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The quasar $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relation through cosmic time – II. Evidence for evolution from $z = 3$ to the present age

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ABSTRACT

We study the dependence of the $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relation on the redshift up to $z = 3$ for a sample of 96 quasars, the host galaxy luminosities of which are known. Black hole masses were estimated assuming virial equilibrium in the broad-line regions, while the host galaxy masses were inferred from their luminosities. With these data, we are able to pin down the redshift dependence of the $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relation along 85 per cent of the Universe age. We show that, in the sampled redshift range, the $\mathcal{M}_{\rm BH}$–$L_{\rm host}$ relation remains nearly unchanged. Once we take into account the ageing of the stellar population, we find that the $\mathcal{M}_{\rm BH}/\mathcal{M}_{\rm host}$ ratio (Γ) increases by a factor of ∼7 from $z = 0$ to $z = 3$. We show that Γ evolves with z regardless of the radio loudness and of the quasar luminosity. We propose that the most massive black holes, living their quasar phase at high redshift, become extremely rare objects in host galaxies of similar mass in the Local Universe.

Key words: galaxies: active – galaxies: nuclei – quasars: general.

1 INTRODUCTION

Many pieces of evidence suggest that supermassive black holes (BHs) and their host galaxies share a joint evolution throughout cosmic time. In particular, (i) the evolution of the quasar luminosity function (Dunlop & Peacock 1990; Fontanot et al. 2007; Croom et al. 2009) closely matches the trend of the star formation density through cosmic ages (Madau, Pozzetti & Dickinson 1998), (ii) massive BHs are found in virtually all massive galaxies (Kormendy & Richstone 1995; Decarli et al. 2007) and (iii) their mass ($\mathcal{M}_{\rm BH}$) is tightly correlated with the large-scale properties (stellar velocity dispersion, σ_*; luminosity, $L_{\rm host}$; mass, $\mathcal{M}_{\rm host}$) of their host galaxies (see Ferrarese 2006; Gültekin et al. 2009 for recent reviews on this topic).

When and how these relations set in, and which are the physical processes responsible for their onset are still open questions, despite the large efforts perfused from both a theoretical (e.g. Silk & Rees 1998; King 2005; Robertson et al. 2006; Wyithe & Loeb 2006; Hopkins et al. 2007; Malbon et al. 2007) and an observational point of view (McLure et al. 2006; Peng et al. 2006a,b; Salviander et al. 2007; Woo et al. 2008).

Probing BH–host galaxy relations at high redshift is extremely challenging. Direct measurements of $\mathcal{M}_{\rm BH}$ from gaseous or stellar dynamics require observations capable of resolving the BH sphere of influence, which are feasible only for a limited number of nearby galaxies. The only way to measure $\mathcal{M}_{\rm BH}$ in distant (greater than few tens of Mpc) galaxies is to focus on type 1 active galactic nuclei (AGN), where $\mathcal{M}_{\rm BH}$ can be inferred from the width of emission lines Doppler broadened by the BH potential well and from the AGN continuum luminosity (see e.g. Vestergaard 2002), assuming the virial equilibrium. Quasars therefore represent the best tool to probe $\mathcal{M}_{\rm BH}$ at high redshift, thanks to their huge luminosity. Indeed, large-field spectroscopic surveys allowed the estimate of $\mathcal{M}_{\rm BH}$ in several thousands of objects (see, for instance, Shen et al. 2008a; Labita et al. 2009a,b). On the other hand, the AGN light in quasars outshines the emission from the host galaxies, making their detection challenging. Only recently, limitations due to intrinsic [e.g. the nucleus-to-host galaxy luminosity ratio (N/H)] and extrinsic (e.g. the angular size of the host with respect to the angular resolution of the observations) effects could be overcome. Optical images from the *Hubble Space Telescope* (*HST*) and near-infrared (NIR) observations from both space and ground-based telescopes could resolve ∼300 quasar host galaxies up to $z \sim 3$ (see e.g. Kotilainen et al. 2009 and references therein). Preliminary studies suggest that, for a given galaxy mass, BHs in high-z AGN are more massive than their low-z counterparts (e.g. McLure et al. 2006; Peng et al. 2006a,b).

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A number of limitations potentially affect the studies of the $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relation through cosmic time as follows. (1) All the works to date use different $\mathcal{M}_{\rm BH}$ proxies as a function of redshift (i.e. based on different broad emission lines: usually 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, to the sampled N/H, to the steepness of the bright end of the galaxy and quasar luminosity functions may hinder the study of the evolution of the $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relation (see, for instance, 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 data sets.

This study represents a significant effort in overcoming all these limitations: Thanks to UV and optical spectra of low-redshift quasars (Labita et al. 2006; Decarli et al. 2008) and to optical spectra of mid- and high-redshift quasars (Decarli et al. 2009b, hereafter Paper I), we can probe $\mathcal{M}_{\rm BH}$ using both high and low ionization lines in a wide range of redshifts, for the largest data set adopted so far in this kind of studies.

In Paper I, we presented the sample and inferred BH masses. Here, we describe the data sources for the host galaxy luminosities, infer $\mathcal{M}_{\rm host}$ and address the evolution of the $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relation.

Throughout the paper, we adopt a concordance cosmology with $H_0 = 70\,{\rm km\,s^{-1}\,Mpc^{-1}}$, $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$. We converted the results of other authors to this cosmology when adopting their relations and data.

2 $L_{\rm host}$ AND $\mathcal{M}_{\rm host}$ IN DISTANT QUASARS

For the purposes of this work, we have to define a homogeneous compilation of quasar host galaxy luminosities from data available in the literature. After that, we use the rest-frame *R*-band luminosities to infer the host galaxy stellar masses. We refer to Kotilainen et al. (2009) for a detailed discussion of technicalities in the luminosity estimate of quasar host galaxies from high-resolution imaging.

2.1 Host galaxy luminosities from the literature

For a complete list of data sources, we refer to the sample description in Paper I. Apparent magnitudes in the filters of the observations are converted to rest-frame *R*-band absolute magnitude as follows:

$$M_R = m_f - 5\log D_{\rm L}(z) - C(z) - A_f, \qquad (1)$$

where f is the original filter of the observations, $D_{\rm L}(z)$ is the luminosity distance of the quasar in the cosmological frame we adopted, $C(z)$ is a term accounting for filter and *k*-correction, as derived by assuming an elliptical galaxy template (Mannucci et al. 2001), and A_f is a term accounting for the Galactic extinction, as derived from the H I maps in Schlegel, Finkbeiner & Davis (1998). We remark that in order to minimize filter and colour corrections, we selected observations performed using filters roughly sampling the rest-frame *R* band. Moreover, the *R*-band luminosity is only marginally sensitive to the age of the stellar content. Thus, uncertainties in $C(z)$ due to the chosen host galaxy template are negligible ($\lesssim$0.1 mag) for the purposes of this work.

Low-z data taken with the *HST*-Wide Field Camera have been analysed by many authors, and different m_f estimates are available for the same object and *on the same data*. In particular, the studies of Bahcall et al. (1997), Hamilton, Casertano & Turnshek (2002) and Dunlop et al. (2003) significantly overlap on to the recent reanalysis presented by Kim et al. (2008a,b). When comparing the reported apparent host galaxy and nuclear magnitudes, we find that the average offset is usually negligible ($\lesssim$0.2 mag), but a significant scatter is present (rms $\sim$ 0.3–0.5 mag). When more than one estimate of m_f was available, we adopted the most recent one. No images of the mid- and high-z quasars in our sample were analysed independently by different groups; thus no superposition happens for these objects.

2.2 Host galaxy masses

In order to infer the stellar mass from the host galaxy luminosity, we have to adopt a stellar *R*-band mass-to-light ratio and consider its dependence on cosmic time. If the majority of the stellar population of massive galaxies did form at high redshift, as suggested by several pieces of evidence (Gavazzi et al. 2002; Thomas et al. 2005; Renzini 2006; Cappellari et al. 2009; Cirasuolo et al. 2009), one may assume that the mass-to-light ratio passively evolves from the formation ($z = z_{\rm burst}$) to the present age. On the other hand, if quasar host galaxies suffer intense star formation episodes from $z = 3$ to $z = 0$ (for instance, due to merger events), the evolution of the stellar mass-to-light ratio becomes more complex and is, in principle, different from object to object. For the sake of simplicity, following Kotilainen et al. (2009) we will consider here only the scenario of a passively evolving stellar population with $z_{\rm burst} = 5$. This is justified by the selection of quasars with bulge-dominated host galaxies, where old stellar populations are expected. Furthermore, as we will discuss in Section 4, this assumption is conservative with respect to the main results of our study.

With this caveat in mind, we find that the redshift dependence of the host galaxy luminosity observed, e.g., in Kotilainen et al. (2009) is practically removed when we take into account the evolution of the stellar population. The stellar mass of the host galaxies in our sample is nearly constant, with an average value of few times $10^{11}\,{\rm M_\odot}$.

Table 1 lists our final estimates of the host galaxy luminosities and masses for the quasars in our sample.

3 EVOLUTION OF THE $\mathcal{M}_{\rm BH}$–$L_{\rm host}$, $\mathcal{M}_{\rm host}$ RELATIONS

In Fig. 1, we compare our $\mathcal{M}_{\rm BH}$ estimates with the predictions of the Bettoni et al. (2003) relation, defined on $z \approx 0$ galaxies, and with the expectations in the case of a fixed $\mathcal{M}_{\rm BH}/\mathcal{M}_{\rm host} = 0.002$ ratio, as observed in local inactive galaxies (see e.g. Marconi & Hunt 2003).

The $\mathcal{M}_{\rm BH}$–$L_{\rm host}$ relation appears rather insensitive to the cosmic time, independently of which line is adopted in the virial estimate of $\mathcal{M}_{\rm BH}$. When correcting for the evolution of the stellar mass-to-light ratio, we find a clear increase ($\sim$0.7 dex) of the $\mathcal{M}_{\rm BH}/\mathcal{M}_{\rm host}$ ratio with respect to what was observed in the Local Universe. In Fig. 2, $\mathcal{M}_{\rm BH}$, $\mathcal{M}_{\rm host}$ and their ratio Γ are plotted all together as a function of redshift. The linear best fit of $\log\Gamma$ is

$$\log\Gamma = (0.28 \pm 0.06)\,z - (2.91 \pm 0.06), \qquad (2)$$

suggesting that galaxies with similar stellar masses harbour BHs approximately seven times more massive at $z = 3$ than galaxies at $z = 0$.

In Fig. 3, we study separately radio-loud quasars (RLQs) and radio-quiet quasars (RQQs), finding that both samples are consistent with the $\log\Gamma$–z relation found for the whole sample. The only remarkable difference is in the offset, in the sense that, at any redshift, both BHs and host galaxies in RLQs are $\sim$0.2 dex more massive than in RQQs (e.g. Dunlop et al. 2003; Labita et al. 2009c).

Table 1. The sample in this study as follows: (1) quasar name, (2) catalogue redshift, (3) host galaxy *R*-band absolute magnitude (not corrected for stellar ageing), (4) host galaxy stellar mass and (5) reference for the host galaxy luminosity – (1) low-*z HST*-based observation (see Paper I); (2) Falomo et al. (2004); (3) Kukula et al. (2001); (4) Ridgway et al. (2001); (5) Falomo et al. (2005); (6) Kotilainen et al. (2009); (7) Kotilainen et al. (2007); (8) Hyvönen et al. (2007a); (9) Kotilainen, Falomo & Scarpa (1998); (10) Kotilainen & Falomo (2000); (11) Decarli Treves & Falomo (2009a).

Quasar name (1)	z (2)	M_R (mag) (3)	Host galaxy log $\mathcal{M}_{host}$ ($M_\odot$) (4)	Ref M_R (5)	Quasar name (1)	z (2)	M_R (mag) (3)	Host galaxy log $\mathcal{M}_{host}$ ($M_\odot$) (4)	Ref M_R (5)
PKS 0000−177	1.465	−24.5	12.0	2	1116+215	0.177	−22.2	11.5	1
Q0040−3731	1.780	−22.8	11.3	2	1150+497	0.334	−23.4	11.9	1
SGP2:36	1.756	−23.7	11.7	3	1202+281	0.165	−21.4	11.2	1
SGP5:46	0.955	−22.4	11.4	3	1208+322	0.388	−23.5	12.0	1
0054+144	0.171	−22.9	11.8	1	1216+069	0.331	−22.1	11.4	1
SGP4:39	1.716	−21.7	10.9	3	MRK 0205	0.071	−23.3	12.0	1
PKS 0100−270	1.597	−23.4	11.6	2	1222+125	0.415	−23.7	12.0	1
LBQS 0100+0205	0.393	−22.3	11.5	1	3C2 73	0.158	−22.8	11.8	1
0110+297	0.363	−23.6	12.0	1	1230+097	0.415	−24.0	12.2	1
PKS 0113−283	2.555	−24.7	11.8	5	Z124029−0010	2.030	−25.5	12.3	6
0119−370	1.320	−23.7	11.8	2	PG 1302−102	0.286	−23.1	11.8	1
0133+207	0.425	−22.8	11.7	1	1307+085	0.155	−21.1	11.1	1
3C 48	0.367	−25.6	12.8	1	1309+355	0.184	−22.6	11.7	1
HB 890137+012	0.260	−23.5	12.0	1	1402+436	0.320	−23.3	11.9	1
0152−4055	1.650	−23.4	11.6	2	PG 1416−129	0.129	−21.7	11.3	1
PKS 0155−495	1.298	−24.4	12.0	2	1425+267	0.366	−24.3	12.3	1
PKS 0159−11	0.669	−22.3	11.4	10	Z143220−0215	2.476	−23.2	11.2	6
B0204+2916	0.109	−22.4	11.6	1	Z144022−0122	2.244	−24.6	11.9	6
0244+194	0.176	−22.0	11.4	1	1444+407	0.267	−22.3	11.5	1
KUV 03086−0447	0.755	−23.7	11.9	8	PKS J1511−10	1.513	−23.5	11.6	2
MZZ 01558	1.829	−23.0	11.3	4	1512+37	0.371	−23.3	11.9	1
US 3828	0.515	−22.6	11.6	8	PKS 1524−13	1.687	−23.9	11.7	3
Q0335−3546	1.841	−23.5	11.5	7	3C 323.1	0.266	−21.9	11.4	1
PKS 0348−120	1.520	−24.8	12.1	2	1549+203	0.250	−22.0	11.4	1
PKS 0349−14	0.614	−25.2	12.6	10	HS 1623+7313	0.621	−22.2	11.4	8
PKS 0402−362	1.417	−24.8	12.2	2	1635+119	0.146	−22.2	11.5	1
PKS 0403−132	0.571	−21.3	11.0	9	3C 345	0.594	−25.5	12.7	1
PKS 0405−123	0.574	−23.1	11.7	9	3C 351	0.372	−24.2	12.2	1
PKS 0414−06	0.773	−25.0	12.4	10	1821+643	0.297	−24.9	12.6	1
PKS 0420−014	0.915	−24.5	12.2	9	3C 422	0.942	−24.2	12.1	3
PKS 0440−00	0.607	−23.3	11.8	3	MC 2112+172	0.878	−24.1	12.1	3
0624+6907	0.370	−24.6	12.4	1	Q2125−4432	2.503	−23.0	11.2	6
PKS 0710+11	0.768	−25.6	12.7	10	PKS 2128−12	0.501	−21.8	11.2	9
MS 0824.2+0327	1.431	−23.8	11.8	7	PKS 2135−14	0.200	−22.9	11.8	1
MS 08287+6614	0.610	−22.9	11.7	8	2141+175	0.211	−22.9	11.8	1
PKS 0838+13	0.684	−23.1	11.7	10	Z215539−3026	2.593	−24.2	11.6	6
US 1867	0.513	−25.8	12.8	1	2201+315	0.295	−23.7	12.1	1
0903+169	0.411	−23.5	12.0	1	PKS 2204−20	1.923	−23.1	11.3	3
TON 392	0.654	−23.4	11.8	8	Z222702−3205	2.177	−24.7	11.9	6
MS 09441+1333	0.131	−23.3	12.0	1	Q2225−403A	2.410	−25.0	12.0	6
0953+415	0.234	−22.3	11.5	1	Q2225−403B	0.932	−23.2	11.7	11
1001+291	0.330	−24.0	12.2	1	PKS 2227−08	1.562	−22.9	11.4	2
1004+130	0.240	−23.6	12.1	1	2247+140	0.235	−23.0	11.8	1
Z101733−0203	1.343	−21.8	11.0	7	Z225950−3206	2.225	−24.7	11.9	6
PKS 1015−31	1.346	−24.5	12.1	7	Z231751−3147	2.628	−23.4	11.3	6
PKS 1018−42	1.280	−25.1	12.3	2	Z232755−3154	2.737	−24.4	11.6	6
1058+110	0.423	−24.0	12.2	1	PKS 2345−167	0.576	−24.4	12.3	9
1100+772	0.315	−23.8	12.1	1	Q2348−4012	1.500	−22.1	11.1	2

Table 2 and Fig. 4 report the slopes of the best linear fit of log Γ as a function of z in each subsample.

3.1 Is the trend of Γ an artefact?

In this section, we discuss the possible effects that could bias the estimate of Γ, in order to probe the reliability of the trend observed in Figs 1–3.

3.1.1 *The luminosity function bias*

Lauer et al. (2007) showed that, because of the steepness of the bright end of the galaxy luminosity (mass) function and the presence of intrinsic scatter in the $\mathcal{M}_{BH}$–L_{host}($\mathcal{M}_{host}$) relation, very massive BHs are preferentially found in relatively faint (less massive) galaxies rather than in extremely bright (massive) galaxies, which are very rare. Since high-z samples are dominated by massive

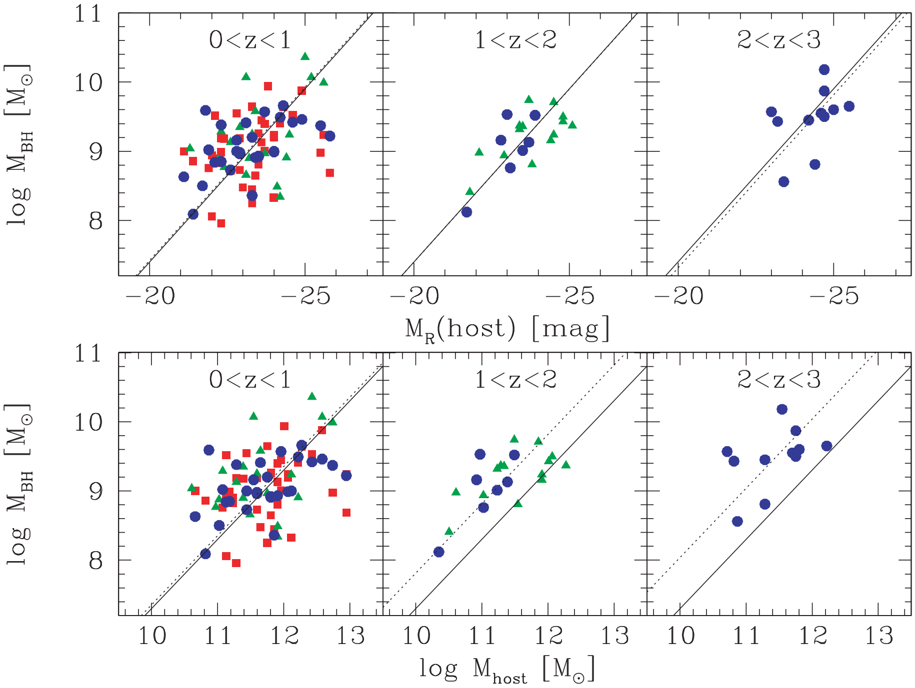

Figure 1. The $\mathcal{M}_{\rm BH}$–$L_{\rm host}$ and $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relations in three different redshift bins. Squares (triangles, circles) mark quasars in which $\mathcal{M}_{\rm BH}$ is derived from Hβ (Mg II, C IV). The reference (solid) line is the Bettoni et al. (2003) relation (upper panels) or the $\mathcal{M}_{\rm BH}/\mathcal{M}_{\rm host} = 0.002$ case (lower panels). The dotted line is the best fit to the data, assuming the same slope of the rest-frame relations. No significant redshift evolution is observed when comparing $\mathcal{M}_{\rm BH}$ with the observed host galaxy luminosities. On the other hand, a clear offset is apparent in the $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relationship as a function of the redshift.

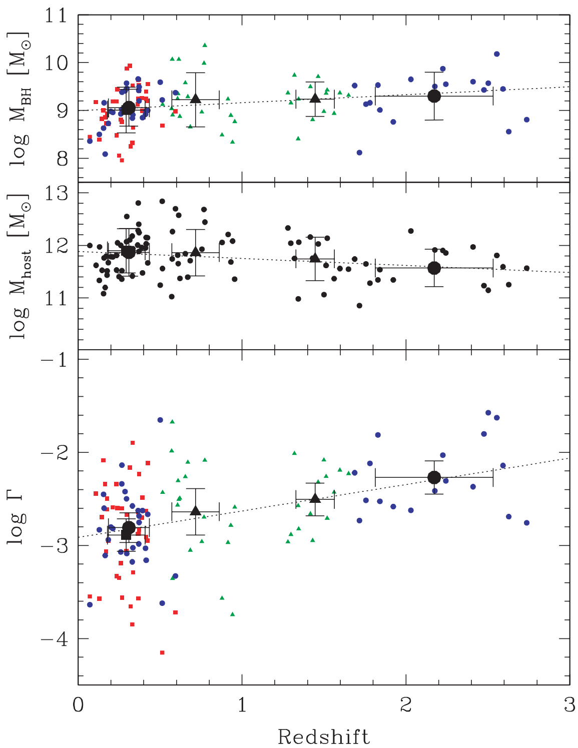

Figure 2. The redshift dependence of $\mathcal{M}_{\rm BH}$ (top panel), $\mathcal{M}_{\rm host}$ (middle panel) and their ratio Γ (bottom panel). The symbol code follows Fig. 1. The best linear fits are plotted. The average points with rms as error bars of the Hβ subsample (big square), of the low- and high-z C IV data (big circles) and of the Mg II data with redshift <1 and >1 (big triangles) are also shown.

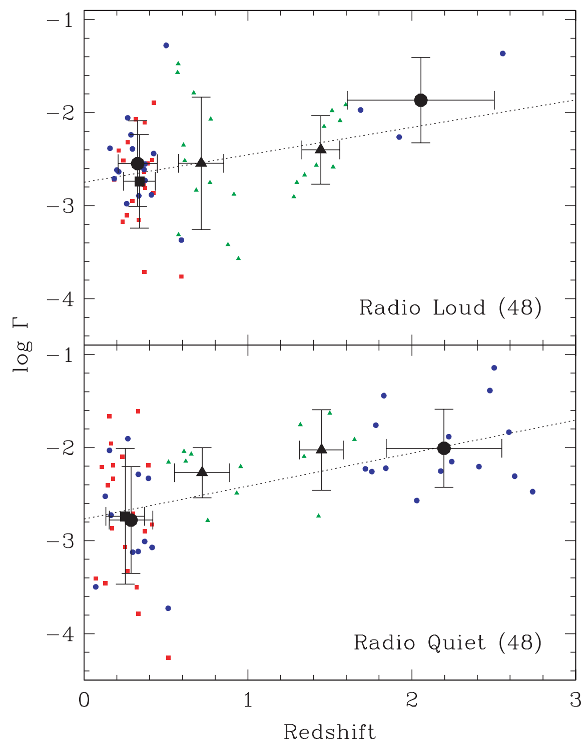

Figure 3. The redshift dependence of Γ for RLQs (top panel) and RQQs (bottom panel) separately. The symbol code is the same as in Fig. 2. The number of objects in each subsample is also provided in parenthesis.

Table 2. Slope of the best linear fit of $\log \Gamma = \alpha z + \beta$, for the whole sample and various subsamples (Column 1). The number of objects in each subsample in given in Column 2. Uncertainties on the slope (Column 3) are analytically derived from the least-square minimization criterion.

Subset (1)	Number of objects (2)	α (3)
All	96	(0.28 ± 0.06)
RLQs	48	(0.24 ± 0.11)
RQQs	48	(0.31 ± 0.07)
$M_* > M_{\rm V} > M_* - 1$	33	(0.32 ± 0.10)
$-26 > M_{\rm V} > -27$	31	(0.32 ± 0.11)
N/H > 5	43	(0.33 ± 0.11)
N/H < 5	53	(0.25 ± 0.07)

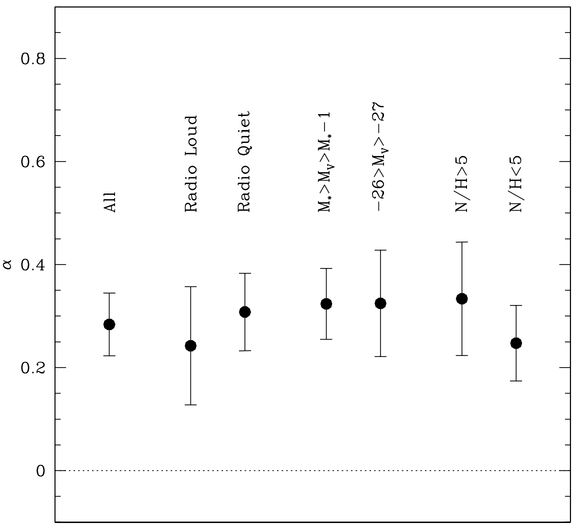

Figure 4. The slope of the log Γ versus z linear fit in our data, for each subsample. Error bars are the 1σ uncertainties as derived from the fit algorithm (see Table 2). All the subsets have consistent slopes around ∼0.3 dex. A non-evolving scenario (horizontal, dotted line) mismatches with the observations in all the cases.

objects, the bias increases with z, possibly mimicking an evolution in Γ.

In order to quantify the relevance of this bias, we assume that $\mathcal{M}_{\rm BH}$ mostly depends on the quasar luminosity. This is consistent with the relatively small range of Eddington ratios we sample. If σ_μ, the cosmic scatter of the $\mathcal{M}_{\rm BH}$–$L_{\rm host}$ relation, is constant in $L_{\rm host}$, at a given redshift the bias depends on the shape of the luminosity function of quasars, $\Psi(M)$ (see equation 25 in Lauer et al. 2007). We assume the quasar luminosity function and its purely luminosity evolution as reported by Boyle et al. (2000), basing on the 2-degree Field Quasar Redshift (2QZ) survey: $M_*(z) = -22.0 - 2.5\ (1.34\ z - 0.27\ z^2)$. As a consequence, as long as we sample the same range of the quasar luminosity function *at any redshift*, the bias is kept constant. A constant bias is irrelevant for the purposes of our study, since our main aim is to probe the *redshift dependence* of the BH–host galaxy relations, not their absolute normalization.

From fig. 1 of Paper I, we note that the constant luminosity cut at $-26 > M_V > -27$ and the $M_* > M_V > M_* - 1$ cut roughly bracket the objects in our sample over 5 mag in M_V. Hence, if we consider the whole sample, the bias on $\mathcal{M}_{\rm BH}$ will lie within the expectations from these two cases. Our estimate of the redshift evolution of the bias in these two cases is plotted in Fig. 5 for two different values

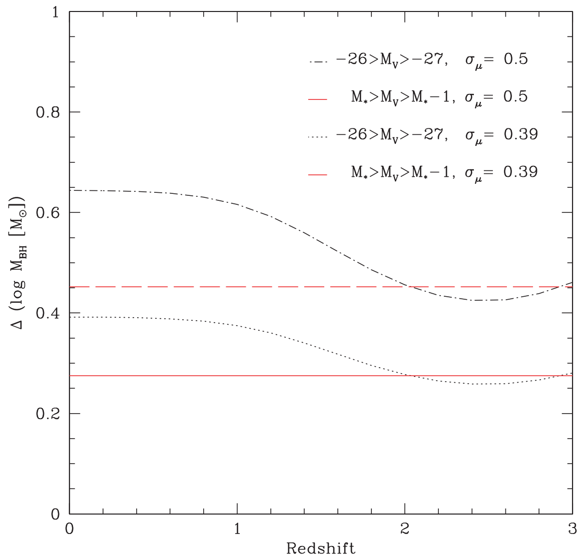

Figure 5. The bias on the prediction of $\mathcal{M}_{\rm BH}$ from the $\mathcal{M}_{\rm BH}$–$L_{\rm host}$ relation with respect to the expectation from the luminosity functions of galaxies and quasars, plotted as a function of redshift. The bias estimates are obtained by integrating the luminosity function of quasars over the adopted luminosity cuts: $-26 > M_V > -27$ (dot–dashed and dotted lines) and $M_* > M_V > M_* - 1$ (dashed and solid lines). We plot the limit cases with $\sigma_\mu = 0.5$ (dot–dashed and dashed lines) and $\sigma_\mu = 0.3$ (dotted and solid lines). We note that, in the worst case, the bias increases by 0.22 dex (i.e. a factor of 1.66) from $z = 2.5$ to $z = 0$.

of σ_μ, namely 0.39 from Bettoni et al. (2003) and the conservative value $\sigma_\mu = 0.5$. We conclude that the bias accounts for $\lesssim$0.11 dex, which is ≈ a factor of 1.3 moving from $z = 0$ to $z = 3$. As the observed dependence of Γ is approximately six times larger, it cannot be explained in terms of this selection effect. As a further check, Fig. 6 shows the log Γ– z plane only for the objects lying in the two luminosity cuts considered in this discussion. The observed trend is unchanged, independently of the adopted luminosity cut (see Table 2 and Fig. 4).

3.1.2 *The effects of the N/H*

All the objects in our reference sample are selected on the basis of their total luminosity, which is dominated by the nuclear light in quasars. This possibly introduces a bias in the sense that the higher is the N/H, the harder is the measure of the host galaxy luminosity, especially at high z. In Fig. 7, we show that the redshift dependence of Γ in objects with high- and low-N/H is similar. Moreover, we stress that if we include the unresolved quasars in this analysis, the trend would be even steeper, as they all lie at high z. Analogously, this argument can be applied for possible contaminations from disc-dominated galaxies at high redshift, where the morphology classification may be more doubtful. In this case, as $\mathcal{M}_{\rm BH}$ is sensitive to the bulge mass rather than to the total galaxy mass, we should consider smaller values of $\mathcal{M}_{\rm host}$ for such galaxies, which would increase the value of Γ at high z.

3.1.3 *The role of radiation pressure*

Marconi et al. (2008, 2009) suggest that the virial estimates of $\mathcal{M}_{\rm BH}$ may yield lower limits to the *true* BH mass, as the radiation pressure is not taken into account. As long as the broad-line region

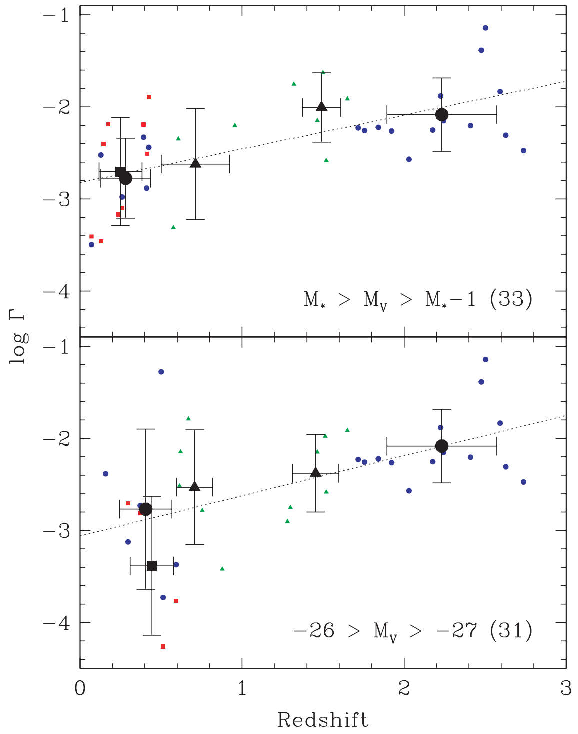

Figure 6. The same as Fig. 3, for objects with $M_* > M_V > M_* - 1$ (top panel) and with $-26 > M_V > -27$ (bottom panel). No significant difference is observed in the two subsets.

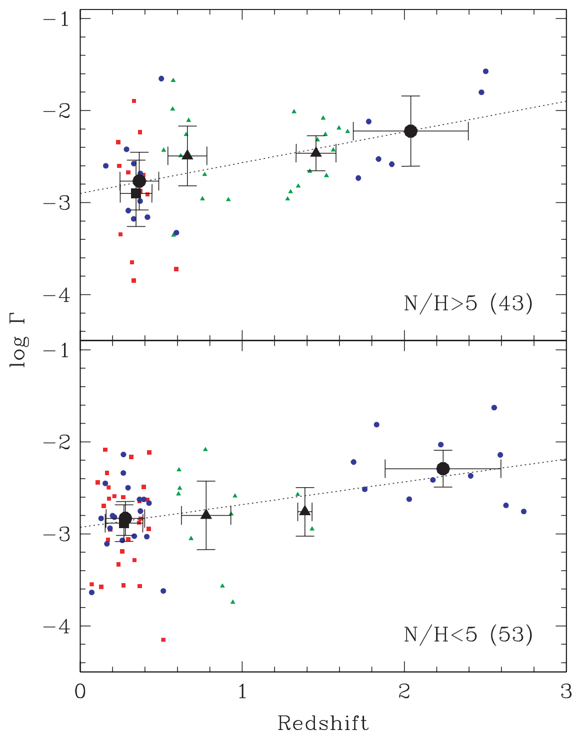

Figure 7. The same as Fig. 3, for objects with N/H > 5 (top panel) and N/H < 5 (bottom panel). Again, no significant difference is reported.

(BLR) clouds are virialized, a correction can be applied by adding a term depending on the BLR column density N_H and the quasar luminosity. There is still no strong constraint on the values of N_H. X-ray variability studies performed on nearby, lower luminosity AGN suggest that the column densities may be relatively high (e.g. Risaliti et al. 2009; Turner & Miller 2009, and references therein), thus preventing radiation pressure from sustaining BLR clouds motion. However, as a clear comprehension of the radiation pressure role in the BLR is still missing, especially in the most luminous AGN, we limit our discussion to the following consideration: since the average luminosity of our data increases with z, the radiation pressure effect is expected to become more severe at higher z, leading to an even steeper trend of Γ than the one observed in Figs 1 and 2.

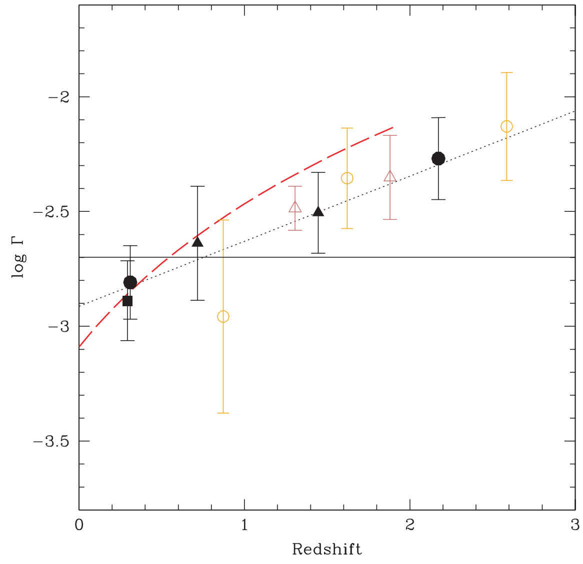

Figure 8. The average values of Γ for the quasars in our sample (filled symbols), together with the linear best fit (dotted line). Error bars are the 2σ uncertainties in the average values for each data bin. For a comparison, the trend found in the study of radio-loud AGN by McLure et al. (2006) is plotted as a dashed line. We also plot the average Γ values of the 51 lensed and non-lensed quasars from Peng et al. (2006a,b, empty circles) and of the 89 AGN from Merloni et al. (2010, empty triangles). The horizontal solid line represents the constant $\Gamma = 0.002$ case. All together, the data depict a clear increase of Γ with z.

4 DISCUSSION

4.1 Comparison with previous results

As a key result of this analysis, we find that the $\mathcal{M}_{BH}/\mathcal{M}_{host}$ ratio significantly increases with redshift. Hereafter, we compare these findings with those of other studies available in the literature.

McLure et al. (2006) match the average trend of $\mathcal{M}_{BH}$ observed in 38 RLQs at $z < 2$ with the typical stellar masses of massive radio galaxies in the same redshift bins. This approach relies on the assumption that quasar host galaxies are comparable, at any redshift, with massive radio galaxies. The major caveat here is that their results may be biased by the different histories of quasar and radio galaxies (for instance, note that the luminosity functions of AGN evolve differently for various luminosity subclasses). Nevertheless, McLure et al. (2006) find an increase of Γ comparable to the one observed in the present study (see Fig. 8). Our results extend these findings to RQQs and beyond the peak age of quasar activity.

Peng et al. (2006a,b) address the evolution of the $\mathcal{M}_{BH}$–$\mathcal{M}_{host}$ relation as a function of redshift in ∼20 low-z quasars and in ∼30 high-z lensed quasars imaged with the *HST*. Their data show a larger scatter than ours, possibly due to uncertainties in the modelling of the lens mass distribution and the lens light subtraction. They find that there is practically no evolution in the $\mathcal{M}_{BH}$–L_{host} relation. On the other hand, when correcting for the evolution of the stellar population, they find an excess (a factor of 3–6) in the $\mathcal{M}_{BH}$ values at high z with respect to the prediction from the local $\mathcal{M}_{BH}$–$\mathcal{M}_{host}$ relation, in qualitative agreement with our findings.

Merloni et al. (2010) study the $\mathcal{M}_{BH}$–$\mathcal{M}_{host}$ ratio in a sample of 89 type 1 AGN with $1 < z < 2.2$ from the redshift survey in the Cosmological Evolution Survey (zCOSMOS). BH masses are derived through the standard virial assumption, while the host galaxy luminosities and stellar masses are inferred from multiwavelength fitting of the spectral energy distribution of the targets (with no direct information about the morphology of the galaxies). This technique is effective with intermediate to low-luminosity AGN, while it cannot be applied to quasars as bright as ours, where the nuclear light overwhelms the galaxy contribution. They find that the average Γ is higher than what was observed in the Local Universe, the excess scaling as $(1 + z)^{0.74}$, consistently with the trend observed in our data in the same redshift bin. Jahnke et al. (2009) observed 10 of the targets in Merloni's sample with the *HST* and independently derived host galaxy luminosities with a procedure similar to the one adopted in our data sources (see e.g. Kotilainen et al. 2009). They find no evolution in the $\mathcal{M}_{BH}$–$\mathcal{M}_{host}$(total) ratio. However, clues of the occurrence of discs are present; thus the $\mathcal{M}_{BH}$–$\mathcal{M}_{host}$(bulge) ratio is expected to evolve as $(1 + z)^{1.2}$, in agreement with our findings.

Bennert et al. (2009) address the $\mathcal{M}_{BH}$–L_{host} relation in a sample of 23 Seyfert galaxies with $0.3 < z < 0.6$. They study the morphology of the host galaxies of these objects using NIR observations from the *HST*. A careful modelling is adopted in order to disentangle nuclei, bulges and disc components. BH masses are derived in a way similar to that presented in Paper I. Once corrected for the evolution of the stellar population, they find $\Gamma \propto (1 + z)^{(1.4\pm0.2)}$, in good agreement with our results.

Additional indication of an evolution of Γ comes from the relation of $\mathcal{M}_{BH}$ with the stellar velocity dispersion, σ_*, of the host galaxy. In particular, it is remarkable that these works suggest that the higher is the redshift, the more massive is the BH for a given σ_*. For instance, Salviander et al. (2007) use the width of the [O III] narrow emission line as a proxy of the stellar velocity dispersion and study the $\mathcal{M}_{BH}$–σ_* relation in a sample of ∼1600 quasars up to $z = 1.2$ taken from the Sloan Digital Sky Survey (SDSS). They find that $\mathcal{M}_{BH}$ at high redshift are ∼0.2 dex larger than what is expected from the local $\mathcal{M}_{BH}$–σ_* relation. A smaller evolution ($\lesssim$0.1 dex), albeit with small significance, is also proposed by Shen et al. (2008b), based on a sample of 900 type 1 AGN with $z \lesssim 0.4$. More recently, Woo et al. (2008) and Woo et al. (in preparation) address the $\mathcal{M}_{BH}$–σ_* relation in Seyfert galaxies up to $z \sim 0.6$ and find an overall $\mathcal{M}_{BH}$ excess at high redshift with respect to the prediction from low-z relationships. These findings support our results, notwithstanding the different characteristic luminosities, morphologies and stellar contents of the sampled targets with respect to those examined in our analysis.

It is interesting to note that the $z = 6.42$ quasar SDSS J1148+5251 has a BH mass of a few $\times 10^9$ M$_\odot$ (Willott, McLure & Jarvis 2003) and a dynamical mass of $\sim 5 \times 10^{10}$ M$_\odot$ of the host galaxy (Walter et al. 2003, 2004), yielding $\Gamma \sim 0.1$, which is in agreement with the extrapolation of our results at that redshift ($\Gamma \approx 0.13$) and well beyond the $\Gamma = 0.002$ value observed in the Local Universe.

These results as a whole support a picture where, for a given quasar host galaxy, its central BH at high redshift is 'overmassive' with respect to its low-z counterparts. This picture is also consistent with the constraints on the $\mathcal{M}_{BH}$–$\mathcal{M}_{host}$ evolution derived from the comparison between the galaxy stellar mass function and the quasar luminosity function (Somerville 2009).

4.2 Why does Γ evolve?

The interpretation of the observed evolution in the $\mathcal{M}_{BH}$–$\mathcal{M}_{host}$ ratio is challenging. Exotic scenarios involving BH ejection from their host galaxies due to gravitational wave recoil or three-body scatter may be applicable for a few peculiar targets (e.g. see Komossa, Zhou & Lu 2008, but see also Bogdanovic, Eracleous & Sigurdsson 2009; Dotti et al. 2009; Heckman et al. 2009 for alternative explanations), but they are not applicable to the general case. Thus,*if* high-z quasars are destined to move towards the local $\mathcal{M}_{BH}$–$\mathcal{M}_{host}$, the unavoidable consequence of our results is that, at a given $\mathcal{M}_{BH}$, galaxy masses increase from $z = 3$ to the present age. Hereafter, we sketch three possible basic pictures for that. We also present an alternative scenario, in which the fate of high-z quasars may be different, the remnants of high-z quasars keeping high Γ values down to the present age.

Galaxy growth by mergers. A first scenario involves substantial mass growth of quasar host galaxies through merger events. It is remarkable that strong gravitational interactions may trigger intense gas infall in the centre of galaxies and may even lead to the activation of BH accretion. This is observed in a number of relatively low-redshift AGN (e.g. Bennert et al. 2008, 2009) showing dense close environments or disturbed morphologies, and confirmed by the presence of young stellar populations in some quasar host galaxies (Jahnke, Kuhlbrodt & Wisotzki 2004; Jahnke et al. 2007). Two arguments disfavour this scenario. First, theoretical models based on the structure evolution in a Λ cold dark matter cosmology (e.g. Volonteri, Haardt & Madau 2003) predict that a massive galaxy experience only a few (1–2) major merger events from $z = 3$ to $z = 0$. However, our study shows that a factor of ∼7 increase of the stellar mass of the host galaxies is required from $z = 3$ to $z = 0$, which means that the host galaxies have to suffer ≥ three major mergers in this redshift range. Secondly, several pieces of evidence suggest that massive inactive galaxies, as well as quasar host galaxies, have already formed/assembled the majority of their mass in very remote Cosmic epochs ($z \gtrsim 3$; see e.g. Kotilainen et al. 2009, and references therein). The stellar population may experience episodic rejuvenation, but this only marginally affects the mean age of the stellar content: the stellar shells observed, e.g., by Canalizo et al. (2007) and Bennert et al. (2008) in low-redshift quasar host galaxies account for 5–10 per cent of the total stellar population. Similarly, in a comparison with inactive galaxies of similar mass, Jahnke et al. (2004) find that quasar host galaxies are on average only 0.3 mag bluer. If the galaxies enter the quasar phase ∼1 Gyr after the activation of the starburst, as suggested by the authors of that study, then the involved mass is ∼30 per cent of the initial mass of the galaxy. Moreover, if the quasar host galaxies contain a significant fraction of young stellar populations, then the mass-to-light ratio would be smaller. Therefore, young host galaxies at high z would yield a Γ–z relation even steeper than that reported in Fig. 2.

Stellar mass growth through gas consumption. Another possible interpretation is that high redshift quasar host galaxies are gas rich and form a significant fraction of their stellar content in relatively recent Cosmic epochs. This is consistent with a picture in which the BH mass is somehow sensitive to the energetic budget of the galaxy or its dynamical mass rather than its stellar mass (see, for instance, Hopkins et al. 2007). This scenario is disfavoured as all the quasar host galaxies in our sample are massive elliptical, and the stellar content of these galaxies is usually old. Moreover, if significant star formation occurred in quasar host galaxies in the redshift range explored in this work, the evolution of Γ would be much steeper, making this scenario even less realistic.

Evolution of the Fundamental Plane. A number of studies suggest that inactive, massive elliptical galaxies were more compact in the high redshift than in the Local Universe (Trujillo et al. 2006; but see also Cappellari et al. 2009). In particular, an evolution of the Faber–Jackson relation is predicted, implying that the higher is z, the higher is the galaxy velocity dispersion σ_*. If $\mathcal{M}_{\rm BH}$ constantly regulates the host galaxy σ_* (e.g. Silk & Rees 1998) so that the $\mathcal{M}_{\rm BH}$–σ_* relation does not evolve significantly, then even a small (a factor of ∼1.6) increase of σ_* for a given galaxy would yield an excess of a factor of 7 in Γ. The main limit of this picture is that studies of the evolution of the $\mathcal{M}_{\rm BH}$–σ_* relation through redshift do find an increase of the average $\mathcal{M}_{\rm BH}$ for a given σ_*, when moving from the Local to high-z Universe (Salviander et al. 2007; Woo et al. 2008; Bennert et al. 2009).

Remnants of high-z quasars as rare outliers. We propose a scenario in which the local counterparts of high-z quasars are high-mass outliers above the $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relation. The more massive is the BH, the earlier it experiences its quasar phase (Marconi et al. 2004; Merloni 2004). Our study shows that these objects have higher expected Γ, but they are extremely rare, and contribute marginally to the presently known $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relation. In particular, the $2 < z < 3$ quasars should appear as inactive massive galaxies with $\mathcal{M}_{\rm BH} \sim 10^{9.5}\,{\rm M}_{\odot}$ in the nearby Universe. In order to quantify the occurrence of such objects in the Local Universe, we assume the mass function of quasars: $\Phi(\mathcal{M}_{\rm BH} \sim 10^{9.5}\,{\rm M}_{\odot}, 2 < z < 3) \approx 4 \times 10^{-9}\,{\rm Gpc}^{-3}\,{\rm M}_{\odot}{}^{-1}$ (Vestergaard & Osmer 2009), and take a volume corresponding to the most distant inactive BH for which a direct measurement of the mass is available.[1] Under these assumptions, we expect virtually no objects (0.2 in the whole volume) with such high values of Γ.

Using the same arguments for targets at intermediate redshift ($1.0 < z < 1.5$), we expect a few (∼2) objects. Quasars at $z \sim 1.2$ have Γ values ∼0.3 dex larger than those at $z = 0$. This offset is close to the one observed for the handful of objects populating the high-mass end of the local $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relation (e.g. Marconi & Hunt 2003). This scenario is thus consistent both with the Γ– z relation of quasars and with the observed shape of the local $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ galaxy relation of nearby inactive galaxies.

5 CONCLUSIONS

In this paper, we studied the $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ relations as a function of redshift in a sample of 96 quasars from the present age to $z = 3$, i.e. 85 per cent of the Universe age. We found that the $\mathcal{M}_{\rm BH}$–$\mathcal{M}_{\rm host}$ ratio increases by a factor of ∼7 from $z = 0$ to $z = 3$. This trend is not affected by significant contributions due to target selection criteria and observational biases. Moreover, it is independent of the quasar luminosity and of the radio loudness.

We interpret this trend as an indication that the most massive BHs, living their quasar phase at high redshift, keep their high Γ down to the present age, becoming very rare objects in the Local Universe. A fully consistent interpretation of these results in terms of the common history of BHs and galaxies requires further efforts in refining the picture sketched here. In particular, two key points are yet to be clarified: (i) how the mechanisms of quasar feedback act on to the host galaxies and (ii) what is the role of both dry and wet mergers concerning the quasar activity and in triggering star formation. Moreover, a better knowledge of the $\mathcal{M}_{\rm BH}$–host galaxy relations (improving statistics at high masses) will clarify whether very massive, quiescent BHs can actually be found in galaxies in the Local Universe.

[1]The BH at the centre of the brightest cluster galaxy in Abell 1836, at 147 Mpc; see Dalla Bontà et al. (2009)

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