Co-Evolution of Central Black Holes and Galaxies
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Merger-Induced Quasars, Their Light Curves, and Their Host Halos

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Abstract. We revisit a basic model of quasar activation by major mergers of dark matter halos (with "galactic" masses of $\lesssim 10^{13}\, M_{\odot}\, h^{-1}$). This model usually consists of two main ingredients: the halo merger rate describing triggering, and a quasar light curve, which describes the evolution of individual quasars. We show how the matching between model predictions and a variety of new, independent data sets allows one to efficiently constrain several aspects of black hole growth and evolution that must be taken into account in future studies by more advanced models of galaxy formation. Our results can be summarized as follows: (1) A descending phase modelled such that quasars in more massive halos shut down faster than those in less massive ones allows a good description of the bright end of the AGN luminosity function at all epochs and is compatible with downsizing, with more massive galaxies shutting down star formation earlier. (2) We measure the average bias of type 2 AGNs in SDSS to be $b = 1.233 \pm 0.195$, independent of luminosity in the range $42.5 \leqslant \log L(\mathrm{erg\,s^{-1}}) \leqslant 45.5$. Such a value of the bias implies that faint AGNs at $z < 0.3$ are mainly hosted by halos more massive than $\sim 10^{11.5-12} M_{\odot}\, h^{-1}$. The black hole mass function predicted by this model is flatter than previously found. (3) The high clustering signal measured at $z > 3$ in SDSS forces successful models to be characterized by rather short delay times of $t_{\mathrm{delay}} \lesssim 10^{8}$ yr between the triggering and the shining epochs, implying massive "seed" BHs $\gtrsim 10^{5} M_{\odot}\, h^{-1}$ and initial super-Eddington growth. (4) The low number counts of X-ray AGNs measured in recent deep surveys are better reproduced by models with a minimal post-peak phase and a higher minimum hosting halo mass at high redshifts. (5) Cross-correlating the feedback-constrained M_{BH}–M relation, with the redshift-dependent M_{star}–M relation obtained from the cumulative number-matching of the stellar and halo mass functions, we find a factor of ~ 2 larger BH-to-stellar mass ratio at high redshifts. We discuss the meaning of such trends in connection with the mild, positive evolution in the M_{BH}-σ_{star} relation, and the strong observed evolution in the sizes and velocity dispersions of their hosts.

Keywords. black hole physics, methods: statistical, galaxies: evolution, galaxies: active, (cosmology:) large-scale structure of universe

1. Introduction

Our universe is well-described by a ΛCDM expanding cosmology, where structures assemble hierarchically via mergers of dark matter halos. These halos provide the gravitational potential wells where gas can cool and fragment, allowing the formation of stars and galaxies (e.g., White & Rees 1978). It is natural to expect that halo mergers are followed by the mergers of the galaxies they harbor. Moreover, it has been suggested that major mergers of gas-rich galaxies are an efficient mechanism to feed super-massive black holes (BHs). This suggestion is supported by hydrodynamic simulations, where mergers produce gravitational torques, which induce strong gas inflows into the center (e.g., Hernquist 1989). In this scenario, the hierarchical assembly of halos serves as the backbone of the co-evolution of galaxies and their nuclear BHs. The problem with this picture is that while the halo hierarchy continues today, observations show that the peak of quasar activity (and galaxy formation) has already passed (e.g., Osmer 1982). Reconciling these two seemingly contradictory pictures requires a deeper understanding of the evolution of BHs and their host galaxies. Different galaxy formation models often reach opposite conclusions on BH evolution, even though they match similar sets of observables (e.g., Lapi *et al.* 2006; Malbon *et al.* 2007). However, our poor knowledge of BH evolution and accretion physics still prevents us from drawing any firm conclusion. For this reason it is essential to step back and attempt to probe some of the central mechanisms regulating BH evolution with more transparent and basic recipes. Here we discuss a simple and concise model, based on very general and widely adopted (and accepted) physical assumptions. We show that by matching the predictions of such a basic model with a variety of different observations, we can identify quite general and important characteristics of BH evolution, which must be seriously considered by more advanced galaxy formation models.

2. The Model

Our model consists of two ingredients: (1) the halo merger rate, which describes major mergers as the trigger of AGN activity, and (2) the light curve, which describes the evolution of individual quasars. These two ingredients are described below.

We adopt as input the merger rate $R(\xi, M, z)$ at redshift z of halos of mass m with halos of mass m' (with $\xi = m/m' \leqslant 1$), producing halos of mass $M = m + m'$. The merger rate per unit halo, $R(\xi, M, z)/n(M, z)$, with $n(M, z)$ is the halo mass function derived from Sheth & Tormen (1999), is fitted from numerical simulations by Fakhouri & Ma (2008), and we use their results in our calculations. Their fit is a simple product of functions of M, ξ and z, and is accurate to the 10–20% level, a negligible uncertainty with respect to the error bars in the observables we will be comparing with.

We assume that once the merger takes place (at some triggering time $t_{\rm trig}$) the BH begins to accrete at some constant multiple of the Eddington rate λ_0. The light curve here is in the ascending phase of fast accretion, and the associated bolometric luminosity is $\mathcal{L} = \lambda_0 L_{\rm Edd}$, with $L_{\rm Edd}$ the Eddington luminosity. The ascending phase reaches its peak luminosity when the feedback is powerful enough to unbind gas from the potential well. Subsequently, accretion by the BH becomes substantially inefficient, and is eventually terminated. Following Wyithe & Loeb (2003), we postulate this condition to have the form

$$\frac{L_{\rm peak}}{(10^{44}{\rm erg\ s^{-1}})} = 7\left(\frac{M}{10^{12}M_\odot h^{-1}}\right)^{5/3}(1+z)^{5/2}\,, \tag{2.1}$$

where M is the mass of the host dark matter halo at the time of triggering. As also shown in hydrodynamic simulations (e.g., Hopkins *et al.* 2006), accretion is halted as the feedback energy couples to the gas reservoir, leading to a nearly self-similar power-law decay, $\mathcal{L}(t) \propto t^{-\alpha}(M)$. We model the descending phase as a *mass-dependent* power-law, to make contact with direct observations concluding that star formation in massive systems is quenched faster than in less massive ones (e.g., Bundy *et al.* 2008).

The luminosity function is defined as the comoving number density of quasars *shining* with bolometric luminosity between L and $L + dL$ at redshift $z_{\rm shine}$. We model this as

$$\Phi(L, z_{\rm shine})dL = dL\int_{z_{\rm zhi}}^{\infty} dz_{\rm trig}\int dM\int_{M/4}^{M/2} dm \tag{2.2}$$

$$\times R(m, M-m, z_{\rm trig})\,\delta_d(L-\mathcal{L}(z_{\rm shine}))\,W_\Sigma[L_{\rm peak}, M, z_{\rm trig}]. \tag{2.3}$$

Let us explain this expression physically — it can be interpreted as two selection effects.

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First consider all mergers producing halos of mass M at some redshift $z_{\rm trig} > z_{\rm shine}$. The first selection is imposed by the Dirac delta, which only chooses those M-halos whose associated AGN light curve $\mathcal{L}$ shines in the $(L, L+dL)$ bin precisely at our redshift $z_{\rm shine}$ of interest. For some, this luminosity will be in the ascending phase while for others it will be in the descending phase. The second selection is on the type of mergers involved. The integral from $M/4$ to $M/2$ only chooses those mergers where the ratio of the constituents is $m/(M-m) > 1/4$ ($\xi > \xi_{\rm min} \sim 0.3$). Lastly, just like the Magorrian relations have scatter, it is natural to model our self-regulation condition with some scatter. For this purpose, we assume that the $L_{\rm peak}$–M relation has a log-normal distribution of width $\Sigma \sim 0.3$ dex.

To further test our models, we compute the large scale clustering as a function of luminosity and redshift $b(L, z_{\rm shine})$ by summing up the contributions of all halos that shine with luminosity L and $L+dL$ between $z_{\rm trig}$ and $z_{\rm shine}$. In doing so, we also take into account the passive evolution of the bias between any $z' > z_{\rm shine}$ and $z_{\rm shine}$ via the Fry (1996) formula with the halo bias $b(M, z)$ taken from Sheth *et al.* (2001).

3. Results

As presented by Shankar *et al.* (2010), our basic model (with $M_{\rm min} \gtrsim 4\times 10^{11}\, M_\odot\, h^{-1}$ and $\xi > 0.25$) can reproduce the bolometric luminosity function (see Figure 1) and bias as a function of luminosity at all redshifts $0.1 \lesssim z \lesssim 6$. In the alternative framework in which all BHs of any mass are characterized by the same (mass-independent) light curve,

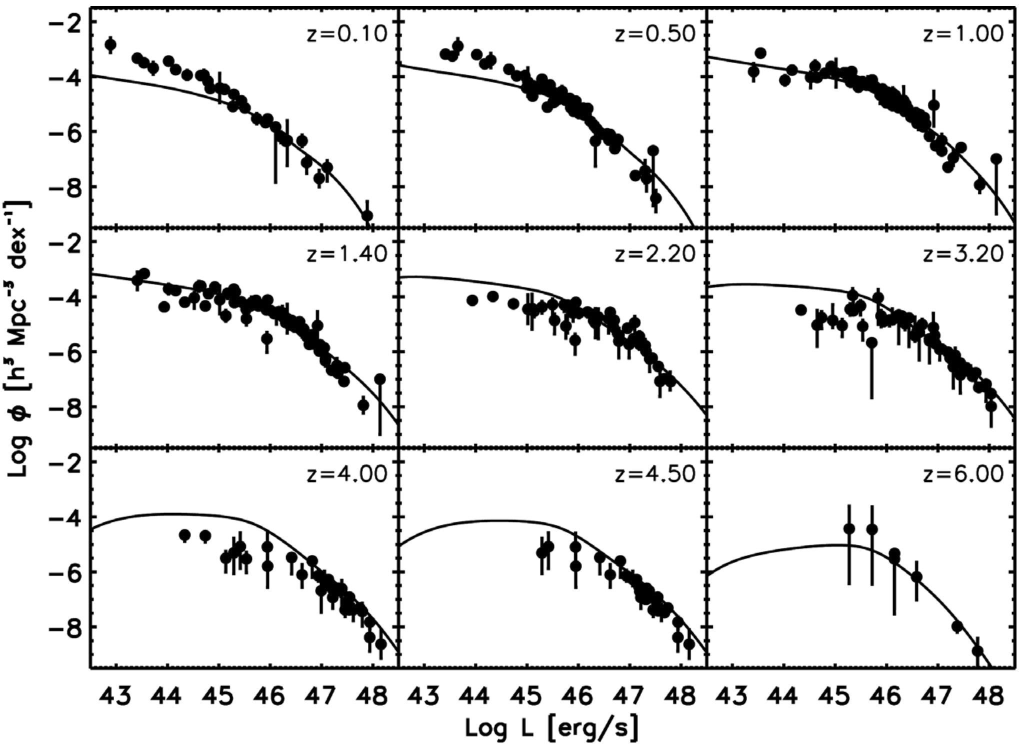

Figure 1. Predicted bolometric luminosity function at different redshifts, as labeled. At low redshifts, the major-merger model fails to reproduce the faint end of the luminosity function, as expected. All the data are from Shankar *et al.* (2009) and references therein.

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the low-z bright-end AGN luminosity function is inevitably overproduced (e.g., Wyithe & Loeb 2003). The success of the model discussed here is actually quite noticeable. In fact, as discussed by several authors (e.g., Scannapieco & Oh 2004; Shen 2009), the simultaneous match to the low and high-redshift luminosity function within AGN feedback-constrained theoretical frameworks requires additional input physics (and parameters) for the models to be successful (such as progressive gas exhaustion, radio-mode feedback, etc.). Another interesting feature of this basic model is that the faint end of the predicted luminosity function flattens out at $z \gtrsim 1.5$ (see Figure 1), with an increasing flattening up to $z \sim 6$. If planned deep future surveys with *JWST* unveil a non-negligible population of faint AGNs at $z \gtrsim 5$, this will be direct proof that major mergers alone cannot be the only trigger of quasar activity, not even at very high redshifts. The model described here also naturally yields Eddington ratio distributions well described by a Gaussian with a median and dispersion around the mean very similar to what is observed by, e.g., Kollmeier *et al.* (2006).

A model composed of only major mergers, the number of which rapidly declines with time, cannot account for the large population of $z \lesssim 1$ faint AGNs (see upper panels of Figure 1). So what is producing those faint AGNs? We measure the average bias of type 2 AGNs in the Sloan Digital Sky Survey (SDSS) to be $b = 1.233 \pm 0.195$, independent of

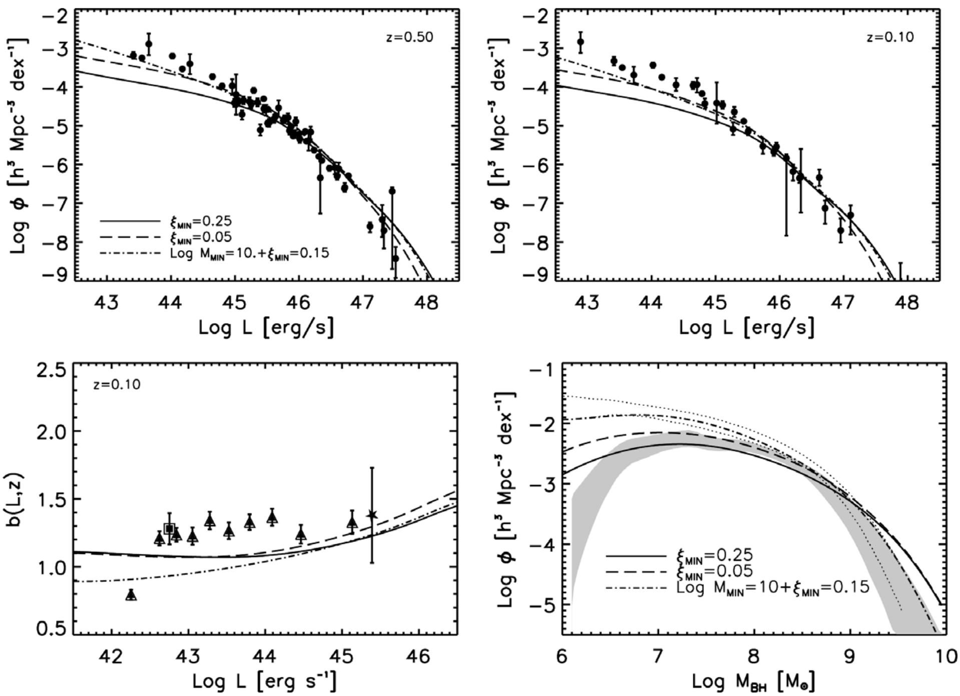

Figure 2. Comparison between the reference model, characterized by having only major merger events in massive halos (solid lines), and two other models. One model is specified by having fainter AGNs produced in less massive halos, with $\log(M_{\rm min}/M_{\odot}h^{-1}) = 10$ (dot-dashed lines), and another one where the faintend of the AGN luminosity function is produced by black holes in more massive halos triggered also by minor events with $\xi > 0.05$ (long-dashed lines). Only the latter model is simultaneously more consistent with the clustering data (*lower left*) and the $z < 1$ luminosity function (*upper*). This same model also produces a flatter black hole mass function at $z \sim 0$ (*lower right*); the gray band is the local black hole mass function computed from the velocity dispersion function of early-type galaxies, while the dotted lines are from Shankar *et al.* (2009).

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luminosity in the range $42.5 \leqslant \log L(\mathrm{erg\ s^{-1}}) \leqslant 45.5$ (Figure 2, lower left). Such a value of the bias implies that faint AGNs at $z \lesssim 0.5$ are mainly hosted by halos more massive than $M \sim 10^{11.5-12} M_{\odot}\, h^{-1}$, thus favoring models (long dashed lines in Figure 2) in which AGN activity is triggered in halos undergoing major and minor mergers (with $\xi \geqslant 0.05$), producing low Eddington-rate quasar events.

The integrated BH mass function from the major-merger model alone (solid lines in Figure 2) is consistent with the local BH mass function derived from the early-type galaxy population (grey band in lower right panel of Figure 2) if the radiative efficiency is $\epsilon \leqslant 0.1$. This result is robust against systematics affecting the bolometric corrections or the exact shape of the quasar luminosity function. We find that the major plus minor-merger model (long-dashed lines) predicts a similarly flat BH mass function at $z = 0$, while a pure major-merger model extended to the very low host halo masses of $M \sim 10^{10} M_{\odot}\, h^{-1}$ (dot-dashed lines) produces a much steeper BH mass function, but is not consistent with the clustering data (lower left panel of Figure 2), although it still matches the luminosity function (upper panels of Figure 2). Independent, secure measurements of the local BH mass function are needed to further constrain viable models.

The high clustering signal measured at $z > 3$ in SDSS forces successful models to be characterized by rather short delay times of $t_{\mathrm{delay}} \lesssim 10^8$ yr between the triggering and the shining epochs. If the delay time is in fact too long, the bias characterizing the high-σ peaks of quasar host halos will rapidly drop as $b \propto (1+z)^{1.5}$ for the masses of interest here. Such conditions for short delays are more easily met if the "seed" BH mass is $\gtrsim 10^5 M_{\odot}$, and the initial growth is super-Eddington, as shown in the left panel of Figure 3.

The right panel of Figure 3 shows instead that the exponential drop characterizing the $z > 3$ number counts of X-ray AGNs (Brusa *et al.* 2009) is better reproduced by models with a minimal post-peak phase (labeled as "CUT" in the Figure), a condition that reduces the probability for a BH to shine at lower luminosities, lower Eddington ratios, and a higher minimum halo mass ($M_{\mathrm{min}} \gtrsim 10^{12} M_{\odot}\, h^{-1}$) hosting quasars.

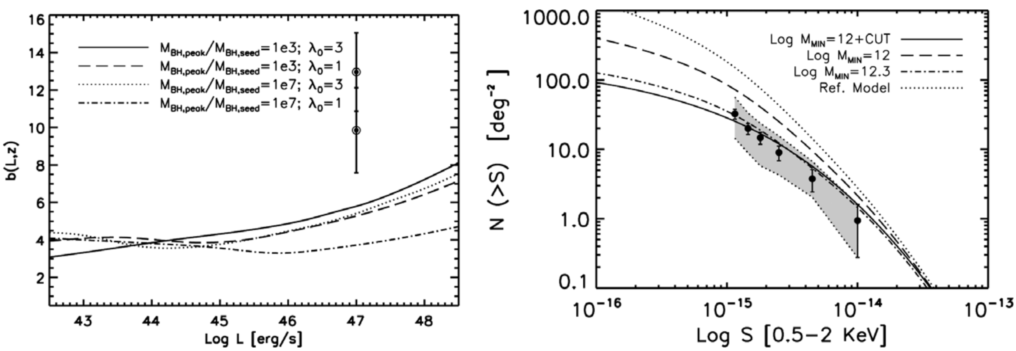

Figure 3. *Left:* Comparison among models characterized by different delay times. Models with longer delays between the virialization epoch and the shining of the quasar, i.e., with lower λ_0 and/or higher ratios between peak and seed masses, as labeled, tend to generate a lower bias at fixed luminosity due to the passive evolution of the bias, especially relevant at high redshifts. The high-z quasar clustering measured by Shen *et al.* (2007) favors models characterized by massive seeds and high Eddington ratios, conditions which minimize the delay. *Right:* Predicted X-ray number counts for different models, as labeled, compared with the data by Brusa *et al.* (2009) at $z > 3$. Overall, the available data favor models with a higher M_{min} and possibly a minimal descending phase.

4. Discussion

We find, intriguingly, that a merger-driven model like the one presented here cannot be, by construction, self-consistent. In fact, applying the self-regulation condition to the incoming merging halos at their respective triggering epochs would force them to host BHs much more massive than the final BH in the descendant halo. This proves that the BH mass at the triggering in the descendant halo must be close to the true seed BH mass, or at least it should not have experienced any previous major, self-regulated growth.

On other grounds, a feedback-constrained relation $M_{\rm BH}$–$V_{\rm vir}$ is consistent with a non-evolving $M_{\rm BH}$–$\sigma_{\rm star}$ relation, if $\sigma_{\rm star}$ is simply proportional to $V_{\rm vir}$ at all times. However, recent observations suggest that at fixed stellar mass, early-type, massive galaxies at high-z were more compact with a higher $\sigma_{\rm star}$ at the moment of the quasar shining, implying a lower BH mass at fixed velocity dispersion. On the other hand, direct observations and cumulative arguments (Shankar *et al.* 2009b) support, if anything, a mild *positive* evolution in the normalization of the $M_{\rm BH}$–$\sigma_{\rm star}$ relation. We speculate that such apparent contradictions might be resolved by allowing the galactic host to have a smaller bulge stellar mass associated with the BH at the moment of the quasar shining. Cross-correlating the feedback-constrained $M_{\rm BH}$–M relation, with the redshift-dependent $M_{\rm star}$–M relation obtained from the cumulative number matching of the stellar and halo mass functions, we in fact find tentative evidence for a factor of $\gtrsim 2$ larger BH-to-stellar mass ratio at high redshifts, which might support the above argument and also some direct observations and clustering measurements.

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