass by disrupting stellar discs, a channel that should not contribute to black hole growth. The relative importance of these two paths of bulge formation may lead to lighter bulges for a given black hole mass at high redshift, as disks have a smaller stellar fraction (see also Malbon et al. 2007).

5. Concluding remarks

The overall growth of SMBH through accretion is now quite well sampled, mainly thanks to multi-wavelength coverage of X-ray selected AGN in large surveys. The main missing ingredients here are the exact census of the heavily obscured (Compton thick) objects and a more robust determination of bolometric corrections as a function of luminosity, black hole mass and Eddington ratios (Vasudevan & Fabian 2007). The kinetic luminosity function of AGN is less well constrained than the radiative one, due to a poorer knowledge of both high redshift radio luminosity functions and the robust calibration of the relationship between mechanical power and radio luminosity.
Notwithstanding these last open issues, we have argued here that strong observational indications can be gathered on the cosmological evolution of the SMBH population and of its overall energy output rate. The final link between such studies and the understanding of the physical relations between growing black holes and their hosts will rest on future progresses in the joint study of AGN and galaxies. In particular, the redshift evolution of the scaling relations will likely be an important testbed for structure formation models.

From the observational point of view, it will be very important to explore methods to derive robust black hole mass estimates in high redshift samples of obscured AGN, that can be selected purely on the basis of their host galaxy properties. Broad emission lines at longer wavelengths, where the effect of obscuration are less severe, could be very useful in this respect. Also, a better understanding of the differences in the hosts’ properties of active and inactive black holes is needed to allow a more meaningful comparison with the local scaling relations, and a better assessment of their evolution. From the theoretical point of view, more efforts should be devoted to derive robust predictions for the coupled evolution of slope, normalization and intrinsic scatter in the scaling relations.

Acknowledgments. I am grateful to my collaborators A. Bongiorno, M. Brusa, S. Heinz, and all the members of the COSMOS and zCOSMOS teams for their essential contribution to the work presented here.

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