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Co-Evolution of Supermassive Black Holes and Their Host Galaxies

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Abstract. We study the evolution of the $M_{\rm BH}/M_{\rm host}$ relation up to $z = 3$ for a sample of 96 quasars with known host galaxy luminosities. Black hole masses are estimated assuming virial equilibrium in the broad-line regions, while the host galaxy masses are inferred from their luminosities. With this data, we are able to pin down the evolution of the $M_{\rm BH}/M_{\rm host}$ relation over 85% of the age of the universe. While the $M_{\rm BH}/L_{\rm host}$ relation remains nearly unchanged, taking into account the aging of the stellar population, we find that the $M_{\rm BH}/M_{\rm host}$ ratio (Γ) increases by a factor ~ 7 from $z = 0$ to $z = 3$. We show that the evolution of Γ is independent of radio loudness and quasar luminosity. We propose that the most massive black holes, in their quasar phase at high-redshift, become extremely rare objects in host galaxies of similar mass in the local universe.

Keywords. galaxies: active, galaxies: evolution, galaxies: high-redshift, galaxies: nuclei (galaxies:) quasars: general

1. Introduction

Many pieces of evidence suggest that supermassive black holes (BHs) and their host galaxies share a joint evolution: (1) the evolution of the quasar luminosity function (LF; Fontanot *et al.* 2007) closely matches the evolution of the star formation density (Madau *et al.* 1998), (2) massive BHs are found in virtually all massive galaxies (Decarli *et al.* 2007), and (3) their masses $M_{\rm BH}$ are tightly correlated with the stellar velocity dispersion σ_*, luminosity $L_{\rm host}$, and mass $M_{\rm host}$ of their host galaxies (e.g., Gultekin *et al.* 2009).

When and how these relations set in, and which are the physical processes responsible for their onset are still open questions, despite large efforts both theoretically (e.g. Wyithe & Loeb 2006; Hopkins *et al.* 2007) and observationally (McLure *et al.* 2006; Peng *et al.* 2006; Salviander *et al.* 2007; Woo *et al.* 2008).

Probing BH–host galaxy relations at high redshift is extremely challenging. Direct measurements of $M_{\rm BH}$ from gaseous or stellar dynamics require observations capable of resolving the BH sphere of influence, which is feasible only for a limited number of nearby galaxies. The $M_{\rm BH}$ can be measured in galaxies at distances larger than a few tens of Mpc only in type 1 AGN, where it can be inferred from the width of emission lines Doppler-broadened by the BH potential well and from the AGN continuum luminosity (e.g., Vestergaard 2002), assuming virial equilibrium. Quasars therefore represent the best tool to probe $M_{\rm BH}$ at high redshift, thanks to their huge luminosities. Indeed, large-field spectroscopic surveys allow estimates of $M_{\rm BH}$ for several thousands of objects (e.g., Shen *et al.* 2008; Labita *et al.* 2009a). On the other hand, the nuclei in quasars outshine the emission from the host galaxies, making their detection challenging. Only recently have the intrinsic (e.g., the nucleus-to-host luminosity ratio N/H) and extrinsic (e.g., the angular size of the host with respect to the angular resolution of the observations) limitations have been overcome, with the current total of $\sim$ 300 resolved quasar host galaxies up to $z \sim 3$ (e.g., Kotilainen *et al.* 2009).

A number of limitations can affect studies of the evolution of the $M_{\rm BH}$–$M_{\rm host}$ relation:

1. All studies to date use different $M_{\rm BH}$ proxies as a function of redshift (usually based on Hβ at $z \lesssim 0.5$, Mg II for $0.5 \lesssim z \lesssim 2$, and C IV at $z \gtrsim 1.6$).

2. Selection biases related to luminosity or flux limits, range of N/H sampled, and the steepness of the bright end of the galaxy and quasar LFs (e.g., Lauer *et al.* 2007).

3. As the properties of quasar host galaxies are directly observed only in a limited number of objects, poor statistics usually affect the available datasets. This study represents a significant effort in overcoming all these limitations. For a full discussion, see Decarli *et al.* (2009a,b).

2. Evolution of the $M_{\rm BH}$–$L_{\rm host}$, $M_{\rm host}$ Relations

In Figure 1, we compare our $M_{\rm BH}$ estimates with the predictions of Bettoni *et al.* (2003) relation, defined by $z \approx 0$ galaxies, and with the expectations of a fixed $M_{\rm BH}/M_{\rm host} = 0.002$ ratio, as observed in local inactive galaxies (Marconi & Hunt 2003).

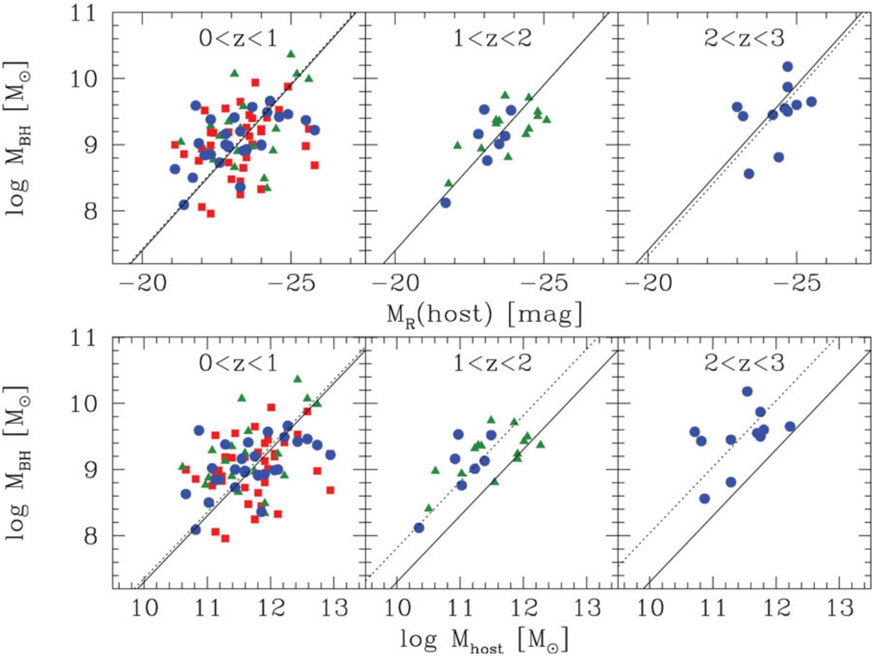

Figure 1. The $M_{\rm BH}$–$L_{\rm host}$ and $M_{\rm BH}$–$M_{\rm host}$ relations in three redshift bins. Squares, triangles and circles mark quasars in which $M_{\rm BH}$ is derived from Hβ, Mg II, and C IV, respectively. The solid line is the Bettoni *et al.* (2003) relation (*upper panels*) or $M_{\rm BH}/M_{\rm host} = 0.002$ (*lower panels*). The dotted line is the best fit to the data, assuming the slope of the rest-frame relations. Clear evolution is apparent in the $M_{\rm BH}$–$M_{\rm host}$ relationship as a function of redshift.

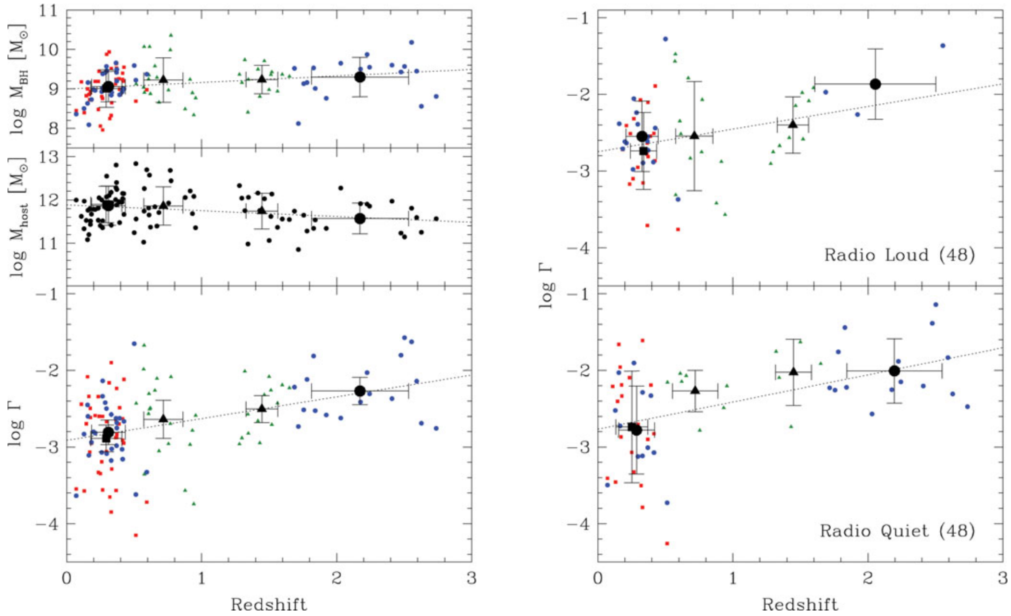

Figure 2. *Left*: The redshift dependence of $M_{\rm BH}$ (*top panel*), $M_{\rm host}$ (*middle panel*), and Γ (*bottom panel*). Symbols are as in Figure 1. The best linear fits, and the average points with rms as error bars of the Hβ (big square), the low- and high-z C IV (big circles) and the Mg II data with redshift $z < 1$ and $z > 1$ (big triangles) are shown. *Right*: The redshift dependence of Γ for radio-loud (*top panel*) and radio-quiet quasars (*bottom panel*).

The $M_{\rm BH}$–$L_{\rm host}$ relation appears insensitive to cosmic epoch, independent of which line is used to estimate $M_{\rm BH}$. When correcting for the evolution of the stellar mass-to-light ratio, we find a clear increase (~ 0.7 dex) of the $M_{\rm BH}/M_{\rm host}$ ratio with respect to the local universe. In the left panel of Figure 2, $M_{\rm BH}$, $M_{\rm host}$, and their ratio Γ are plotted as a function of redshift. The linear best fit of log Γ suggests that galaxies with similar stellar masses harbour BHs ∼ 7 times more massive at $z = 3$ than galaxies at $z = 0$.

In the right panel of Figure 2, we compare radio-loud (RLQ) and radio-quiet quasars (RQQ), finding that both are consistent with the log Γ–z relation for the whole sample. The only difference is the offset, in the sense that, at any redshift, both BHs and host galaxies in RLQs are ∼ 0.2 dex more massive than in RQQs (e.g., Labita *et al.* 2009b).

2.1. *The Luminosity Function Bias*

Because of the steepness of the bright end of the galaxy luminosity (mass) function and intrinsic scatter in the $M_{\rm BH}$–$L_{\rm host}$ ($M_{\rm host}$) relation, very massive BHs are preferentially found in relatively faint (less massive) galaxies rather than in very rare, extremely bright (massive) galaxies (Lauer *et al.* 2007). Since high-z samples are dominated by massive objects, this bias increases with z, possibly mimicking evolution in Γ.

To quantify this bias, we assume that $M_{\rm BH}$ mostly depends on quasar luminosity. This is consistent with the relatively small range of Eddington ratio sampled. If σ_μ, the cosmic scatter of the $M_{\rm BH}$–$L_{\rm host}$ relation is constant in $L_{\rm host}$, at a given redshift the bias depends on the shape of the quasar LF. We assume the purely luminosity-evolving LF by Boyle *et al.* (2000). As a consequence, as long as we sample the same range of the quasar LF *at any redshift*, the bias is constant. A constant bias is irrelevant for this study, since our main aim is to probe the *redshift dependence* of the BH–host galaxy relations, not their absolute normalization.

The constant luminosity cut at $-26\,\mathrm{mag} > M_V > -27\,\mathrm{mag}$ and the $M_* > M_V > M_* - 1$ cut roughly bracket the objects in our sample over five magnitudes in M_V. Hence, for the whole sample, the bias on $M_{\rm BH}$ will lie within the expectations from these two cases. We calculate that the bias accounts for $\lesssim 0.11$ dex, i.e., about a factor 1.3 from $z = 0$ to $z = 3$. As the observed dependence of Γ is ~ 6 times larger, it cannot be explained by this selection effect.

2.2. *The Effects of the N/H Ratio*

All the quasars in our sample are selected on the basis of their total luminosity, which is dominated by the nuclear light. This introduces a possible bias, where for higher N/H, it is more difficult to measure the host-galaxy luminosity, especially at high-z. However, the redshift-dependence of Γ in high- and low-N/H objects is similar. Moreover, if we include any unresolved quasars, the trend would be even steeper, as they all lie at high-z.

2.3. *The Role of Radiation Pressure*

Marconi *et al.* (2009) suggest that the virial estimates of $M_{\rm BH}$ may yield lower limits to the *true* BH mass, if radiation pressure is not taken into account. If the BLR clouds are virialized, a correction can be applied by adding a term depending on the BLR column density $N_{\rm H}$ and quasar luminosity. However, as the role of the radiation pressure in the BLR is still not clearly understood, especially in the most luminous AGN, we only note that since the average luminosity in our sample increases with z, the radiation pressure effect is expected to become more severe at higher z, leading to an even steeper increase in Γ than that observed.

3. Discussion

3.1. *Comparison with Previous Results*

We find that the $M_{\rm BH}/M_{\rm host}$ ratio significantly increases with redshift. Here we compare that result with those of other studies in the literature.

McLure *et al.* (2006) match the average trend of $M_{\rm BH}$ observed in 38 RLQs at $z < 2$ with typical stellar masses of massive radio galaxies at same redshifts. This approach assumes that quasar host galaxies are comparable to massive radio galaxies. Their results may be biased by the different histories of quasar and radio galaxies (e.g., the LFs of AGN evolve differently for various luminosity subclasses). Nevertheless, McLure *et al.* (2006) find an increase of Γ comparable to that observed here. Our results extend these findings to RQQs and beyond the peak age of quasar activity.

Peng *et al.* (2006) study the evolution of the $M_{\rm BH}$–$M_{\rm host}$ relation in ~ 20 low-z quasars and in ~ 30 high-z lensed quasars imaged with *HST*. Their data show a large scatter, possibly due to uncertainties in the modelling of the lens mass distribution and the lens light subtraction. They find practically no evolution in the $M_{\rm BH}$–$L_{\rm host}$ relation, but correcting for the evolution of the stellar population, there is a clear increase in Γ at high-z with respect to the local $M_{\rm BH}$–$M_{\rm host}$ relation, in agreement with our findings.

Merloni *et al.* (2010) study the $M_{\rm BH}$–$M_{\rm host}$ ratio in 89 type 1 AGN with $1 < z < 2.2$ from the zCOSMOS survey. BH masses are derived virially, while the host-galaxy luminosities and stellar masses are inferred from multiwavelength fitting of the SEDs. This technique is effective for intermediate to low-luminosity AGN, though it cannot be applied to quasars, where the nuclear light overwhelms the galaxies. They find that the average Γ is higher than observed locally, consistent with the trend observed in our study. Jahnke *et al.* (2009) observed 10 targets with *HST* and independently derived host galaxy luminosities with a procedure similar to that adopted here (see, e.g., Kotilainen *et al.* 2009). They find no evolution in the total $M_{\rm BH}$–$M_{\rm host}$ ratio. However, as disks are present in many of their targets, the bulge $M_{\rm BH}$–$M_{\rm host}$ ratio is expected to evolve in agreement with our findings.

Additional indications of the evolution of Γ comes from the evolution of $M_{\rm BH} - \sigma_*$ relation. Salviander *et al.* (2007) use the width of the [O III] narrow emission line as a proxy for σ_* and study the $M_{\rm BH}$–σ_* relation in ~ 1600 quasars up to $z = 1.2$ from SDSS. They find that $M_{\rm BH}$ at high redshift are ~ 0.2 dex larger than expected from local $M_{\rm BH}$–σ_* relation. Smaller evolution ($\lesssim 0.1$ dex) is also proposed by Shen *et al.* (2008), for 900 type 1 AGN with $z \lesssim 0.4$. Woo *et al.* (2008) address the $M_{\rm BH}$–σ_* relation in Seyfert galaxies up to $z \sim 0.6$, and find an $M_{\rm BH}$ excess at high redshift. These findings support our results, notwithstanding the different characteristic luminosities, morphologies, and stellar contents of the sample targets.

These results depict a scenario where, for a given quasar host galaxy, the central BH at high redshift is over-massive with respect to its low-z counterparts. This picture is also consistent with the constraints on the $M_{\rm BH}$–$M_{\rm host}$ evolution derived from the comparison between the galaxy stellar mass function and the quasar LF (Somerville 2009).

3.2. *Why Does* Γ *Evolve?*

If high-z quasars move towards the local $M_{\rm BH}$–$M_{\rm host}$ relation, the unavoidable consequence of our results is that, at a given $M_{\rm BH}$, galaxy masses increase from $z = 3$ to the present age. We sketch three ways for this, and an alternative scenario, where the remnants of high-z quasars keep high Γ values down to the present age.

The first scenario involves substantial *mass growth of quasar host galaxies through mergers*. Strong gravitational interactions may trigger intense gas infall into galaxy centres and lead to activation of BH accretion. However, ΛCDM models (e.g., Volonteri *et al.* 2003) predict for a massive galaxy only one or two major mergers from $z = 3$ to $z = 0$, whereas the required increase in the stellar mass of the host galaxies indicates that they would have to suffer three or more major mergers. Furthermore, massive inactive galaxies and quasar host galaxies are likely to have already assembled the majority of their mass at $z \gtrsim 3$ (e.g., Kotilainen *et al.* 2009). Any episodic rejuvenation of stellar population only marginally affects the mean age of stellar content. If galaxies enter the quasar phase ~ 1 Gyr after the activation of the starburst, then the mass involved is ~ 30 % of the initial mass of the galaxy. Moreover, if quasar host galaxies contain a significant young stellar population, then their M/L ratio would be smaller. Therefore, young host galaxies at high-z would yield even steeper Γ–z relation than that observed here.

Another interpretation is that *high-redshift quasar host galaxies are gas rich*, and form a significant fraction of their stellar content relatively recently. In this picture, the BH mass is more sensitive to the energy budget or dynamical mass of the galaxy than its stellar mass (e.g., Hopkins *et al.* 2007). This scenario is disfavoured as all the host galaxies in our sample are massive ellipticals, whose stellar content is usually old. Moreover, if significant recent star formation occurred in quasar host galaxies, the evolution of Γ would be much steeper, making this scenario even less realistic.

Inactive, massive ellipticals may be *more compact at high redshift* than locally (Trujillo *et al.* 2006). In particular, at high z, the velocity dispersion σ_* is higher. If $M_{\rm BH}$ regulates the host galaxy σ_* (e.g., Silk & Rees 1998) so that the $M_{\rm BH}$–σ_* relation does not evolve significantly, then even a small (a factor ~ 1.6) increase of σ_* for a given galaxy would yield a factor of 7 increase in Γ. However, the average $M_{\rm BH}$ for a given σ_* appears to increase from the local to the high-z universe (Salviander *et al.* 2007; Woo *et al.* 2008).

We propose an alternative scenario where the local counterparts of high-z quasars are *high-mass outliers* above the $M_{\rm BH}$–$M_{\rm host}$ relation. The more massive the BH, the earlier it experiences its quasar phase. These objects are expected to have high Γ, but they are extremely rare, and contribute only marginally to the present $M_{\rm BH}$–$M_{\rm host}$ relation. In particular, $2 < z < 3$ quasars should appear locally as inactive massive galaxies with $M_{\rm BH} \sim 10^{9.5}\, M_\odot$. Assuming the mass function of quasars by Vestergaard & Osmer (2009), in a volume corresponding to the most distant inactive BH with a direct mass measurement, virtually no objects are expected with such high values of Γ.

4. Conclusions

We have studied the $M_{\rm BH}$–$M_{\rm host}$ relation as a function of redshift in a sample of 96 quasars from the present age to $z = 3$, i.e., over 85% of the age of the universe. We find that the $M_{\rm BH}$–$M_{\rm host}$ ratio (Γ) increases by a factor ~ 7 from $z = 0$ to $z = 3$. This trend is not significantly affected by selection criteria or observational biases. Moreover, it is independent of quasar luminosity and radio loudness. This trend indicates that the most massive black holes, in their quasar phase at high redshift, keep their high values of Γ down to the present age, becoming very rare objects in the local universe.

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