Supermassive black hole demography: the match between the local and accreted mass functions

F. Shankar,1⋆ P. Salucci,1 G. L. Granato,1,2 G. De Zotti1,2 and L. Danese1

1SISSA/ISAS, via Beirut 2, I-34014 Trieste, Italy
2INAF - Osservatorio Astronomico di Padova, vicolo dell’Osservatorio 5, I-35122 Padova, Italy

Accepted 2004 July 26. Received 2004 July 19; in original form 2004 April 27

ABSTRACT

We have performed a detailed analysis of the local supermassive black hole (SMBH) mass function based on both kinematic and photometric data and we have derived an accurate analytical fit in the range $10^6 \leq M_{\text{BH}}/M_\odot \leq 5 \times 10^9$. We find a total SMBH mass density of $(4.2 \pm 1.1) \times 10^5 M_\odot \text{Mpc}^{-3}$, about 25 per cent of which is contributed by SMBHs residing in bulges of late-type galaxies. Exploiting up-to-date luminosity functions of hard X-ray and optically selected active galactic nuclei (AGNs), we have studied the accretion history of the SMBH population. If most of the accretion occurs at constant $\dot{M}_{\text{BH}}/M_{\text{BH}}$, as in the case of Eddington-limited accretion and consistent with recent observational estimates, the local SMBH mass function is fully accounted for by mass accreted by X-ray selected AGNs, with bolometric corrections indicated by current observations and a standard mass-to-light conversion efficiency $\epsilon \simeq 10$ per cent. The analysis of the accretion history highlights that the most massive BHs (associated with bright optical quasi-stellar objects) accreted their mass faster and at higher redshifts (typically at $z > 1.5$), while the lower-mass BHs responsible for most of the hard X-ray background have mostly grown at $z < 1.5$. The accreted mass function matches the local SMBH mass function if, during the main accretion phases, $\epsilon \simeq 0.09 \pm 0.04, -0.03$ and the Eddington ratio $\lambda = L/L_{\text{Edd}} \simeq 0.3 \pm 0.1$ (68 per cent confidence errors). The visibility time, during which AGNs are luminous enough to be detected by the currently available X-ray surveys, ranges from $\approx 0.1 \text{ Gyr}$ for present-day BH masses $M_{\text{BH}}^0 \simeq 10^6 M_\odot$ to $\approx 0.3 \text{ Gyr}$ for $M_{\text{BH}}^0 \geq 10^9 M_\odot$. The mass accreted during luminous phases is $\geq 25$–30 per cent even if we assume extreme values of $\epsilon$ ($\epsilon \simeq 0.3$–0.4). An unlikely fine tuning of the parameters would be required to account for the local SMBH mass function accommodating a dominant contribution from ‘dark’ BH growth (due, for example, to BH coalescence).

Key words: black hole physics – galaxies: active – galaxies: evolution – galaxies: nuclei – cosmology: miscellaneous.

1 INTRODUCTION

The paradigm that quasars and, more generally, active galactic nuclei (AGNs) are powered by mass accretion on to a supermassive black hole (SMBH), proposed long ago (Salpeter 1964; Zel’dovich & Novikov 1964; Lynden-Bell 1969), has received very strong support from spectroscopic and photometric studies of the stellar and gas dynamics in the very central regions of local spheroidal galaxies and prominent bulges. These studies established that in most, if not all, galaxies observed with high enough sensitivity a central massive dark object (MDO) is present with a well-defined relationship between the MDO mass and the mass or the velocity dispersion of the host galaxy spheroidal component (Kormendy & Richstone 1995; Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002; Kormendy 2004). Although there is no direct evidence that all MDOs are black holes (BHs), the evidence for a singularity is actually very tight in the Galaxy (Schödel et al. 2002; Ghez et al. 2003) and alternative explanations are severely constrained in NGC 4258 (Miyoshi et al. 1995; see also, for example, Kormendy 2004).

Soltan (1982) showed that, in the framework of the above paradigm, the total accreted mass density can be inferred from the observed quasi-stellar object (QSO)/AGN counts. The basic ingredients of the calculation are (i) the bolometric correction $k_{\text{bol}}$, (ii) the effective redshift and the corresponding $K$-correction, and (iii) the mass-to-radiation conversion efficiency $\epsilon$. When more precise luminosity functions (LFs) of QSO/AGNs became available, Chokshi &

*E-mail: shankar@sissa.it
Turner (1992) presented a first estimate of the accreted mass density and derived constraints on the corresponding mass function (MF). Small & Blandford (1992) tried to relate the LF of optically selected AGNs to the local SMBH MF in galaxies for several possible accretion histories. Salucci et al. (1999) showed that the LF of the galaxy spheroids (encompassing E and S0 galaxies, and bulges of spiral galaxies) combined with the relationship between the spheroid and the central MDO mass allows an accurate evaluation of the local MF of the SMBHs. They concluded that the distribution of the mass that fuelled the nuclear activity, as traced by the LFs of QSOs and of AGNs contributing the X-ray background, matches the local SMBH MF, provided that $\epsilon \simeq 0.1$ and the ratio of bolometric to Eddington luminosity $\lambda = L_{bol}/L_{edd}$ declines with luminosity and/or look-back time. It was also shown that the high-mass tail of the local MF is due to the remnants of the bright optically selected QSOs, while at low masses the remnants of the AGNs producing most of the X-ray background largely dominate.

Recent estimates of the local MF also exploited the relationship between SMBH mass and velocity dispersion of the host spheroid (see, for example, Aller & Richstone 2002; Yu & Tremaine 2002; McLure & Dunlop 2004; Marconi et al. 2004), to reach, however, somewhat discrepant conclusions.

The aim of this paper is to compare the local MF of SMBHs with the MF of the mass accreted during the nuclear activity, in order to shed light on important open questions such as the following.

(i) Is there room for a significant ‘dark’ accretion? In particular, can BH merging be the main process building the present-day SMBH MF?
(ii) How do the X-ray and optical views of BH mass build-up compare?
(iii) What is the typical Eddington ratio of AGNs when they accrete most of their mass?
(iv) How long does the visible phase of the AGNs last?
(v) Do we really need a mass-to-radiation conversion efficiency higher than the standard value of $\epsilon \simeq 0.1$, as recently argued (see, for example, Elvis, Risaliti & Zamorani 2002)?

The local SMBH MF, including the contribution from the spheroidal components of late-type galaxies, is re-estimated, exploiting and extending the technique outlined by Salucci et al. (1999) and recently presented by Shankar et al. (2003). The accreted MF will be derived using up-to-date LFs as a function of cosmic time for optically and X-ray selected AGNs.

The paper is organized as follows. In Section 2 we critically discuss the relationships between luminosity, mass and velocity dispersion of the spheroidal components of galaxies ($L_{sph}$, $M_{sph}$, and $\sigma$), and $M_{BH}$. In Section 3 we present and discuss two estimates [derived via the velocity dispersion function (VDF) and the LF, respectively] of the local SMBH MF. In Section 4 the accreted mass density is estimated. In Section 5 the accreted mass function (AMF) is computed and compared with the local MF of SMBHs. The accretion history and the AGN visibility times are analysed in Section 6. In Section 7 we present a discussion of the results and the conclusions.

The standard flat cold dark matter (CDM) cosmological model has been used, with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_k = 0.7$.

---

2 CORRELATIONS AMONG SMBH MASS, GALAXY LUMINOSITY AND VELOCITY DISPERSION

The SMBH MF can be derived by coupling the statistical information on local LFs of galaxies with relationships among luminosity (or related quantities such as stellar mass and velocity dispersion) and the central BH mass (see, for example, Salucci et al. 1999).

Because the BH mass correlates with the luminosity and velocity dispersion of the bulge stellar population, we need separate LFs for different morphological types (which have different bulge to total luminosity ratios), and it is convenient to use galaxy LFs derived in bands as red as possible, where the old bulge stellar populations are more prominent.

2.1 Bulge luminosity versus black hole mass

McLure & Dunlop (2002), analysing a sample of 72 active and 20 inactive galaxies, found that the central BH mass and the total $R$-band magnitude, $M_R$, of the bulge are strictly related. In particular, considering only inactive elliptical galaxies with accurate measurements of BH mass, the relation, converted to $H_0 = 70$, reads

$$\log \left( \frac{M_{BH}}{M_{\odot}} \right) = -0.50(\pm0.05)M_R - 2.69(\pm1.04), \quad (1)$$

with a scatter of $\Delta \log M_{BH} = 0.33$. It is worth noticing that the relationship has been used to derive B-band magnitudes, translated to $R$ band assuming an average colour $(B-R) = 1.57$. A larger scatter $\Delta \log (M_{BH}) \simeq 0.45$ was found by Kormendy & Gebhardt (2001), who used a sample including also lenticular and spiral galaxies.

For galaxies observed with a spatial resolution high enough to resolve the BH sphere of influence, Marconi & Hunt (2003) report a tight relation between the SMBH mass and the host galaxy bulge $K$-band luminosity

$$\log \left( \frac{M_{BH}}{M_{\odot}} \right) = 1.13(\pm0.12) \left( \log \left( \frac{L_K}{L_{K,\odot}} \right) - 10.9 \right) + 8.21(\pm0.07), \quad (2)$$

with a scatter $\Delta \log M_{BH} = 0.31$. Translating equation (1) to the $K$ band using the colour $R-K = 2.6$ (Kochanek et al. 2001, with $R-K_{20} = -0.2$) as discussed in Section 3.1, it is apparent that the Marconi & Hunt (2003) relationship yields higher BH masses at fixed luminosity. Correspondingly, the derived SMBH mass density is up to a factor of 2 higher than that obtained from equation (1). A closer analysis shows that most of the discrepancy is due to SMBHs in spiral galaxies and can be ascribed to the uncertainty in the evaluation of their bulge component. Because most of the local mass density is contributed by BHs in E and S0 galaxies, we decided to exploit the relationship reported in equation (1).

As pointed out by McLure & Dunlop (2002), their $M_{K} - \log M_{BH}$ relation is compatible with a linear relation between BH and spheroidal mass, $M_{sph}$. Indeed, inserting the result found by Borriello, Salucci & Danese (2003), $M_{sph}/L_R \propto L_R^{0.21(\pm0.03)}$, we obtain $M_{BH} \propto M_{sph}^{0.10(\pm0.12)}$.

2.2 Velocity dispersion versus black hole mass

While the presence of a strong correlation between BH mass and velocity dispersion of the stellar spheroid, $M_{BH} - \sigma$, is undisputed (Ferrarese & Merritt 2000; Gebhardt et al. 2000), the value of its
slopel is stil debated. A detailed analysis of the available data by Tremaine et al. (2002) yields

$$\log \left( \frac{M_{\text{BH}}}{10^{8} M_{\odot}} \right) = 4.02(\pm 0.32) \log (\sigma_{200}) + 8.13(\pm 0.06), \tag{3}$$

where $\sigma_{200}$ is the line-of-sight velocity dispersion in units of 200 km s$^{-1}$. The slope is in reasonable agreement with the findings of Ferrarese (2002), $M_{\text{BH}} \propto \sigma^{5.8 \pm 0.2}$. It should also be noted that the velocity dispersions used by Tremaine et al. (2002) refer to a slit aperture $2r_e$, while those reported by Ferrarese refer to $r_e/8$. The scatter around the mean relationship is small, $\Delta \log M_{\text{BH}} = 0.3$, possibly consistent with pure measurement errors.

The low-mass and low-velocity dispersion regime is quite difficult to investigate. The analysis of M33 by Gebhardt et al. (2001) yields an upper limit on the BH mass ($\sim 1500 M_{\odot}$) more than 10 times below the central value predicted by equation (3). However, the larger upper limit ($\sim 3000 M_{\odot}$) claimed by Merritt, Ferrarese & Joseph (2001) is consistent with the steeper $M_{\text{BH}}-\sigma$ relation found by Ferrarese (2002). The estimate of Filippenko & Ho (2003) of the mass of the central BH in the least luminous type 1 Seyfert galaxy known, NGC 4395, ($M_{\text{BH}} \lesssim 10^{5}-10^{6} M_{\odot}$) is not inconsistent with equation (3). However, it should also be mentioned that the BH mass in this case has been estimated using indirect rather than dynamical arguments. The efforts to detect the so-called intermediate mass BHs ($10^{4} \lesssim M_{\text{BH}} \lesssim 10^{6} M_{\odot}$) in galactic centres and therefore to constrain the very low $\sigma (<50$ km s$^{-1}$) end of the $M_{\text{BH}}-\sigma$ relation have been recently reviewed by van der Marel (2004).

It is worth noticing that the $M_{\text{BH}}-\sigma$ relationship does not need to keep a power-law shape down to low $M_{\text{BH}}$ or $\sigma$ values. On the contrary, Granato et al. (2004) presented a model for the coevolution of QSOs and their spheroidal hosts whereby, in the least massive bulges, the BH growth is increasingly slowed down by supernova heating of the interstellar medium as the bulge mass (hence $\sigma$) decreases. As a result, $M_{\text{BH}}$ is expected to fall steeply with decreasing $\sigma$, for $\log (\sigma \text{ (km s}^{-1})] \lesssim 2.1$. This model also predicts that the observed spread around the mean relationship is a natural one, deriving mainly from the different virialization redshifts of host haloes.

### 3 Local SMBH Mass Function

The local SMBH MF can be estimated either from the local LF or from the local VDF of spheroidal galaxies and galaxy bulges, through the $M_{\text{BH}}-L_{\text{int}}$ relation or the $M_{\text{BH}}-\sigma$ relation, respectively. Previous studies (Aller & Richstone 2002; Yu & Tremaine 2002) have shown that the two methods may yield estimates of the local mass density of SMBHs differing by a factor of $\sim 2$. On the other hand, Ferrarese (2002), McLure & Dunlop (2004) and Marconi et al. (2004) found very good agreement between the results of the two methods.

#### 3.1 Local Luminosity Functions of Spheroids and Bulges

The LFs best suited for our purpose are those in red and infrared bands, which are more directly linked to the mass in old stars. Moreover, we need separate LFs for the various morphological types with different bulge to total luminosity ratios. We will use the $K$-band LF by Kochanek et al. (2001), the $K_{s}$-band LF by Cole et al. (2001), and the $r'$-band LF by Blanton et al. (2001, 2003), Nakamura et al. (2002) and Bernardi et al. (2003). To compare LFs defined in different bands we must set up a common definition of the total magnitude/luminosity and of average colours.

Because we are interested in the total luminosity of spheroidal components of galaxies, we adopt as total magnitudes those obtained with a de Vaucouleurs profile. We have therefore corrected by $-0.2$ the surface brightness limited magnitudes, $K_{s}$, of the Two-Micron All-Sky Survey (2MASS) sample and the Petrosian magnitudes, used by Blanton et al. (2001, 2003) and by Nakamura et al. (2002). Both magnitude systems in fact are defined for apertures which contain $\sim 80$ per cent of the total flux for the adopted profile. For the Kron magnitudes of Cole et al. (2001), in the $K_{s}$ band, we used a brightening of $-0.11$, which is required to convert them to an $r^{1/4}$ luminosity profile.

Magnitudes were converted to the $R$ band using the mean colours $-R-K_{s} = 2.51$ and $-r^{*} = -0.11$ (Blanton et al. 2001). We assume an error of 0.1 mag on colours and include it in our estimate of the final errors on the SMBH MF.

As illustrated by Fig. 1, the different estimates of the LF are in very good agreement with each other, except for that by Blanton et al. (2003), which is low at bright magnitudes (by a factor of $\sim 4$ at $M_{R} < -24$). Indeed, the Schechter function adopted by the latter authors falls below their own data points at $M_{R} - 5 \log (H_{0}/100) = -23$ (cf. their fig. 5). The classification by Kochanek et al. (2001) allows a clear-cut distinction between early- and late-type galaxies. A similar classification has also been proposed by Nakamura et al. (2002). Figs 2 and 3 show that the agreement is quite satisfactory.
also for early and late types separately, although the early-type LF by Bernardi et al. (2003) misses objects fainter than $M_K \simeq -21$ because of their velocity dispersion criterion ($\sigma > 70$ km s$^{-1}$ and signal-to-noise ratio $> 10$).

3.2 From the local luminosity function to the SMBH mass function

Based on table 1 of Fukugita, Hogan & Peebles (1998), to obtain the LF of the spheroidal components, we adopt the average $R$-band bulge to total luminosity ratios $f_{eb} = 0.85 \pm 0.05$ for early-type galaxies and $f_{eb} = 0.30 \pm 0.05$ for late-type galaxies.

The SMBH MF was then computed convolving the LF with the $M_{\text{BH}} - L_{\text{bulge}}$ relation by McLure & Dunlop (2002) (see equation 1), assuming a Gaussian distribution around the mean with a dispersion $\Delta \log(M_{\text{BH}}) = 0.33^{+0.07}_{-0.05}$. These uncertainties encompass most of the values quoted in the recent literature (see Section 2.2). The errors on the SMBH MF include the overall uncertainties on the LF, on the bulge fractions, on the SMBH–$M_\odot$ relation and its scatter. The uncertainties on the LF, including those on colours, contribute about 70 per cent of the error budget.

The SMBH MF in early-type galaxies, shown in Fig. 4, has been estimated using the LF of Nakamura et al. (2002), converted to $R$ band, and equation (1). The match with the MF computed via the VDF and the $M_{\text{BH}} - \sigma$ relation (see below) is very good. The corresponding SMBH mass density amounts to $\rho_{\text{BH}}^0(E) = 3.1^{+0.5}_{-0.8} \times 10^9 M_\odot$ Mpc$^{-3}$, in excellent agreement with the findings of McLure & Dunlop (2004) and Marconi et al. (2004), and 30 per cent higher than the estimate by Yu & Tremaine (2002) and Aller & Richstone (2002).

The MF of SMBHs hosted by spiral bulges was computed in the same way, using the LF for late-type galaxies by Nakamura et al. (2002). Their local mass density is $\rho_{\text{BH}}^0(Sp) = (1.1 \pm 0.5) \times 10^9 M_\odot$ Mpc$^{-3}$, bringing the overall mass density to $\rho_{\text{BH}}^0 = (4.2 \pm 1.1) \times 10^9 M_\odot$ Mpc$^{-3}$. The local number density of SMBHs with $M_{\text{BH}} > 10^7 M_\odot$ is $n_{\text{SMBH}} = (1.3 \pm 0.25) \times 10^{-2}$ Mpc$^{-3}$, as illustrated by Fig. 5, the main contribution to the global mass density comes from the range $2 \times 10^6 < M_{\text{BH}} < 1 \times 10^9 M_\odot$, mostly populated by SMBHs in early-type galaxies, while less massive BHs are preferentially hosted in late-type objects.

Our determination is very close to the result by Marconi et al. (2004), who used a methodology similar to ours. As suggested by Aller & Richstone (2002), the MF can be well represented by a four-parameter function, which for our determination (per unit $\text{d log } M_{\text{BH}}$) takes the form

$$\Phi(M_{\text{BH}}) = \Phi_0 \left(\frac{M_{\text{BH}}}{M_\odot}\right)^{\alpha+1} \exp \left[ -\left(\frac{M_{\text{BH}}}{M_\odot}\right)^\beta \right],$$

with $\Phi_0 = 7.7 (\pm 0.3) \times 10^{-3}$ Mpc$^{-1}$, $M_\odot = 6.4 (\pm 1.1) \times 10^7 M_\odot$, $\alpha = -1.11 (\pm 0.02)$ and $\beta = 0.49 (\pm 0.02) (H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$).

The formula holds in the range $10^6 \leq M_{\text{BH}}/M_\odot \lesssim 5 \times 10^9$.

3.3 Local velocity dispersion function

The local VDF can be derived from the local galaxy LF exploiting the luminosity–$\sigma$ relation (Gonzalez et al. 2000; Sheth et al. 2003), well established for spheroidal galaxies (Faber & Jackson 1976). The analysis of a sample of 86 nearby E and S0 galaxies yields (de Vaucouleurs & Olson 1982; Gonzalez et al. 2000)

$$M_{\text{BH}} = (-19.71 \pm 0.08) - (7.7 \pm 0.7) \log \sigma_{200} + 5 \log h,$$

where $\sigma_{200}$ is the velocity dispersion criterion ($\sigma > 70$ km s$^{-1}$ and signal-to-noise ratio $> 10$).
with \( h = H_0 / 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \). However, data for larger samples suggest a steeper relation. Using about 9000 early-type galaxies selected from the Sloan Digital Sky Survey (SDSS), Bernardi et al. (2003) found \( L_{r^*} \propto \sigma^{3.91} \), where \( \sigma \) refers to an \( r_e/8 \) aperture. The VDF of the SDSS has actually been obtained with a fixed aperture of 1.5 arcsec and then converted to the \( r_e/8 \) aperture following the conversion suggested by Jørgensen, Franx & Kjaergaard (1995).

Estimates of the local VDF have been derived by Shimasaku (1993) and Gonzalez et al. (2000) (see Kochanek 2001, for a comprehensive review) and, more recently, by Sheth et al. (2003), who were the first to allow for the distribution (assumed Gaussian with a luminosity-dependent width) of data points around the best-fitting relationship.

To make a fuller exploitation of the data by Bernardi et al. (2003), we have used them to derive the bivariate distribution \( p_{ij} = p(L_i, \sigma_j) \), yielding the fraction of objects in the \( r^* \)-luminosity bin centred at \( L_i \) and in the velocity dispersion bin centred at \( \sigma_j \). The 9000 objects in the samples, covering an absolute magnitude range \(-18 \leq M_r \leq -27\) and a velocity dispersion range \( 1.8 \leq \log(\sigma) \leq 2.7 \) (\( \sigma \) in km s\(^{-1}\)) have been subdivided in 19 equal-width magnitude bins and 170 equal-width log \( \sigma \) bins. The VDF is then estimated as

\[
n(\sigma) = \sum_i p_{ij} n_i \tag{6}
\]

where \( n_i = n(L_i) \) is the \( r^* \)-band LF for early-type galaxies by Nakamura et al. (2002, Fig. 2). The resulting VDF is shown in Fig. 6 with its errors, computed using the formula for the propagation of errors in a multivariate function with independent random errors in each variable. The uncertainties are larger towards the two extremes, where the number of sampled objects decreases, and smaller around the knee of the function. We have checked that our results are independent of the bin size.

Using the \( K \)-band LF (Kochanek et al. 2001) converted to the \( r^* \) band adopting a colour \( K - r^* = -2.73 \), appropriate for early-type galaxies (Blanton et al. 2001; Kochanek et al. 2001), we find differences in the VDF of at most 0.15 dex. From Fig. 6 it is apparent that our estimate is very close to that of Sheth et al. (2003), apart from the more rapid decline at low velocity dispersions, due to the selection criteria adopted by Bernardi et al. (2003), as noted above.

The contribution from late-type galaxy bulges to the VDF is rather difficult to assess. In fact, the bulge to disc mass ratios depend more on morphology than on luminosity and on rotational velocity. Although for a given morphological type a correlation between the bulge velocity dispersion and the maximum rotational velocity may be expected, the use of the Tully–Fisher relation (among luminosity and rotation velocity) to infer the velocity dispersion is rather unsafe (see the discussions of Ferrarese 2002 and Sheth et al. 2003).

### 3.4 From the velocity dispersion function to the SMBH mass function

In order to obtain an estimate of the local MF of SMBHs, the local VDF for early-type galaxies can be convolved with the \( M_{\text{BH}} - \sigma \) relation of Tremaine et al. (2002). The SDSS velocity dispersions (Bernardi et al. 2003) given for an aperture of \( r_e/8 \), have been converted to a \( 2r_e \) aperture using equation (16) of Tremaine et al. (2002), while the \( M_{\text{BH}} - \sigma \) relation of Tremaine et al. (2002) has been estimated with velocity dispersions taken within an aperture corresponding to \( 2r_e \). We assume a Gaussian distribution of BH masses at constant \( \sigma \), with a dispersion \( \Delta = 0.30_{-0.07} \) dex.

Fig. 7 shows the SMBH MF estimates derived from the VDF obtained through the bivariate probability distribution and from the VDF by Sheth et al. (2003). The shaded area shows the uncertainties on the former estimate, including the contributions from errors on both the VDF and \( \Delta \). Again, the decline for \( M_{\text{BH}} \leq 10^7 M_\odot \) is due to the incompleteness of the SDSS sample at low velocity dispersions. The integrated mass density of SMBH in early-type galaxies is \( \rho_{\text{BH}}^0 = 2.8 \times 10^3 M_\odot \text{ Mpc}^{-3} \) or \( \rho_{\text{BH}} = 3.0^{+0.9}_{-0.6} \times 10^4 M_\odot \text{ Mpc}^{-3} \) if we use the VDF by Sheth et al. (2003) or that obtained through the bivariate probability function, respectively. As noted above, the evaluation of the contribution of SMBHs hosted by late-type galaxies through this method is hampered by the poor knowledge of the local VDF for their bulges. Adopting the tentative estimate by Sheth et al. (2003) for the late-type galaxy contribution to the VDF, coupled with equation (3), with the same scatter \( \Delta = 0.3 \), we obtain \( \rho_{\text{BH}} = 1.2 \times 10^5 M_\odot \text{ Mpc}^{-3} \), which is consistent with the estimate derived from the LF.

Wyithe & Loeb (2003) obtained a lower estimate of the total mass density mainly because they neglected the scatter \( \Delta \) of the \( M_{\text{BH}} - \sigma \) relationship.

![Figure 6. Velocity dispersion function. The solid line is the estimate obtained from the Nakamura et al. (2002) LF coupled with the bivariate (luminosity, \( \sigma \)) distribution derived from the SDSS data in the \( r^* \) band; its uncertainty region is shown by the dashed lines. The three-dots-dashed line is the estimate by Sheth et al. (2003).](https://example.com/fig6.png)

![Figure 7. Estimates of the local MF of SMBHs hosted by early-type galaxies, derived from the VDFs in Fig. 6 coupled with the \( M_{\text{BH}} - \sigma \) relation by Tremaine et al. (2002). The grey area represents the uncertainties on the estimate based on the bivariate (luminosity, \( \sigma \)) distribution.](https://example.com/fig7.png)
4 ACCRETED MASS DENSITY

Soltan (1982) showed that the total mass density accumulated by accretion on BHs powering QSOs can be deduced from QSO counts, under quite simple assumptions. If $\epsilon$ is the mass-to-radiation conversion efficiency, the bolometric luminosity is

$$L_{\text{bol}} = \epsilon M_{\text{acc}} c^2$$

and the mass accretion rate reads

$$M_{\text{BH}} = (1 - \epsilon) M_{\text{acc}}.$$  

The conversion of luminosities measured in a given band to bolometric luminosities requires the knowledge of bolometric corrections $k_{\text{bol}}$ (see, for example, Elvis et al. 1994), which may depend on luminosity and/or redshift. The mass accreted up to the present time by all AGNs brighter than $L$ can be written as

$$\rho_{\text{acc}} (> L) = \frac{1 - \epsilon}{\epsilon c^2} \int_0^{z_{\text{max}}} \frac{dz}{z} dL' \times k_{\text{bol}} (L', z) n(L', z) L',$$  

where $n(L', z)$ is the comoving LF. As noted by Soltan (1982), $\rho_{\text{acc}}$ is independent of $H_0$ and of the QSO lifetime.

The most complete AGN surveys are those at X-ray (hard and soft), optical and radio wavelengths. The latter selection is however rather inefficient, because only $\sim$10 per cent of AGNs are radio loud.

4.1 Mass accreted on optically selected QSOs

The 2dF survey (Boyle et al. 2000; Croom et al. 2004) has provided an accurate determination of the redshift-dependent LF of optically selected AGNs with $M_B < -22.5$ and $z < 2.2$. Croom et al. (2004) showed that the data are consistent with pure luminosity evolution of the form $L_B(z) = L_B(0) \times 10^{0.4 (21.5 - 2z)}$ (for a $\Lambda$CDM model with $\Omega_m = 0.3$), peaking at $z_p \approx 2.74$ and exponentially declining at higher redshifts. Although the LF is poorly known for $z > 2.4$, there is strong evidence (see Fan et al. 2001; Osmer 2004, for a recent review), for a rapid decrease with increasing redshift of the space density of bright QSOs for $z \geq 3$. More recently, very deep X-ray (Barger et al. 2003) and optical (Cristiani et al. 2004) surveys have provided strong constraints on the space density of less luminous QSOs at high redshift. As illustrated by Fig. 8, the Croom et al. (2004) power-law model provides a sufficiently accurate description also of the data at $z \approx 4$.

Inserting such a model in equation (9), and integrating it up to $z = 6$, we obtain, for $k_{\text{bol}}^\Delta = 11.8$, appropriate for $L_{\text{opt}} = (L, v)_B$ with $v_B = 6.8 \times 10^{14}$ Hz (Elvis et al. 1994) and $\epsilon = 0.1$

$$\rho_{\text{acc}}^\Delta = 1.4 \times 10^8 k_{\text{bol}}^\Delta M_{\odot} \text{Mpc}^{-3},$$  

with objects at $z \leq 2.2$ contributing $\rho_{\text{acc}}^\Delta = 0.8 \times 10^8 M_{\odot} \text{Mpc}^{-3}$. Using the Boyle et al. (2000) LF, which is however inconsistent with high-redshift data, $\rho_{\text{acc}}^\Delta$ increases by 20 per cent. Thus, the mass density accreted on BHs powering the optical QSO emission is a factor of $\sim 3$ lower than the estimated local SMBH mass density.

The estimate of $\rho_{\text{acc}}^\Delta$ is affected by uncertainties on $k_{\text{bol}}^\Delta$ and on $\epsilon$. An upper limit of $k_{\text{bol}}^\Delta = 16$ can be derived from the Elvis et al. (1994) sample. On the other hand, recent data point to a lower bolometric correction than that used in equation (10). For instance, McLure & Dunlop (2004) find $k_{\text{bol}}^\Delta \approx 8$, and Vestergaard (2004) finds $k_{\text{bol}}^\Delta = 9.7$ for higher-redshift QSOs. On the whole, we attribute to $k_{\text{bol}}^\Delta$ an uncertainty of about 30 per cent. It is worth noticing that no dependence of the bolometric correction on optical luminosity has been reported.

The efficiency $\epsilon$ of conversion of accreted mass into outgoing photons can be as high as $\epsilon \approx 0.4$ for extreme Kerr BHs. On the other hand, no firm lower limit to $\epsilon$ can be set; in extreme cases, a BH can grow without radiating any photons at all. However, the low value of $\rho_{\text{acc}}^\Delta$ does not necessarily imply a low value of $\epsilon$, because an additional important contribution to the local BH mass density is expected from highly absorbed hard X-ray selected AGNs, contributing a large fraction of the X-ray background energy density, but only marginally represented in optical surveys.

4.2 Mass accreted on X-ray selected AGNs

Recent data (see Hasinger 2004, for a review) have shown that a large fraction of the hard X-ray background is contributed by partially or completely covered AGNs in the luminosity range $\log(L_{2-10keV}) = 42-44$ erg s$^{-1}$ and at redshifts $z = 0.5-1$. A comprehensive study of the redshift-dependent hard X-ray AGN LF, including the distribution of the absorption column density $N_{\text{H}}$, has been recently carried out by Ueda et al. (2003, U03 hereafter). In the following we will refer to their luminosity-dependent density evolution (LDDE) model, with the additional fraction of AGN with $24 < \log(N_{\text{H}}) < 25$ required in order to fit the X-ray background with the most recent normalizations (Vecchi et al. 1999; Barcons, Mateos & Ceballos 2000; Gilli 2004). The additional AGN fraction implies an increase of the mass density by 25 per cent.

Unfortunately, the available information on the overall spectral energy distribution of hard X-ray selected objects (and particularly of the faint ones, which are the most relevant to estimate the low-mass end of the MF) is scanty, so that estimates of the bolometric corrections are difficult. The bolometric correction, $k_{\text{bol}}^{2-10} \approx 32$, derived by Elvis et al. (1994), refers to optically bright quasars. Evidence for an increase of the hard X-ray to optical luminosity ratio, $L_{\text{HIS}} / L_{\text{opt}}$ with decreasing optical luminosity, has been reported by Vignali, Brandt & Schneider (2003). Bolometric corrections, $k_{\text{bol}}^{2-10} \approx 12-18$, substantially smaller than the Elvis et al. (1994) value, have been estimated at least for a few Seyfert galaxies (Fabian 2004). Moreover, in order to match the optical LF of Boyle et al. (2000) starting from the hard X-ray LF, U03 had to assume that $L_{\text{HIS}} / L_{\text{opt}} \propto L_{2-10keV}^{-2.7}$, in close agreement with the observational data by Vignali et al. (2003).
The luminosity dependence of the X-ray to optical luminosity ratio does not necessarily imply a higher efficiency of low-luminosity objects in producing X-ray (compared to optical) photons. An alternative explanation, borne out by evidence of larger covering factors for Seyfert galaxies compared to QSOs, is stronger dust extinction for lower-luminosity objects which are less capable of pushing away the surrounding medium, as suggested long ago (Cheng, Danese & de Zotti 1983).

If the optical/ultraviolet bolometric correction is independent of luminosity, the U03 relationship between ultraviolet and X-ray luminosity implies

\[ k_{\text{bol}}^{2-10} = 17 \left( \frac{L_{2-10}}{10^{43} \text{ erg s}^{-1}} \right)^{0.43}. \] (11)

Inserting equation (11) into equation (9), assuming \( \epsilon / (1 - \epsilon) = 0.1 \) and integrating over the luminosity and redshift intervals (41.5 \( \leq \log (L_{2-10}\text{keV}) \leq 46.5 \) and \( z \leq 3 \)) investigated by U03, we find

\[ \rho_{\text{acc}}^{\text{X}} \approx 4.1 \times 10^5 \text{ M}_\odot \text{ Mpc}^{-3}. \] (12)

If we extrapolate the LF up to \( z = 6 \), we obtain a mass density larger by 15 per cent.

As a consistency check, we have subtracted the contribution of type 2 AGNs, following the prescriptions given by U03, in order to obtain the contribution to the local mass density of type 1 objects only. We find

\[ \rho_{\text{acc}}^{\text{X},1} \approx 1.5 \times 10^5 \text{ M}_\odot \text{ Mpc}^{-3}, \] (13)

in close agreement with the result obtained using the optical LF (equation 10). The relatively large contribution of the optically selected AGNs to the local BH mass density (>30 per cent), despite their small (<20 per cent) contribution to the intensity of the hard X-ray background, reflects their lower X-ray to optical luminosity ratio. Because \( \rho_{\text{acc}}^{\text{X},1} \propto [(1 - \epsilon)/\epsilon] k_{\text{bol}}^{2-10} \) and \( \rho_{\text{acc}}^{\text{X}} \propto [(1 - \epsilon)/\epsilon] k_{\text{bol}}^{2-10} \), from the agreement between the two estimates we can conclude that the uncertainty in \( k_{\text{bol}}^{2-10} \) is similar to that on \( \rho_{\text{bol}}^{\text{X}} \), i.e. \( \pm 30 \) per cent.

The mass accretion history is illustrated by Fig. 9 showing the increase with decreasing redshift of the comoving accreted mass density, \( \rho_{\text{acc}}(z) \), as inferred from the optical (dot-dashed line) and the hard X-ray (solid line) epoch-dependent comoving LF \( n(L, z) \).

\[
\rho_{\text{acc}}(z) = \frac{1 - \epsilon}{\epsilon^2} \int_z^{z_{\text{max}}} \frac{dz'}{(1 + z')} \int_{L_{\text{min}}}^{L_{\text{max}}} L' \, dL' \times k_{\text{bol}} L' n(L', z),
\] (14)

where the X-ray (but not the optical) bolometric correction is a function of luminosity, as discussed above. As shown by Fig. 9, most of the accretion occurs at \( z > 1.5 \) for optically selected AGNs, and at \( z < 1.5 \) for hard X-ray selected AGNs.

The close correspondence of the accreted mass density inferred from the hard X-ray LF with the local SMBH mass density \( \rho_{\text{BH}} \approx 4.2 \pm 1.0 \times 10^5 \text{ M}_\odot \text{ Mpc}^{-3} \) (see Table 1) for \( \epsilon / (1 - \epsilon) = 0.1 \) shows that there is not much room for really ‘dark’ accretion (i.e. for accretion with radiative efficiency \( \epsilon < 0.1 \)), confirming the findings by Salucci et al. (1999) and Marconi et al. (2004), unless the luminous phases of the AGNs are characterized by radiative efficiencies much higher than the usually adopted value. However, even if \( \epsilon \) is close to the maximum allowed values (\( \geq 0.3-0.4 \); Thorne 1974) the accreted mass accounts for \( >25-30 \) per cent of the local SMBH mass density, and one would be left with the problem of accounting for the correlations between \( M_{\text{BH}} \) and the bulge mass or velocity dispersion which arise naturally as a consequence of feedback associated with radiative accretion (Silk & Rees 1998; Cavaliere, Lapi & Menci 2002; King 2003; Granato et al. 2004).

A more explicit test of the role of accretion is obviously the comparison, presented in the next section, of the resulting MF with the local SMBH MF.

### 5 LOCAL ACCEMETED MASS FUNCTION

The AMF can be derived from the AGN LF once a relationship between luminosity and BH mass is established (Chokshi & Turner 1992). Salucci et al. (1999) compared, under plausible assumptions, the accreted MF with the local SMBH MF to infer information on the accretion history. This point has been recently reexamined by a number of authors (e.g. Aller & Richstone 2002; Yu & Tremaine 2002; McLure & Dunlop 2004; Yu & Lu 2004; Marconi et al. 2004), who reached different conclusions.

Let us assume that the local SMBH mass is mostly due to radiative accretion and that the accretion rate \( M_{\text{BH}} \) is proportional to \( M_{\text{BH}} \) (see, for example, Small & Blandford 1992; Cavaliere & Vittorini 2002; Marconi et al. 2004), at least during the main accretion phases. A recent analysis of SDSS quasars suggests that the two quantities are correlated (McLure & Dunlop 2004), although with a huge scatter, at least partly due to the uncertainties in BH mass estimates. An almost constant \( M_{\text{BH}}/M_{\text{BH}} \) is also expected, according to the physical model of Granato et al. (2004), during the fast growth of the SMBHs and up to the bright quasar phase.

<table>
<thead>
<tr>
<th>Table 1. Local SMBH mass densities.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
</tr>
<tr>
<td>( \rho_{\text{BH}}^0(10^5 \text{ M}_\odot \text{ Mpc}^{-3}h_7^2) )</td>
</tr>
<tr>
<td>Early-type galaxies</td>
</tr>
<tr>
<td>( r^* + M_{\text{BH}} - L_{\text{bulge}} )</td>
</tr>
<tr>
<td>3.1^{+0.9}_{-0.8}</td>
</tr>
<tr>
<td>bivariate VDF + ( (M_{\text{BH}} - \sigma) )</td>
</tr>
<tr>
<td>3.0^{+1.0}_{-0.6}</td>
</tr>
<tr>
<td>Sheth VDF + ( (M_{\text{BH}} - \sigma) )</td>
</tr>
<tr>
<td>2.8</td>
</tr>
<tr>
<td>Late-type galaxies</td>
</tr>
<tr>
<td>( r^* + (M_{\text{BH}} - L_{\text{bulge}}) )</td>
</tr>
<tr>
<td>1.1 ± 0.5</td>
</tr>
</tbody>
</table>

If $M_{\text{BH}}/M_\odot$ is constant, the bolometric luminosity grows exponentially (as does the BH mass)
\[
L_{\text{bol}}(t) = \epsilon M_{\text{BH}} c^2 = \frac{\epsilon}{1 - \epsilon} M_{\text{BH}} c^2
= \frac{\lambda \epsilon^2}{t_E} M_{\text{BH}}(t_0) \exp \left[ \left( \frac{t - t_i}{t_E} \right)^\alpha \right],
\]
with e-folding time
\[
t_E = \frac{\epsilon t_i}{(1 - \epsilon) \lambda},
\]
where $\lambda$ is the average ratio $L/L_{\text{Edd}}$, $t_E$ is the Eddington time and $t_i$ is the time when the growth starts. The e-folding time equals the Salpeter time if $\lambda = 1$.

The growth stops when the SMBH reaches its maximum mass, set equal to its present-day mass $M_{\text{BH}}^0$, i.e. we neglect the mass increase during the declining phase of the light curve (see Yu & Lu 2004). The maximum bolometric luminosity is then
\[
L_{\text{bol}}(\lambda) = \frac{\lambda M_{\text{BH}}^0 c^2}{t_E}.
\]

Under these assumptions, the local SMBH MF is related to the epoch-dependent LF in a given observational band by the energy balance equation
\[
\frac{1 - \epsilon}{\epsilon^2} \int_0^{t_0} dt \int_L L_{\text{bol}}(\lambda, t) = \int_0^{m_{\text{BH}}^0} dM_{\text{BH}} n(M_{\text{BH}}) \left[ M_{\text{BH}} - M_{\text{BH}}^0 \right],
\]
where $L = L_{\text{bol}}(M_{\text{BH}}^0)$. The local MF $n(M_{\text{BH}})$ is straightforwardly obtained by differentiating equation (18) with respect to $M_{\text{BH}}^0$. It is worth noticing that the above equation can also be derived starting from the continuity equation (e.g. Yu & Lu 2004).

In Fig. 10 the estimated AMF derived from the epoch-dependent X-ray LF by U03, assuming Eddington-limited accretion ($\lambda = 1$), is compared with the local SMBH MF (including SMBHs hosted by both early- and late-type galaxies). Although the two curves are rather close to each other, their shapes differ. The fact that the assumption of Eddington-limited accretion leads to an AMF exceeding the SMBH MF in some mass range shows that it cannot be true for all epochs and/or luminosities. Indeed, low-$\gamma$/low-luminosity AGNs are known to be radiating well below the Eddington limit (Wandel, Peterson & Malkan 1999), and recent estimates suggest that quasars are in a sub-Eddington regime up to $z \approx 2$ (McLure & Dunlop 2004; Vestergaard 2004).

The match between the AMF and the local SMBH MF indeed improves significantly (Fig. 11) if we adopt a redshift-dependent Eddington ratio of the form
\[
\lambda(z) = \begin{cases} 
\lambda_0 & \text{if } z \geq 3 \\
\lambda_0 (1 + z)^{\alpha/4} & \text{if } z < 3 
\end{cases},
\]
with $\lambda_0 = 1$ and $\alpha = 1.4$. The discrepancy at $M_{\text{BH}}^0 \geq 10^8 M_\odot$ is only marginally significant, being at slightly more than 1$\sigma$ level. On the other hand, the generally higher AMF estimate derived from the X-ray LF, compared to that from the optical LF, reflects the strong luminosity dependence of the fraction of type 2 AGNs, which are represented in the X-ray, but not in the optical LF (see Fig. 11). This significant difference from the optical LF surveys (e.g. Hasinger 2004) have shown that the type 2 fraction increases from $\approx 30$ per cent at high luminosities ($L_{2-10\text{keV}} \approx 10^{44}$ erg s$^{-1}$) to $\approx 70$–80 per cent at low luminosities ($L_{2-10\text{keV}} \lesssim 3 \times 10^{42}$ erg s$^{-1}$), consistent with the results of optical spectroscopic surveys of complete samples of nearby galaxies, without pre-selection (Huchra & Burg 1992; Ho, Filippenko & Sargent 1997). As a check, we have computed and plotted in Fig. 12 the cumulative accreted mass function obtained by summing the contribution of the optically selected QSOs to that of type 2 X-ray selected AGNs; again, the agreement with the local SMBH mass density function is very good.

We checked that a dependence of $\lambda$ on luminosity, as suggested by Salucci et al. (1999), rather than on redshift, yields an equally good fit.

Requiring that the AMF matches the local SMBH MF, we obtain constraints on the radiative efficiency and on the maximum value of the Eddington ratio (equation 19). A minimum $\chi^2$ analysis yields $\epsilon \approx 0.09(\pm 0.04, -0.03)$ and $\lambda_0 \approx 0.3(0.3, -0.1)$ (68 per cent confidence errors; see Fig. 13). The constraints on the parameter $\alpha$ ruling the evolution of the Eddington ratio (equation 19) are rather loose ($0.3 \leq \alpha \leq 3.5$).
6 ACCRETION HISTORY AND AGN VISIBILITY TIMES

Replacing $t_0$ with $t$ in equation (18) and differentiating with respect to $z$ and $M_{\text{BH}}^0$, we obtain the contributions to the $n(M_{\text{BH}}^0)$ from different cosmic epochs, shown for several values of $M_{\text{BH}}^0$ in Fig. 14, which evidences that mass is accreted earlier and more rapidly by the more massive BHs.

The mean time spent by an AGN at $L > L_{\text{vis}}$, averaged over the MF, is written

$$\langle \tau_{\text{vis}}(L) \rangle = \int_{0}^{\infty} \int_{L_{\text{vis}}}^{\infty} \frac{dL\ln(L)}{dM_{\text{BH}}^0 n(M_{\text{BH}}^0)}.$$  

(20)

As noted by Yu & Tremaine (2002), $\langle \tau_{\text{vis}} \rangle$ is independent of $\epsilon$. It depends however on $k_{\text{bol}}$ and on $\lambda$ because

$$L = \frac{\lambda}{k_{\text{bol}}} \frac{\dot{M}_{\text{BH}}}{c^2}.$$  

(21)

Adopting the U03 LF, we find $\langle \tau_{\text{vis}} \rangle \simeq 1.5 \times 10^8$ yr if we adopt a redshift-dependent Eddington ratio (equation 19) and $\simeq 8 \times 10^7$ yr if we keep $\lambda = \lambda_0$.

This is however a lower limit to the time interval $\tau_{\text{vis}}$, spent at $L > L_{\text{vis}}$, the minimum luminosity included in the LF. If $M_{\text{BH}}^0 = \text{const}$, the duration of the visible phase is simply

$$\tau_{\text{vis}}(M_{\text{BH}}^0) = t_{\text{ef}} \ln \left[ \frac{L_{\text{max}}(M_{\text{BH}}^0)}{L_{\text{min}}(M_{\text{BH}}^0)} \right] = t_{\text{ef}} \ln \left[ \frac{M_{\text{BH}}}{M_{\text{BH}}^0} \right].$$  

(22)

where $M_{\text{BH}}^0$ is the BH mass when radiative accretion yields luminosity $L > L_{\text{vis}}$. In the case of the X-ray LF of U03, the minimum 2–10 keV luminosity included at $z \simeq 0.8$, where the contribution to the X-ray background peaks, is $\log(L_{\text{min}}) \simeq 42$–42.4. With the bolometric correction given by equation (11), the corresponding minimum BH mass is

$$M_{\text{BH}}^0 = \frac{5 \times 10^4}{\lambda} \frac{L_{\text{min}}}{10^{32} \text{erg s}^{-1}} M_{\odot}.$$  

(23)

The minimum BH mass contributing to the LF of optically selected QSOs for the bolometric correction by Elvis et al. (1994) is

$$M_{\text{BH}}^0 = \frac{3 \times 10^7}{\lambda} 10^{-0.4(22.5 - M_{\text{BH}}^0)} M_{\odot},$$  

(24)

where $M_{\text{BH}}^0 \simeq -22.5$ (Boyle et al. 2000; Croom et al. 2004).

The condition that the AGN visibility timescales determined via the LF and via the local SMBH MF are equal

$$\int_{0}^{t_{\text{vis}}} \int_{L_{\text{vis}}}^{\infty} \frac{dL\ln(L)}{dM_{\text{BH}}^0 n(M_{\text{BH}}^0)} \ln \left( \frac{M_{\text{BH}}}{M_{\text{BH}}^0} \right)$$  

(25)

adds further constraints on $\epsilon$ and $\lambda_0$. Using the U03 LF and assuming a 30 per cent uncertainty on the bolometric correction for X-ray luminosities, we find an allowed range for $\epsilon$ similar to that following from the match between the AMF and the local SMBH MF (0.06 $\leq \epsilon \leq$ 0.13) while the constraints on the Eddington ratio are looser (0.5 $\leq \lambda_0 \leq$ 2).

7 DISCUSSION AND CONCLUSIONS

The analysis reported in the first part of the paper shows that the local MF of SMBHs can be rather accurately assessed. In more detail, the MF of SMBHs hosted in early-type galaxies can be obtained exploiting the velocity dispersion or LFs of host galaxies, coupled with the $M_{\text{BH}}$-$\sigma$ or $M_{\text{BH}}$-$L_{\text{sph}}$ relationships, respectively. The results obtained in these two ways are in remarkable agreement with

small uncertainties up to $M_{\text{BH}} \geq 10^9 M_\odot$ (cf. Fig. 7). The contribution from SMBHs hosted by late-type galaxies is more uncertain, and is mostly confined to the low-mass end of the MF.

The overall SMBH mass density amounts to $\rho_{\text{BH}} = (4.2 \pm 1.1) \times 10^4 M_\odot \text{Mpc}^{-3}$, with a contribution from SMBHs in late-type galaxies of $\approx 25$ per cent. This value of $\rho_{\text{BH}}$ is higher than those found by Yu & Tremaine (2002), Aller & Richstone (2002) and McLure & Dunlop (2004) (who have not considered the contribution from SMBHs residing in late-type galaxies), but is in excellent agreement with the results by Marconi et al. (2004). The local number density of the SMBHs more massive than $10^6 M_\odot$ is $n(M_{\text{BH}} > 10^6 M_\odot) \approx 1.7 \times 10^{-2} \text{Mpc}^{-3}$, which corresponds to the number of bulges and spheroids with $M_{\text{ph}} > 5 \times 10^8 M_\odot$.

The Soltan (1982) argument applied to the hard X-ray selected AGNs, allowing for a luminosity-dependent bolometric correction (Fabian 2004; U03), yields, for a mass-to-radiation conversion efficiency $\epsilon = 0.1$, an accreted mass density of $\rho_{\text{BH}}^{\text{acc}} \approx 4.1 \times 10^4 M_\odot \text{Mpc}^{-3}$, in close agreement with the local SMBH mass density. This indicates that most of the BH masses were accumulated by radiative accretion, as previously concluded by Salucci et al. (1999). Optically selected QSOs account for only $\approx 25$ per cent of the total SMBH mass density. The dominant contribution comes from type 2 AGNs, mostly missed by optical surveys.

Not only the mass density but also the MFs of the SMBHs and of the accreted mass match remarkably well, if we allow for a decrease of the Eddington ratio $\lambda = L/L_{\text{Edd}}$ with redshift (equation 19), as suggested by observations (McLure & Dunlop 2004; Vestergaard 2004). Optically selected, type 1 AGNs account for the high-mass tail of the AMF, while type 2 AGNs take over at lower masses, reflecting the strong increase with decreasing luminosity of the type 2 to type 1 ratio demonstrated by hard X-ray surveys (e.g. Hasinger 2004) and consistent with the outcome of spectroscopic surveys of complete samples of nearby galaxies, without pre-selection (Huchra & Burg 1992; Ho et al. 1997).

The alternative possibility that most of the mass has been accumulated by ‘dark’ accretion (i.e. accretion undetectable by either optical or hard X-ray surveys, as in the case of BH coalescence), is severely constrained by the above results. In order to make room for this possibility, one has to assume that the radiative efficiency during the visible AGN phases is at the theoretical maximum of $\epsilon = 0.3$–0.4. However, even in this case (unless the bolometric correction is far lower than currently estimated) the contribution of radiative accretion to the local SMBH mass density is $\gtrsim 25$ per cent, and one is left with the problem of fine tuning the radiative and non-radiative contributions in order not to break down the match with the local SMBH MF obtained with radiative accretion alone. One would also face the problem of accounting for the tight relationships between BH mass and mass or velocity dispersion of the spheroidal host, naturally explained by feedback associated to radiative accretion. For these reasons, it is unlikely that the present-day SMBH MF has been built mostly through ‘dark’ accretion or merging of BHs.

If indeed the SMBH MF has to be accounted for by radiative accretion, the requirement that it fits together with the AMF constrains the radiative efficiency and the maximum Eddington ratio to $\epsilon \approx 0.09$ ($+0.04$, $-0.03$) and $\lambda_{\text{BH}} \approx 0.3$ ($+0.3$, $-0.1$) (68 per cent confidence errors). The condition that the mean AGN visibility time-scale computed via the LF and via the local MF are equal (equation 25) yields an allowed range for $\epsilon$ very close to the above ($0.06 \leq \epsilon \leq 0.13$) and looser (but consistent) constraints on $\lambda_{\text{BH}}$.

The analysis of the accretion history highlights that the most massive BHs (associated with bright optical QSOs) accreted their mass faster and at higher redshifts (typically at $z > 1.5$), while the lower mass BHs responsible for most of the hard X-ray background have mostly grown at $z < 1.5$ (see Figs 9 and 14). The different evolutionary behaviour of the two AGN populations can be understood if gas accretion is regulated by star formation and by feedback both from supernova explosions and nuclear activity (e.g. Kawakatu & Umemura 2002; Granato et al. 2004). In this framework it is expected that the hosts of the most massive BHs have the oldest stellar populations (Cattaneo & Bernardi 2003).

The mass-weighted duration of the luminous AGN phase is found to be $(\tau_{\text{vis}}) \approx 0.8$–$1.5 \times 10^8$ yr. Using a similar method, Yu & Tremaine (2002) obtained slightly lower values, because they used in equation (20) the optical QSO LF and the local MF of SMBHs in early-type galaxies, which, as shown in Section 3, is only partly accounted for by optically selected QSOs. From a detailed modelling of the luminosity evolution of individual QSOs, Yu & Lu (2004) derived a lower limit $\tau_{\text{vis}} \gtrsim 4 \times 10^8$ yr.

If the accretion rate per unit BH mass, $M_{\text{BH}}/M_{\text{BH}}$, is constant (as in the case of Eddington-limited accretion) during the main accretion phases, the visibility times increase with BH mass (equation 22). This is consistent with the finding by McLure & Dunlop (2004) that the ratio of SMBHs in their optically selected sample at $z \approx 2$ to the corresponding number density at the present day increases with BH mass. These authors estimate, for the most massive BHs ($M_{\text{BH}} \geq 10^8 M_\odot$), a lower limit to $\tau_{\text{vis}}$ (lifetime in their terminology) of $10^8$ yr.

Setting $\lambda = 1$ and $\epsilon/(1 - \epsilon) = 0.1$ and inserting in equation (22) the value of $M_{\text{BH}}^{\text{vis}}$ given by equation (24) with $M_{\text{BH}}^{\text{vis}} = -22.5$, we obtain $\tau_{\text{vis}}(10^8 M_\odot) \approx 2 \times 10^8$ yr. Inserting instead in equation (22) the value of $M_{\text{BH}}$ given by equation (23) with $\log(L) = 42$ we obtain $\tau_{\text{vis}}(10^9 M_\odot) \approx 1.2 \times 10^9$ yr, $\tau_{\text{vis}}(10^9 M_\odot) \approx 3 \times 10^8$ yr and $\tau_{\text{vis}}(10^8 M_\odot) \approx 4.4 \times 10^8$ yr. Such visibility times increase with decreasing redshift for $z < 3$ (equation 19).

On the contrary, Marconi et al. (2004) infer mean ‘lifetimes’ increasing with decreasing present-day BH masses. For $\lambda = 1$ and $\epsilon = 0.1$ they obtain $\approx 1.5 \times 10^8$ yr for $M_{\text{BH}} > 10^9 M_\odot$ and $\approx 6 \times 10^6$ yr for $M_{\text{BH}} < 10^9 M_\odot$. However, the latter ‘lifetime’ corresponds to $\approx 11$-foiling times, i.e. to a mass increase by a factor of $4.5 \times 10^7$. However, then for a large fraction of their ‘lifetime’ low-mass BHs are too faint to be included in actual LFs (cf. equations 23 and 24).

In this context we also note that the amount of time spent just above the threshold for inclusion in the LF by objects reaching large luminosities/masses cannot be constrained by the LFs themselves, because such objects are too rare to contribute significantly to the faint end of the LF.

Our estimates for $\tau_{\text{vis}}$ are within the broad constraints imposed on one side by the QSO evolution time-scale (<1 Gyr) and on the other side by the proximity effect (>10$^9$ yr; see Martin 2004). The low ‘lifetimes’ inferred (although with large uncertainties) from clustering properties of optical QSOs (Martini & Weing 2001; Martini 2004) depend basically on the crude assumption that as soon as a massive halo virializes, the QSO appears, without any delay.

Short visibility times ($\tau_{\text{vis}} \lesssim 0.02$ Gyr) are also implied by the models of QSO LFs presented by Haehnelt, Natarajan & Rees (1998), and Wyithe & Loeb (2003). However, Hosokawa (2002) has shown that, in the same general framework, the QSO LF can be reproduced with substantially higher values of $\tau_{\text{vis}}$. Again, short time-scales mainly follow from the assumption of immediate QSO ignition at the virialization of the host DM halo. As shown and discussed by Monaco et al. (2000) and Granato et al. (2001), a delay between virialization and AGN ignition is a key ingredient to understand the QSO LF and the relationship between evolutionary histories of QSOs and of massive spheroidal galaxies hosting...
them. Granato et al. (2004) have presented a detailed physical model quantifying such delay and its increase with decreasing mass.

**ACKNOWLEDGMENTS**

We thank P. Monaco, P. Tozzi, A. Marconi and A. Cavaliere for helpful discussions. We are very grateful to the referee for perceptive comments that helped significantly to improve the paper. This work is supported in part by a MIUR/COFIN grant.

**REFERENCES**

Aller M. C., Richstone D., 2002, AJ, 124, 3035


Bernardi M. et al., 2003, AJ, 125, 1811


Lynden-Bell D., 1969, Nat, 223, 690


Schödel R. et al., 2002, Nat, 419, 694


Vignali C., Brandt W. N., Schneider D. P., 2003, AJ, 125, 433


This paper has been typeset from a TeX/LaTeX file prepared by the author.