Mass function of the dormant black holes and the evolution of the Active Galactic Nuclei

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ABSTRACT

Under the assumption that accretion onto massive black holes powers active galactic nuclei (AGN), the mass function (MF) of the BHs responsible for their past activity is estimated. For this, we take into account not only the activity related to the optically selected AGN, but also that required to produce the Hard X–Ray Background (HRXB). The MF of the Massive Dark Objects (MDOs) in nearby quiescent galaxies is computed by means of the most recent results on their demography. The two mass functions match well under the assumption that the activity is concentrated in a single significant burst with $\lambda = L/L_{\text{Edd}}$ being a weakly increasing function of luminosity. This behaviour may be indicative of some level of recurrence and/or of accretion rates insufficient to maintain the Eddington rates in low luminosity/low redshift objects. Our results support the scenario in which the early phase of intense nuclear activity occurred mainly in early type galaxies (E/S0) during the relatively short period in which they had still an abundant interstellar medium. Only recently, with the decline of the QSO luminosities, did the activity in late type galaxies (Sa/Sab) become statistically significant.

1 INTRODUCTION

The number counts of AGN’s and the intensity of the backgrounds at high energies show that the activity in nuclei of galaxies was much higher in the past than in the local universe. If we accept the paradigm that nuclear activity in galaxies is sustained by accretion onto massive BHs (see Rees 1996 for a review), then the problem of the location and discovery of the remnants of such past activity immediately arises. There is evidence for the presence of Massive Dark Objects (MDOs) in the centers of most, if not all, nearby galaxies with a large spheroidal component. The mass of MDOs has been evaluated by using very high resolution spectroscopy and photometry of the centers of nearby host galaxies. Observations with HST have allowed a significant breakthrough in the angular resolution and have led to an enormous increase in sensitivity and precision of mass estimates (Magorrian et al. 1998, hereafter M98; van der Marel 1997, hereafter VdM97; Ford et al 1997, hereafter F97; for a review, see Kormendy and Richstone 1995, hereafter KR95). As a result, a large number of MDOs have been detected suggesting that we are discovering the fossil of the past nuclear activity. Here we will assume that MDOs are the BHs now dormant after a shining past.

The main purpose of this paper is to show that the mass function of the BHs we infer from the observations of the past activity of AGN and QSOs corresponds to the MDO mass function of the local non active galaxies.

M98 have successfully exploited the very high resolution of HST photometry and ground based spectroscopy of 36 E and S0 galaxies in order to estimate their MDO masses. In spite of the large scatter in the data, they also confirmed the existence of correlation between the mass of the hot galactic component $M_{\text{sph}}$ and the MDO/BH mass, $M_{\text{MDO}}$, already suggested by Kormendy (1993) and KR95 and successively claimed by M98 and van der Marel (1998) (hereafter VdM98, by analysing a sample of 46 early type galaxies). These large samples, together with several smaller ones (e.g. F97; VdM97; H98) allow to estimate the distribution function of the ratio $M_{\text{MDO}}/M_{\text{sph}}$ and then to evaluate the mass function of the MDOs (see section 2.1).
A different approach to evaluate the MDO/BH mass function relies on the hypothesis that radio emission from the nuclei of radio quiet galaxies is related to the mass of their MDOs. As a matter of fact, a strong correlation between MDO masses and nuclear radio luminosities has been found by Franceschini et al. (1998). This correlation, in connection with the radio LF of the nuclear emission of radio quiet galaxies, can be used to probe the MDO mass function (see section 2.2).

In section 3 we will determine the mass function of the material accreted onto BHs by exploiting the knowledge on the evolution of AGN/QSO LFs. Reliable luminosity functions and cosmic evolutions are presently available for optically and soft X–ray selected objects. On the other hand, we must also consider a class of heavily absorbed AGN, under-represented in the nuclear emission of radio quiet galaxies, can be used to probe the MDO mass function (see section 2.2).

Section 4 the comparison of the MF of the dormant BHs to the accreted MF will be used to cast light on the characteristics of the evolution of the nuclear activity in galaxies of different morphological type.

We will adopt $H_o = 70{\text{km/s Mpc}^{-1}}$ unless otherwise stated. Moreover, $h = H_o / 100{\text{km s}^{-1} \text{Mpc}^{-1}}$.

### 2 ESTIMATES OF THE MDO MASS FUNCTION

#### 2.1 From the optical luminosity function to the MDO mass function

Observations and subsequent analysis have shown that MDOs are quite common in galaxies with significant spheroidal components and that their masses are correlated with the spheroid masses, though with large scatter (Kormendy 1993, KR95; VdM97; VdM98; M98). The mean value of $M_{\text{MDO}} / M_{\text{sph}}$ is still under debate and it ranges from $\langle M_{\text{MDO}} / M_{\text{sph}} \rangle \sim 10^{-2}$ (M98) to $\langle M_{\text{MDO}} / M_{\text{sph}} \rangle \sim 2 \times 10^{-3}$ (H98). The uncertainty is related to different assumptions on dynamical models, particularly on the two-integral phase–space distribution function (VdM97; H98; M98). Exploiting very high resolution HST photometry and ground based spectroscopy, M98 estimated the mass of 36 MDOs in the centers of nearby galaxies, mainly E and S0s. They found that the distribution of the ratio $x = M_{\text{MDO}} / M_{\text{sph}}$ can be described by a Gaussian distribution in log $x$:

$$f(\log x) = N \exp \left( -\frac{1}{2} (\log x - \log x_o)^2 / \sigma^2 \right)$$  (1)

where $N$ is a normalization constant. The best fit values found by M98 are $\log x_o \equiv \log( M_{\text{MDO}} / M_{\text{sph}} ) = -2.28$ and $\sigma = 0.5$. Analyzing the very high resolution photometry of 46 early type galaxies and reproducing it by means of the models proposed by Young (1980), VdM98 found $\log M_{\text{MDO}} \simeq -1.83 + \log L_V$ with rms scatter $\sigma \sim 0.3$ dex. Using standard values of $M/L_V \simeq 5.5 h (L_V / L_\odot)^{0.25}$ for spheroids (see below), this corresponds to $\langle \log M_{\text{MDO}} / M_{\text{sph}} \rangle \simeq -2.64$.

We have constructed a sample of 30 galaxies, for which at least two independent mass estimates of their MDOs are available in the literature (KR95, VdM97, VdM98, H98, F98, M98). Taking the geometric mean as the best estimate of the ratio $x$, we have found that a Gaussian distribution in log $x$, with $\langle \log x \rangle = -2.60$ and $\sigma = 0.3$ is a good description of the data. This result, quite close to that obtained by VdM98 and in agreement with the estimates of H98 and F98, will be adopted as a reference distribution.

The estimate of the spheroid mass function in the local universe is a preliminary step in the evaluation of the MDF. We determine the luminosity function of the spheroids by using the total-luminosity function ($L_{\text{tot}}$) and the estimates of the ratio of the spheroidal to total luminosity $L_{\text{sph}} / L_{\text{tot}}$ for different types of galaxies (E, S0, Sa/Sab, Sbc/Scd). The LFs of early type and spiral galaxies are well known in the range $-23 \leq M_B \leq -17$. In fact, results of different groups (e.g. Efstathiou et al., 1988; Loveday et al., 1992; Zucca et al., 1997; Geller et al., 1997, Heyl et al. 1997), based on different galaxy samples, well agree in the luminosity range relevant to our purpose. In order to represent the LFs of the various Hubble types, we use standard Schechter functions whose parameters $L_\ast$ and $\alpha$ are given in Table 1 for $h = 1$.

### Table 1

| Galaxy type | $\Phi_h h^3$ | $M_B + 5\log h$ | $\alpha$ | $f_{\text{sph}}$ |
|-------------|---------------|-----------------|---------|----------------|
| E           | $2.1 \times 10^{-3}$ | $-20$           | $-0.95$ | 0.9            |
| S0          | $2.4 \times 10^{-3}$ | $-19.6$         | $-0.95$ | 0.65           |
| Sab         | $2.9 \times 10^{-3}$ | $-19.8$         | $-1.0$  | 0.40           |
| Sbc/Scd     | $7.6 \times 10^{-3}$ | $-19.3$         | $-1.3$  | 0.10           |
The ratio $L_{sph}/L_{tot}$ has been investigated by several authors (Simien and de Vaucouleurs 1986, Kent 1985, Kodaira et al. 1986) and it has been found to vary along the Hubble sequence. There is a reasonable agreement on the average values, though intrinsic scatter is significant, particularly in the late types. With the values reported in Table 1, the total luminosity density in spheroids turns out to be $\sim 30\%$ of the total luminosity density, in agreement with Schechter and Dressler (1987) and Fukugita et al. (1998).

From the spheroid LF we infer the MF by adopting $M_{sph}/L_V \simeq 5.5 \, h(L_V/L_\odot)^{0.25}$, corresponding to $M_{sph}/L_B \simeq 6.9 \, h(L_B/L_\odot)^{0.25}$ with $(B-V)=0.90$. This law is compatible at 2 $\sigma$ level with $(M_{sph}/L_V) \propto L_V^{0.18\pm0.03}$ found by M98 and $(M_{sph}/L_B) \propto L_B^{0.35\pm0.05}$ claimed by van der Marel (1991); consistent with stellar evolution models. The spheroid MF is presented in figure 1a. The overall shape of the MF is relatively flat at $M_{sph} \lesssim 10^{11} M_\odot$ and exhibits an exponential decline for $M_{sph} > 10^{11} M_\odot$. At $M_{sph} > 5 \times 10^{10} M_\odot$ the mass function is dominated by spheroids in E and S0 galaxies. The Sa/Sab galaxies exhibit an exponential decline of their MF for $M_{sph} > 10^{10} M_\odot$ and Sbc/Scd galaxies for $M_{sph} > 10^{9} M_\odot$.

The MDOs mass function (hereafter OMF) has been computed by convolving the MF of the spheroids with the adopted log Gaussian distribution with $(M_{MDO}/M_{sph}) = -2.6$ and $\sigma = 0.3$. As it is apparent in figure (1b), the scatter of the ratios $x = M_{MDO}/M_{sph}$ softens the exponential fall off of the luminosity function; the broader the distribution the gentler is the decline. Of course, the convolution relies on the assumption that scatter reflects a real complexity of the physical processes leading to the formation of the BHs in galaxy centres.

The total mass density amounts to $\rho_{MDO} \approx 8.2 \times 10^5 M_\odot/Mpc^3 h^2$, with large fraction $\sim 75\%$ due to MDOs in E and S0 galaxies. Of the remaining 20% is due to MDOs in Sa/Sab galaxies and 5% to MDOs in late type spirals. The results for MDOs in spirals are consistent with the upper limits that Salucci et al. (1998) have derived from the analysis of a large number of high quality rotation curves.

The differences with the MFs derived using the distributions proposed by M98 are apparent from figure 1b. The M98 log Gaussian law predicts a large number density of BHs with mass larger than $10^{10} M_\odot$ and yields a total mass density $\rho_{MDO} \sim 3 \times 10^6 M_\odot/Mpc^3 h^2$, which is higher than the estimate of the local mass density of the accreted matter, based on counts of optically selected AGN, by a factor of about 10–15 (see section 3).

A contrasting result has been obtained by Franceschini et al. (1998), whose mass function, estimated from the optical LF of E/S0 galaxies and the correlation between $M_{MDO}$ and the luminosity of the bulge of the host galaxies, is substantially below our determination and yields a lower total mass density $\rho_{MDO} \sim 10^5 M_\odot/Mpc^3 h^2$. This is partly due to the adopted MF of E and S0 galaxies and partly to the fact that they neglected the broadness of the distribution of the ratio $M_{MDO}/L_{sph}$.

### 2.2 From the radio luminosity function to the MDO/BH mass function

A different but complementary approach to the evaluation of the MF of BHs is based on the idea that the radio emission from cores of normal galaxies is related to the mass of the hosted inactive BHs. Actually, accretion onto dormant BHs occurring at...
of the accretion flow are independent of the mass of the spheroid. When the latter depend on spheroid mass, $\propto M_{sph}$. The probability of correlation by chance turns out to be $\approx 10^{-0.7}$. Wrobel & Heeschen (1991), Slee et al. (1994), Sadler et al. (1995) allow the selection of a sample of 15 objects with galaxies with at least two MDO mass estimates, as specified in the section 2.1. The radio observations reported by Wrobel & Heeschen (1991), Slee et al. (1994) observed a large fraction of objects from the same sample at higher angular resolution; this has provided the radio total power function of Sadler et al. (1988) into the core power function (PF) (figure 2b) suitable for the present study.

By using equation (2), we pass from the radio core PF to the MDO/BH mass function (hereafter RMF). The result is

$$\log P_{\text{core}} \simeq 19.5 + 2.2^{+0.55}_{-0.35} \log \left( \frac{M_{BH}}{10^{6}M_{\odot}} \right),$$

with a slope close to the theoretical inferences for the exponent $\alpha$ (figure) 2a. It is worth noticing that the same value of the slope has been claimed also by McLure et al. (1998).

In order to obtain the MF of BHs in nearby galaxies, we need to convolve equation (2) with the radio luminosity function of the nuclei of quiescent spheroidal galaxies. Sadler et al. (1988) surveyed 114 nearby E and S0 radio-quiet galaxies at 5 GHz to search for weak radio sources and computed the total power function $\phi(P_t)d\log P_t$ at 5 GHz down to $\log P_t(W/Hz) = 19.6$. More recently Slee et al. (1994) observed a large fraction of objects from the same sample at an higher angular resolution; this has provided the $P_t$ vs. $P_{\text{core}}$ relationship: $\log P_{\text{core}} = 19.5 + 0.78 (log P_t - 19.5)$ for $log P_t \geq 19.5$ and $log P_{\text{core}} = log P_t$ at lower powers. We can then convert the radio total power function of Sadler et al. (1988) into the core power function (PF) (figure 2b) suitable for the present study.

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very low rates is possibly advection-dominated with low radiative efficiency (Rees et al. 1982; Abramowicz et al. 1988; Narayan and Yi 1995 a,b). In this regime, a hot ion torus ($T \sim 10^{12}$ $^\circ K$) forms, while the electrons, coupled to the ions only through two-body Coulomb effects, remain at much lower temperature ($T \sim 10^{3}$ $^\circ K$) and emit at radio frequencies via thermal synchrotron. Fabian and Rees (1995) pointed out that the thermal synchrotron emission of the electrons might be detectable in cores of quiescent galaxies. They also noted that most of the elliptical and S0 galaxies exhibit a low-power emitting radio core. The ADAF model predicts for the core radio power $P_c \propto M_{BH}^{5/7}M_{BH}^{2/7}$ (e.g. Mahadevan 1997). The dependence on frequency is quite close to the relationship $P_c \propto \nu^{1/3}$ found by Slee et al. (1994) for a sample of radio cores of E/S0 galaxies. However the ADAF model should be taken with some caution, since new high resolution radio and sub-millimeter observations of three giant elliptical galaxies significantly disagree with its canonical predictions, although the possibility of explaining the observed spectra with modifications of the canonical ADAF is not ruled out (Di Matteo et al. 1998). With Bondi accretion rate $\dot{M} \propto M_{BH}^{2}M_{BH}^{2}$ the ADAFs yield radio powers $P \propto M_{BH}^{5/2}$, if the density and sound velocity at the boundaries of the accretion flow are independent of the mass of the spheroid. When the latter depend on spheroid mass, $\rho \propto M_{sph}^{1/4}$ and $c_s \propto M_{sph}^{1/4}$ we have $P \propto M_{BH}^{7/4}$. Given that self absorbed processes (e.g. jets) yield $P \propto M_{BH}^{2}$, a relationship $P \propto M_{BH}^{5/4}$ with $2.0 \leq \alpha \leq 2.2$ is expected under rather general conditions.

Franceschini et al. (1998) find a significant correlation between the radio power of the cores $P_{\text{core}}$ and the estimated BH mass in 8 objects with $P_{\text{core}} \propto M_{BH}^{2.7+0.6}$. In a new analysis, we searched for high angular resolution radio observations of the galaxies with at least two MDO mass estimates, as specified in the section 2.1. The radio observations reported by Wrobel (1991), Wrobel & Heeschen (1991), Slee et al. (1994), Sadler et al. (1995) allow the selection of a sample of 15 objects with detections both in mass and in radio emission and 6 objects with upper limits in the latter.

The correlation and the linear regressions have been computed with the package ASURV (LaValley, Isobe & Feigelson 1992). The probability of correlation by chance turns out to be $P \lesssim 0.4\%$. The best estimate of the regression is:

$$\log P_{\text{core}}^{5\text{GHz}} \simeq 19.5 + 2.2^{+0.55}_{-0.35} \log \left( \frac{M_{BH}}{10^{6}M_{\odot}} \right),$$

Figure 2. Left panel: a) Mean line regression of $\log P_{\text{core}}$ vs. $\log M_{BH}$. (solid line). Right panel: b) Radio luminosity function (RLF) of the cores of E/S0's. Error bars represent the statistical errors in the total RLF as estimated by Sadler et al. (1988).
The mass density associated to luminosities higher than $L$ is:

$$\rho(>L) = \frac{k_{bol}}{c^2 H_0} \int \frac{1 + z}{(1 + z)^3(1 + \Omega_z)^{1/2}} dz \int_{L}^{L_{max}} Ln(L, z) dL$$

where $L$ is the luminosity in a certain band and $k_{bol}$ is the corresponding bolometric correction, $\Omega$ is the density parameter and $n(L, z)$ is the luminosity function at redshift $z$. As for the conversion efficiency of rest mass of the accreted matter into energy, we adopt $\epsilon = 0.1$, unless otherwise stated. Putting $L = L_{min} \sim 10^{44} \text{ erg/s}$ (e.g. Pei, 1995), we get the local total mass density $\rho_{BH}$. As shown by Soltan (1982) this quantity can be written in terms of source counts and is independent of the cosmological parameters.

The mass function of the matter accreted onto AGN during their activity can now be derived by means of the large amount of data available on spectra and on the evolution of the luminosity function. The increasing evidence of the presence of MDOs (i.e. inactive BHs) in a large number of galaxies with significant spheroids favors the scenario whereby the nuclear activity is a relatively short phase occurring in a large fraction of galaxies. The continuity paradigm is then excluded.

3 THE LOCAL MASS FUNCTION OF THE DORMANT BLACK HOLES

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Figure 3. Left Panel: a) The elliptical’s OMF mass function compared to the mass function, $\phi_{RMF} d\log M_{BH}$, derived from the E/S0 cores radio PF (filled circles). Also shown the RLF derived by Franceschini et al. (1998) Right Panel: b) The total mass function of the relic BHs, $\phi_{AMF} d\log M_{BH}$, derived from the past activity of AGN’s (thick dashed line); also shown the contribution from the AGN’s originating the HXRB (thin-dashed line) and the total mass function for $h = 1/2$ (dotted line).

shown in figure (3a) alongside with its uncertainties. Let us notice that for obtaining the BH mass function, the available statistics can only roughly estimate the uncertainties related to systematic errors in the procedure. While the errors in density represent only the statistical errors of the radio LF, we estimate the errors in mass from the relationship $\log M_{BH}$ versus $\log P_t$, taking into account its uncertainties in the normalization and in the slope. The errors turn out to be about ±0.2 dex. It is worth noticing that the core radio luminosity function exhibits a gentle slope and no exponential decline at least for powers $P < 10^{24}$ W/Hz. This ensures that the possible scatter in the $\log P_{core}$ versus $\log M_{BH}$ relationship does not significantly affect our results.

Franceschini et al. (1998) estimated the MF using the total radio luminosity function of the E and S0 galaxies and the correlation of the total power with the BH mass $P_t \propto M_{BH}^2$. The resulting MF stays significantly below our estimate for $M_{BH} > 2 \times 10^8 M_\odot$ and the predicted total mass density is smaller by a factor of about 3, mainly because of the steeper adopted relationship $P_t - M_{BH}$.

In figure 3a we also plot the MF determined via the optical LF. The comparison should be done with the lower curve, which refers to the E/S0 galaxies as the RMF. Although the two MFs are not completely independent, nonetheless, their agreement supports the reliability of both estimates. The dependence of the two methods on the distance scale is quite similar and thus equivalent matches can be found also for $h = 0.5$. It is worth noticing that the OMFs derived by using the distribution of $\log x$ proposed by M98 (see eq. 1-2 and figure 1b) cannot be reconciled with the RMF.
In the hypothesis of single short events it is likely that the AGN are observed in the highest state of activity, then, we can evaluate the mass of the BH associated to a luminosity $L$, (hereafter the bolometric luminosity) through the assumption
$L = \lambda L_{Edd}$ and $L_{Edd} = M_{BH}c^2/t_E$. The constraint for the latter can be obtained as it follows: if we assume $\lambda$ constant during the accretion, we get:

$$M_{BH}(t_{obs}) = M_{BH}(t_{in}) \exp \left( \frac{\lambda \tau_o}{t_E} \right),$$  \hspace{1cm} (4)

and

$$L(t_{obs}) = \frac{\lambda c^2}{t_E} M_{BH}(t_{obs}) = \frac{\lambda c^2}{t_E} M_{BH}(t_{in}) \exp \left( \frac{\lambda \tau_o}{t_E} \right),$$  \hspace{1cm} (5)

where $t_E = (\sigma T/4\pi m_p) \approx 4 \times 10^8$ yr, and $t_{in}$ and $t_{obs}$ are the initial time of the bright phase and the observing time respectively, and $\tau_o = t_{obs} - t_{in}$. Then, by requiring $M_{BH}(t_{obs}) \gg M_{BH}(t_{in})$ we get the constraint: $\tau_o \geq (2t_E)/\lambda$.

Following equation (4), we write the QSO/AGN luminosity function $\psi(L)$ as

$$\int_L^L d\psi(\gtrsim L) dL = \int_{-\infty}^{\log M_{BH}(L)} M_{a} \phi_{AMF}(M_a) d\log M_a$$  \hspace{1cm} (6)

where $\phi_{AMF}(M_a)$ is the mass function of the accreted mass, $M_a = M_{BH}$. Since $\lambda$ is likely a weakly increasing function of the luminosity, let us then set:

$$\lambda(L) = L/L_E = 10^{\gamma (\log L - 49)} \quad \gamma \simeq 0.2$$  \hspace{1cm} (7)

that follows the findings that the most luminous QSOs radiate at about the Eddington limit, while low luminosity AGN, $L \sim 10^{44}$ erg/s, show $\lambda = L/L_E \sim 0.1 - 0.05$ (see Padovani (1989) and Wandel (1998)). Then, from equation (6) and (7) the MF of the relic BHs can be written as:

$$\phi(M_{BH}) d\log M_{BH} = ln(10) \frac{\psi(\gtrsim L) d\log (\psi(\gtrsim L))}{M_{BH}} \frac{d\log M_{BH}}{d\log L}$$  \hspace{1cm} (8)

Next step is to insert into equations (3) and (8) the information on the luminosity function and its evolution. For the optically selected AGN we adopt the luminosity function and its cosmic evolution for the B-band given by Pei (1995), which is well defined at least up to $z \sim 3.5$. The bolometric correction for the B-band has been taken $k_{bol}(B) = 13$, on the basis of the spectra reported by Elvis et al (1994). The total mass density turns out to be $\rho_{BH} \simeq 2 \times 10^5 M_{\odot}/Mpc^3$, close to the estimate of Chokshi & Turner (1992), who however adopted $k_{bol}(B) = 16.5$.

The mass density of matter accreted on massive BHs powering optically selected AGN has been often used as a reference for the total mass density in BHs. However, as pointed out by Granato et al. (1997), the total amount of the matter accreted onto AGN should include that required to produce the 2-50 keV background (HXRB). In fact, the surveys in the optical and in the soft X–ray bands tend to select especially type I AGN and QSOs (Hasinger 1998) and to lose a significant fraction of absorbed active objects, the so called type II AGN.

Setti and Volonteri (1989) suggested that these AGN yield most of the HXRB (let us remind that type I AGN are well known to be minor contributors to the HXRB). A direct evidence comes from Fiore et al (1998), that, in a survey with BeppoSAX in 5-14 keV band, found about 150 sources corresponding to a surface density of 20 objects/sq degree at the flux limit $F \simeq 6 \times 10^{-14}$ erg/s/cm$^2$. So far, there have been optically identified only 9 sources, 5 of which turn out to be QSO’s and 4 “type II” AGN. The surface density implied by these detections can explain about 40% of the HXRB.

A suitable estimate of the mass density underlying the intensity of the HXRB between 2-50 keV can be obtained through the relationship

$$\rho_{BH} = \frac{E_{bol}}{c^2 e^2} \simeq \frac{k_{bol}(1 + z_e) L}{k(z_e)c}$$  \hspace{1cm} (9)

The intensity in the 2-50 keV band is $I \simeq 1.9 \times 10^{-6}$ erg cm$^{-2}$ sec$^{-1}$, $k_{bol} \simeq 14.5$ is the bolometric correction for 2-50 keV band (see Elvis et al. 1994; Bassani et al. 1998), $z_e$ is the effective emission redshift, which can be assumed $z_e \sim 1$ and $k(z_e)$ is the k–correction for $z = z_e$. The total associated mass density amounts to $\rho_{BH} \sim 3 - 5 \times 10^5 M_{\odot}/Mpc^3$, where the uncertainty reflects the uncertainty on $z_e$, which disappears once $n(L, z)$ is known.

Direct information on $n(L, z)$ for objects selected in hard X–ray bands is still scarce. However, assuming that the HXRB is chiefly ascribed to type II AGN and that the unified schemes are basically valid, then the soft X–ray observations and the shape of the HXRB significantly constrain the luminosity function and the evolution of the type II AGN. In order to compute the mass function, we use the models proposed by Comastri et al. (1995) and by Celotti et al (1995) to reproduce the HXRB. Comastri et al (1995) used a LF in the 0.3-3.5 keV band, while Celotti et al (1995) one referring to the 2-10 keV band. We adopted $k_{bol} = 25$ and $k_{bol} = 38$ respectively, on the basis of the spectra presented by Elvis et al. (1994). Both models assume luminosity evolution $L(z) \propto (1 + z)^k$ with $k \sim 2.6 - 3.0$ and a similar redshift cutoff $z \sim 2 - 3$ beyond which the evolution stops. The constraints imposed by the shape of the HXRB and by the LF and the evolution of the soft X–ray selected AGN,
compel the redshift distribution to be quite similar for both models. Let us notice that the shape of the mass function and the mass density $\rho_{BH}(X-\text{ray}) \approx 4.2 \times 10^5 M_\odot/Mpc^3$ results comfortably very similar in both models.

In figure 3b we show the mass function derived for $\lambda = 1$ and $\lambda$ given by eq (7). The corresponding total mass density is $\rho_{BH} \approx 6.5 \times 10^5 M_\odot/Mpc^3$. It is apparent that optically selected AGN dominate at $M_{BH} > 10^9 M_\odot$, while BHs associated to the X–ray absorbed AGN dominate the MF at $M < 10^8 M_\odot$. Unlike the total mass density, the mass function of the accreted matter (hereafter AMF) does depend on the cosmological parameters. However, as shown it figure (3b), if we decrease $h$ down to 0.5, the AMF, for $M_{BH} > 5 \times 10^8$, changes slightly.

The local LF of AGN in the X–ray bands do not extend below $sim 4 \times 10^{42}$ erg/s so that our estimate includes only objects with $L > 10^{44}$ erg/s and with $M_{BH} > 10^7 M_\odot$, assuming $\lambda \approx 0.1$ at low luminosities. In order to probe masses below this limit we should include the, presently not very well-known contribution from low luminosity active nuclei, such as the LINERS.

In figure (4a) we compare the MF derived from the past activity, assuming $\lambda = 1$ and $\lambda = 0.2$, to the mass functions derived from the optical and radio LFs. The slopes are quite different and the agreement may be considered acceptable only in the range $10^8 M_\odot - 10^{10} M_\odot$. This suggests that the assumption of a constant $\lambda = L/L_E$ is not adequate.

Instead, by using eq. (7), which is motivated on observational grounds, the agreement is excellent. In detail, since the total mass density is constant, the individual masses of low luminosity objects increase while their number decreases, and the AMF of the inactive BHs turns out in good agreement with the MF of the local MDOs (see figure (4b)). This dependence may be suggestive of recurrent activity confined to low mass objects.

4 DISCUSSION AND CONCLUSIONS

The agreement found between the mass functions derived from investigations on MDOs resident in local galaxies and the mass function of the BHs inferred from the past activity of AGN is based on very simple and sound hypotheses: i) the nuclear activity is a single short event; ii) the spectra of the AGN do not greatly depend on redshift; iii) the mass-radiation conversion efficiency of accretion $\epsilon \approx 0.1$; iv) the HXRB is produced by absorbed AGN; v) $\lambda = L/L_E$ is a weak increasing function of the luminosity.

The inclusion in the estimate of the mass deposited in BHs by the activity related to the HXRB is mandatory, independently of the specific model of HXRB one adopts. In fact, the optically selected objects contribute a minor fraction $\lesssim 20\%$ of the HXRB, whose observed intensity implies $\rho_{BH}(X-\text{ray}) \approx 3 - 5 \times 10^5 M_\odot/Mpc^{-3}$.

Let us comment that the idea that ADAF accretion would be responsible for the HXRB (Di Matteo and Fabian, 1997, see also Haenhelt et al 1998), which implies a quite larger $\rho_{BH}(X-\text{ray})$ and a different AMF with respect to the one we have derived, runs against the evidence from the new hard X–ray surveys that have found that obscured objects are responsible for the emission of at least 20% of the HXBR, yet at a rather bright flux limit (Fiore 1998).
The MF computed using the distribution of the ratio \( M_{BH}/M_{sph} \) obtained by M98 is in contrast with that derived from the correlation found between MDO mass and radio core power. If we neglect this fact, the OMF predicted by means of the \( \sigma \) normal distribution of the \( M_{BH}/M_{sph} \) ratio of M98 can match the AMF by assuming an efficiency \( \epsilon = 0.02 \), a factor 5 less than the standard value. Alternatively, the bolometric corrections should be increased by the same unlikely factor.

Large mass densities could be explained by assuming that the mass accreted during bright phases that shows up directly in the optical counts or in the integrated XRB only is a small fraction of the total mass of the BHs; in this case most of the mass must be accreted in a silent phase (in the optical and in the X–ray bands). However, if the silent phase occurred before the bright one, the problem of BH formation at early time would become more intricate and \( \lambda << 1 \) is required at all luminosities. If it is postponed, then extreme obscuration is required.

The dependence on \( H_0 \) of the mass functions is interesting. The shape of the AMF depends slightly on \( H_0 \) while the corresponding total mass density of the accreted matter is independent of \( H_0 \). On the other hand, the mass functions derived from the local radio power function and optical LFs strongly depend on \( H_0 \), with \( M_{MDO} \propto h^{-1} \) and \( \Phi \propto h^3 \) while the mass density in dormant BHs \( \rho_{BH} \propto h^2 \). With the present uncertainties in the derivation of the mass functions it is not possible to discriminate among different values of the Hubble constant. In order to counterbalance the decrease by a factor of about 2 of the total luminosity density due to the change from \( H_0 = 70 \) km/s Mpc\(^{-1} \) to \( H_0 = 50 \) km/s Mpc\(^{-1} \), the average ratio \( M_{BH}/M_{sph} \) must be increased by the same factor. Thus the matching between OMF and AMF is obtained with \( \log x_0 = -2.35 \) and \( \sigma = 0.3 \) in eq (1). The agreement with the RMF is obtained assuming \( log P_{\text{core}}^{\text{GHz}} \sim 19.2 + 2.0 \log (M_{BH}/10^8 M_\odot) \), which is a good fit to the data.

However it is conceivable that in the near future additional high resolution photometric, spectroscopic and radio observations and very deep hard X–ray surveys will allow to significantly reduce the uncertainties in the estimate of OMF, RMF and AMF. At that point the possibility of balancing changes of the distance scale acting on some parameters will be interestingly restricted.

The activity patterns have been investigated by several authors (e.g. Cavaliere and Padovani 1988; Small and Blandford 1992; Haehnelt and Rees 1993; Cavaliere and Vittorini 1998). Cavaliere and Vittorini (1998) propose a scenario in which the energy output, at early times are governed by hierarchically growing environment, while later, the fall in the average luminosity is related to intermittent accretion governed by galaxy–galaxy interactions. Their prediction of the local MF, reported in figure 4b, is below our estimate in the mass range \( 10^7 M_\odot < M_{BH} < 10^9 M_\odot \). The derived total mass density is \( \rho_{BH} \simeq 3.2 \times 10^5 M_\odot \text{Mpc}^{-3} \), falls short by a factor two the total mass accreted onto type I and type II AGN. The difference may be due to the fact that BHs in early type spirals are not considered by Cavaliere & Vittorini (1998).

In conclusion our analysis strongly supports that the nuclear activity is in general a single event, with bolometric luminosities close to the Eddington luminosities \( \lambda = L/L_{Edd} \) but increasing increase from \( \lambda \sim 0.1 \) for \( L \sim 10^{44} \text{ erg sec}^{-1} \) to \( \lambda \sim 1 \) for \( L \sim 10^{48} \text{ erg sec}^{-1} \), as found also by independent studies (see e.g. Padovani 1989). This suggests that recurrent activity occurs in low luminosity objects and/or that their accretion flows are supply–limited and cannot sustain Eddington luminosities.

In our framework type II AGN of small and moderate mass are responsible for most of the HHRXB. These objects can reside in early type galaxies but also in spirals with still significant spheroidal component (Sa/Sab). On the other hand, bright objects such as QSOs at significant redshift should be hosted preferentially by E/S0 galaxies (or by their precursors). This has been recently confirmed by a study of the host galaxies of QSOs with \( M_R > -24 \) (McLure et al. 1998). These author found that a large fraction of the host galaxies are massive elliptical galaxies. This facts add complexity to the problem of the AGN evolution. Not only coordination is required to mimic the luminosity evolution, but also a kind of coordination is required to pass from the high luminosity, high redshift optically selected AGN, preferentially hosted in E/S0 galaxies, to the low luminosity objects, such as the local Seyfert galaxies, hosted preferentially in Sa/Sab galaxies. The discussion of these aspects in relation with the problem of BH formation will be presented in a subsequent paper (Monaco et al 1998).

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