The Interplay among Black Holes, Stars and ISM
in Galactic Nuclei
Proceedings IAU Symposium No. xxx, 2004
T. Storchi-Bergmann, L. C. Ho & H. R. Schmitt, eds.

© 2004 International Astronomical Union
DOI: 10.1017/S1743921304001437

Local supermassive black holes and relics of active galactic nuclei

Alessandro Marconi[1], **Guido Risaliti**[1,2], **Roberto Gilli**[1], **Leslie K. Hunt**[3], **Roberto Maiolino**[1] **and Marco Salvati**[1]

[1]INAF-Osservatorio Astrofisico di Arcetri, Largo Fermi 5, I-50125, Firenze, Italy
email: marconi@arcetri.astro.it

[2]Harvard-Smithsonian Center for Astrophysics, 60 Garden street, Cambridge, MA 02138, USA

[3]INAF-Istituto di Radioastronomia-Sez. Firenze, Largo Fermi 5, I-50125, Firenze, Italy

Abstract. We quantify the importance of mass accretion during AGN phases in the growth of supermassive black holes (BH) by comparing the mass function of black holes in the local universe with that expected from AGN relics, which are black holes grown entirely with mass accretion during AGN phases. The local BH mass function (BHMF) is estimated by applying the well-known correlations between BH mass, bulge luminosity and stellar velocity dispersion to galaxy luminosity and velocity functions. The density of BHs in the local universe is $\rho_{\rm BH} = 4.6^{+1.9}_{-1.4}\, h_{0.7}^2 \times 10^5$ M$_\odot$ Mpc^{-3}. The relic BHMF is derived from the continuity equation with the only assumption that AGN activity is due to accretion onto massive BHs and that merging is not important. We find that the relic BHMF at $z=0$ is generated mainly at $z<3$. Moreover, the BH growth is anti-hierarchical in the sense that smaller BHs ($M_{BH} < 10^7 M_\odot$) grow at lower redshifts ($z<1$) with respect to more massive ones ($z \sim 1-3$). Unlike previous work, we find that the BHMF of AGN relics is perfectly consistent with the local BHMF indicating the local BHs were mainly grown during AGN activity. This agreement is obtained while satisfying, at the same time, the constraints imposed from the X-ray background. The comparison with the local BHMF also suggests that the merging process is not important in shaping the relic BHMF, at least at low redshifts ($z<3$). Our analysis thus suggests the following scenario: local black holes grew during AGN phases in which accreting matter was converted into radiation with efficiencies $\varepsilon = 0.04-0.16$ and emitted at a fraction $\lambda = 0.1-1.7$ and emitted at a fraction $\lambda = 0.1-1.7$ of the Eddington luminosity. The average total lifetime of these active phases ranges from $\simeq 4.5\times10^8$ yr for $M_{BH} < 10^8 M_\odot$ to $\simeq 1.5\times10^8$ yr for $M_{BH} > 10^9 M_\odot$.

1. Introduction

The standard paradigm for Active Galactic Nuclei is that they are powered by mass accretion onto a massive BH ($M_{\rm BH} \sim 10^6 - 10^{10}$ M$_\odot$). Combined with the observed evolution of AGN, this implies that many (if not all) nearby galaxies should host a BH in their nuclei as relic of past AGN activity. BHs are detected in ~ 40 galaxies and their mass correlates with host galaxy structural parameters like bulge luminosity/mass (e.g. Kormendy & Richstone 1995, Marconi & Hunt 2003) and stellar velocity dispersion (Ferrarese & Merritt 2000, Gebhardt *et al.* 2000). It is important to investigate if local BHs are relics of AGN activity (i.e. grown entirely with mass accretion during AGN phases) or if other processes, like merging, play an important role. This can be done by comparing the BHMF of local BHs with that expected from AGN relics (e.g. Marconi & Salvati 2002, Yu & Tremaine 2002). In recent work (Yu & Tremaine 2002, Ferrarese 2002) a discrepancy in the BHMF at high masses ($M_{\rm BH} > 10^8$ M$_\odot$) has been found: more AGN relics are expected than local BHs. This discrepancy can be reconciled by assuming accretion efficiencies larger than the canonically adopted value of $\varepsilon = 0.1$, i.e.

https://doi.org/10.1017/S1743921304001437 Published online by Cambridge University Press

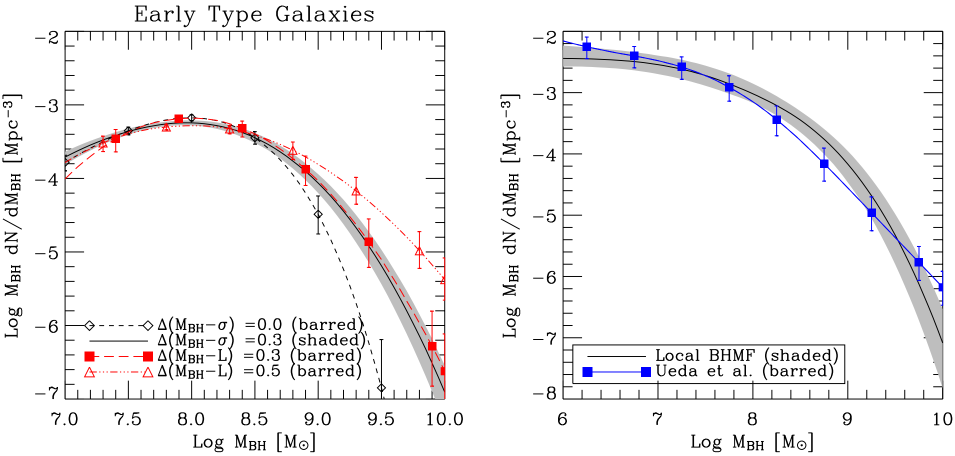

Figure 1. (a) Local BHMF for early type galaxies based on the SDSS sample of Bernardi *et al.* (2003). The shaded area and error bars ("barred") indicate 1σ uncertainties. The Δ indicate the assumed intrinsic dispersions of the $M_{\rm BH}$-$\sigma_\star$ or $M_{\rm BH}$-$L_{\rm bul}$ relations. (b) Best estimate of the local BHMF (shaded area) compared with the BHMF of AGN relics obtained using the luminosity function by Ueda *et al.* (2003), corrected for the missing Compton-thick AGNs.

$\varepsilon > 0.2$. High efficiencies are also required from the comparison of $\rho_{\rm BH}$ derived from the X-ray Background (XRB) and from local BHs (Elvis, Risaliti & Zamorani 2002). We investigate the assumption that massive black holes in nearby galaxies are relics of AGN activity by comparing the local BHMF with that of AGN relics. Our only assumption is that AGN activity is caused by mass accretion onto the central BH. For more details on this work the reader should refer to Marconi *et al.* (2004).

2. The Mass Function of Local Black Holes

The mass function of local BHs can be estimated by simply convolving the existing the galaxy luminosity [$\phi(L)$] or velocity functions [$\phi(\sigma)$] with the $M_{\rm BH}$-$L_{\rm bul}$ and $M_{\rm BH}$-$\sigma_\star$ relations respectively. One has to apply corrections to convert from total to bulge luminosity in the first case and has to take into account the intrinsic dispersion (if any) of the $M_{\rm BH}$-host galaxy relations. In Fig. 1a we verify that the $M_{\rm BH}$-$\sigma_\star$ and $M_{\rm BH}$-$L_{\rm bul}$ relations applied to the galaxy luminosity or velocity function (Bernardi *et al.* 2003, Sheth *et al.* 2003) provide the same BHMF within the uncertainties (estimated with many Montecarlo realizations of the BHMF). The necessary condition is that the two relations have the same intrinsic dispersion as indicated by the cases when $M_{\rm BH}$-$L_{\rm bul}$ has dispersion 0.5 in $\log M_{\rm BH}$ at given $L_{\rm bul}$ and $M_{\rm BH}$-$\sigma_\star$ has 0 intrinsic dispersion. This confirms the result by Marconi & Hunt (2003) that all correlations $M_{\rm BH}$− host-galaxy-properties are equally good, i.e. they have similar intrinsic dispersion. In Fig. 1b we plot the estimate of the local BH mass function obtained considering galaxies from all morphological types. The density in local BHs is $\rho_{\rm BH} = 4.6(-1.4;+1.9)(h/0.7)^2 \times 10^5$ M$_\odot$ Mpc^{-3}. We have used the galaxy luminosity functions by Kochanek *et al.* (2001), Nakamura *et al.* (2003), Marzke *et al.* (1994) and the galaxy velocity function by Sheth *et al.* (2003).

https://doi.org/10.1017/S1743921304001437 Published online by Cambridge University Press

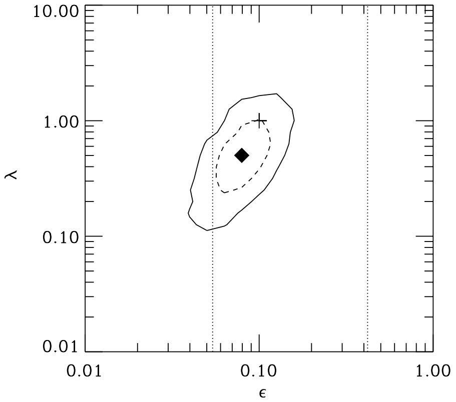

Figure 2. Locus where ε and λ provide the best match between local and relic BHMFs. The solid and dashed lines indicate an average deviation of 1 and 0.7σ between the BHMFs. The diamond marks the ε,λ values providing the best agreement.

3. The Mass Function of AGN Relics

The Mass Function of AGN relics is estimated with the continuity equation which relates the relic BHMF, $N(M, t)$, to the AGN luminosity function (LF), $\phi(L, t)$. The only assumption is that AGNs are powered by mass accretion onto a massive BH and that we can neglect merging of BHs. The efficiency of mass-to-energy conversion is ε and the BH is emitting at the fraction λ of the Eddington luminosity. L in the AGN LF must be the 'bolometric' luminosity. To obtain L, we derive and use bolometric corrections which do not take into account the IR radiation (reprocessed UV radiation). Thus, they are a factor $\sim 30\%$ lower than the values used by previous authors. We consider the Hard X-ray luminosity function by Ueda *et al.* (2003), corrected for the missing Compton-thick AGNs (factor ~ 1.6) and we apply a bolometric correction to obtain $\phi(L, t)$. Assuming that at $z = 3$ all BHs are active (this initial condition does not affect the final results), we can estimate the relic BHMF (with $\varepsilon = 0.1$ and $\lambda = 1$) and compare it with the local BHMF (Fig. 1b). The local BHMF and the relic BHMF are in good agreement within the uncertainties. Thus, it is unlikely that merging can play a major role in shaping the BHMF for $z < 3$. The Ueda *et al.* (2003) LF, corrected for the missing Compton-thick AGNs can also reproduce the XRB spectrum and source counts, thus satisfying the constraints imposed by the XRB. In particular, the disagreement found by Elvis *et al.* (2002) between the density of local massive BHs and that inferred from the X-ray background light can be reconciled noting that the average redshift of the sources making the XRB is not $\langle z\rangle \simeq 2$ but $\langle z\rangle \simeq 1$, as shown by the redshift evolution of the Ueda *et al.* (2003) LF.

Accretion efficiency ε and Eddington ratio λ are the only free parameters for the relic BHMF and Fig. 2 shows the locus where they provide the best match between the relic and local BHMFs. The solid and dashed lines shows the loci where the average deviation between the BHMFs is less than 1 and 0.7σ, respectively. Outside of the solid contour, the agreement between the BHMFs is poor. The dotted lines marks the ε values for a non-rotating Schwarzschild BH and a maximally rotating Kerr BH. Acceptable values are in the range $\varepsilon = 0.04 - 0.16$ and $\lambda = 0.1 - 1.7$.

Fig. 3a shows the average growth history of BHs with different starting masses at $z = 3$. Symbols marks the point when a BH reaches a given fraction of its final mass. At $z < 3$, all BHs gain at least 95% of their final mass but BHs which are more massive than 10^8 $\mathrm{M}_\odot$ grow earlier and gain 50% of their final mass by $z \sim 2$. Smaller BHs grow at lower redshifts ($z < 1$). This anti-hierarchical growth of BHs is a consequence of the redshift evolution of the Ueda *et al.* (2003) LF.

https://doi.org/10.1017/S1743921304001437 Published online by Cambridge University Press

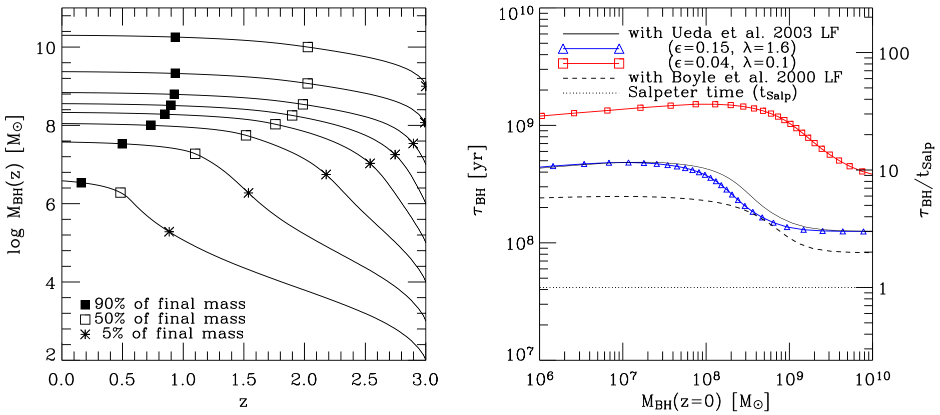

Figure 3. (a) Average growth history of BHs. The symbols indicate the points when a BH reaches a given fraction of its final mass. (b) Average mean lifetimes of active BHs as a function of their mass at $z = 0$. The solid line corresponds the standard case ($\varepsilon = 0.1$, $\lambda = 1$).

Fig. 3b shows the average total lifetimes of active BHs, i.e. the time required for the BH growth since $z = 3$. The solid line shows the "canonical" case with $\varepsilon = 0.1$, $\lambda = 1$. Lines with symbols show limiting cases from Fig. 2. Local high mass BHs ($M_{\rm BH} < 10^9$ M$_\odot$) have been active, on average, $\simeq 1.5 \times 10^8$ yr. On the contrary, the assembly of lower mass BHs has required active phases lasting at least three times that much ($\simeq 1.5 \times 10^8$ yr). The average lifetimes can be as large as 10^9 yr with the smaller ε and λ values compatible with local BHs ($\varepsilon = 0.04$, $\lambda = 0.1$ - see Fig. 2).

Overall, the plots in Fig. 3 indicate that smaller BHs ($M_{\rm BH} < 10^8$ M$_\odot$) find more difficulties in growing than larger one's. Indeed, this is consistent with physical models for the coevolution of BHs and galaxies. Smaller BHs form in shallower potential wells with respect to more massive ones and are thus more subject to feedback from star formation (e.g. supernovae explosions) and from the AGN itself (Menci *et al.* 2004).

References

Bernardi, M., et al. 2003, AJ, 125, 1849

Elvis, M., Risaliti, G., & Zamorani, G. 2002, ApJ, 565, L75

Ferrarese, L. 2002, In *Current High-Energy Emission around Black Holes*, Eds. C.-H. Lee & H.-Y. Chang (Singapore: World Scientific), p. 3

Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9

Gebhardt, K., et al. 2000, ApJ, 539, L13

Kochanek, C. S., et al. 2001, ApJ, 560, 566

Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581

Marconi, A., Risaliti, G., Gilli, R., Hunt, L. K., Maiolino, R., & Salvati, M. 2004, MNRAS, in press (astro-ph/0311619)

Marconi, A., & Hunt, L. K. 2003, ApJ, 589, L21

Marconi, A., & Salvati, M. 2002, In *Issues in Unification of Active Galactic Nuclei*, eds. R. Maiolino, A. Marconi and N. Nagar (San Francisco: ASP), 217

Marzke, R. O., et al. 1994, AJ, 108, 437

Menci, N., et al. 2004, ApJ, 604, 12

Nakamura, O., et al. 2003, AJ, 125, 1682

Sheth, R. K., et al. 2003, ApJ, 594, 225

Ueda, Y., et al. 2003, ApJ, 598, 886

Yu, Q., & Tremaine, S. 2002, MNRAS, 335, 965

https://doi.org/10.1017/S1743921304001437 Published online by Cambridge University Press