Mass function of dormant black holes and the evolution of active galactic nuclei

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Accepted 1999 March 12. Received 1999 February 8; in orginal form 1998 August 28

ABSTRACT

Under the assumption that accretion on to massive black holes (BHs) powers active galactic nuclei (AGNs), 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 AGNs, but also that required to produce the hard X-ray background (HXRB). 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 still had an abundant interstellar medium. Only recently, with the decline of the quasi-stellar object (QSO) luminosities, did the activity in late-type galaxies (Sa/Sab) become statistically significant.

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

1 INTRODUCTION

The number counts of AGNs and the intensity of their backgrounds at high energies show that activity in the 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 on to 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 centres 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 centres 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 (Ford et al. 1997, hereafter F97; van der Marel 1997; Magorrian et al. 1998; for a review, see Kormendy & Richstone 1995). As a result, a large number of MDOs have been detected suggesting that we are discovering the fossils of past nuclear activity. Here we will assume that MDOs are the now dormant BHs after a shining past.

The main purpose of this paper is to show that the mass functions of BHs we infer from observations of past activity of AGNs and QSOs correspond to the MDO mass functions of local non-active galaxies.

Magorrian et al. (1998) 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 \( M_{\text{gal}} \) and the MDO/BH mass, \( M_{\text{MDO}} \), already suggested by Kormendy (1993); Kormendy & Richstone (1995) and successively claimed by Magorrian et al. (1998); van der Marel (1998) (by analysing a sample of 46 early-type galaxies). These large samples, together with several smaller ones (see, for example, F97; van der Marel 1997; Ho 1998, hereafter H98) allow one to estimate the distribution function of the ratio \( M_{\text{MDO}}/M_{\text{gal}} \) and then to evaluate the mass function of the MDOs (see Section 2.1).

A different approach to evaluating 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, Vercellone & Fabian (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 on to BHs by exploiting knowledge about 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 AGNs, under-represented in optical and soft X-ray surveys, that shows up in hard X-ray surveys. These absorbed AGNs are the most likely contributors of a major portion of the intensity of the 2–50 keV X-ray background (HXRB) through BH accretion energy output. In fact, optical identifications of serendipitous sources detected by BeppoSAX in the 5–14 keV band show that absorbed AGNs significantly contribute to the HXRB (Fiore et al. 1998). Moreover, independent observational evidence supports unified schemes for the AGNs, whereby a large fraction of absorbed (type II) AGNs is expected (see Antonucci 1993 for a comprehensive review). Thus, we will derive the mass function of relic BHs by including not only the mass accreted on type I or optically selected AGNs, but also that accreted on type II AGNs.

In Section 4 the comparison of the MF of 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 $H_0 = 70\,\text{km}\text{s}^{-1}\text{Mpc}^{-1}$ unless otherwise stated. Moreover, $h = H_0$ in units of $100\,\text{km}\text{s}^{-1}\text{Mpc}^{-1}$.

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; Kormendy & Richstone 1995; van der Marel 1997, 1998; Magorrian et al. 1998; F97). The mean value of $M_{\text{MDO}}/M_{\text{ph}}$ is still under debate and it ranges from $(M_{\text{MDO}}/M_{\text{ph}})^{\approx 10^{-2}}$ (Magorrian et al. 1998) to $(M_{\text{MDO}}/M_{\text{ph}})^{\sim 2 \times 10^{-3}}$ (H98). The uncertainty is related to different assumptions on dynamical models, particularly on the two-integral phase-space distribution function (van der Marel 1997; H98; Magorrian et al. 1998). Exploiting very-high-resolution HST photometry and ground-based spectroscopy, Magorrian et al. (1998) estimated the mass of 36 MDOs in the centres of nearby galaxies, mainly E and S0s. They found that the distribution of the ratio $x = M_{\text{MDO}}/M_{\text{ph}}$ can be described by a Gaussian distribution in $\log x$:

$$f(\log x) = N \exp \left[-\frac{1}{2} (\log x - \log x_0)^2 / \sigma^2 \right],$$

where $N$ is a normalization constant. The best fit values found by Magorrian et al. (1998) are $\log x_0 = \log(M_{\text{MDO}}/M_{\text{ph}}) = -2.28$ and $\sigma = 0.5$. Analysing the very-high-resolution photometry of 46 early-type galaxies and reproducing it by means of the models proposed by Young (1980); van der Marel (1998) found $\log M_{\text{MDO}} = -1.83 + \log L_V$ with r.m.s. scatter $\sigma \sim 0.3$ dex.

Using standard values of $M/L_V = 5.5 h(L_V/L_V)^{0.25}$ for spheroids (see below), this corresponds to $(\log M_{\text{MDO}}/M_{\text{ph}})^{-2.64}$. We have constructed a sample of 30 galaxies, for which at least two independent mass estimates of their MDOs are available in the literature (Kormendy & Richstone 1995; van der Marel 1997; van der Marel 1998; F98; F98; Magorrian et al. 1998). Taking the geometric mean as the best estimate of the ratio $x$, we have found that a Gaussian distribution in $\log x$, with $(\log x) = -2.60$ and $\sigma = 0.3$, is a good description of the data. This result, quite close to that obtained by van der Marel (1998) and in agreement with the estimates of H98 and F97, 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 MDO MF. 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 $(L_{\text{ph}}/L_{\text{tot}})$ 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. Ef斯塔ïou, Ellis & Peterson 1988; Loveday et al. 1992; Zucca et al. 1997; Geller et al. 1997; Heyl et al. 1997), based on different galaxy samples, agree well 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 $L_\star (M_\star)$ and $\alpha$ are given in Table 1 for $h = 1$.

The ratio $L_{\text{ph}}/L_{\text{tot}}$ has been investigated by several authors (Kent 1985; Simien & de Vaucouleurs 1986; 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 $\sim 30$ per cent of the total luminosity density, in agreement with Schechter & Dressler (1987) and Fukugita, Hogan & Peebles (1998).

From the spheroid LF we infer the MF by adopting $M_{\text{ph}}/L_V = 5.5 h(L_V/L_V)^{0.25}$, corresponding to $M_{\text{ph}}/L_V = 6.9 h(L_V/L_V)^{0.25}$ with $(B-V) = 0.90$. This law is compatible at the 2$\sigma$ level with $(M_{\text{ph}}/L_V) \approx L_{\text{tot}}^{0.03}$ found by Magorrian et al. (1998) and $(M_{\text{ph}}/L_V) \approx L_{\text{tot}}^{0.05}$ claimed by van der Marel (1991), consistent with stellar evolution models. The spheroid MF is shown in Fig. 1(a). The overall shape of the MF is relatively flat at $M_{\text{ph}} \leq 10^{11} M_\odot$ and exhibits an exponential decline for $M_{\text{ph}} > 10^{11} M_\odot$. At $M_{\text{ph}} > 5 \times 10^{10} M_\odot$ the mass function is dominated by spheroids in E and S0 galaxies. The Sa/Sab galaxies exhibit an exponential decline of their MF for $M_{\text{ph}} > 10^{10} M_\odot$ and Sbc/Scd galaxies for $M_{\text{ph}} > 10^{9} M_\odot$.

The MDOs mass function (hereafter OMF) has been computed by convolving the MF of the spheroids with the adopted log Gaussian distribution with $(M_{\text{MDO}}/M_{\text{ph}})^{-2.6}$ and $\sigma = 0.3$. As is apparent in Fig. 1(b), the scatter of the ratios $x = M_{\text{MDO}}/M_{\text{ph}}$

<table>
<thead>
<tr>
<th>Galaxy type</th>
<th>$\Phi \cdot h^3 \times 10^3$ $(\text{Mpc}^{-3})$</th>
<th>$M_\phi + 5 \log h$</th>
<th>$\alpha$</th>
<th>$f_{\text{ph}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>2.1</td>
<td>-20.0</td>
<td>-0.95</td>
<td>0.9</td>
</tr>
<tr>
<td>S0</td>
<td>2.4</td>
<td>-19.6</td>
<td>-0.95</td>
<td>0.65</td>
</tr>
<tr>
<td>Sab</td>
<td>2.9</td>
<td>-19.8</td>
<td>-1.0</td>
<td>0.40</td>
</tr>
<tr>
<td>Sbc/Scd</td>
<td>7.6</td>
<td>-19.3</td>
<td>-1.3</td>
<td>0.10</td>
</tr>
</tbody>
</table>

sofens 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 \( \rho_{\text{MDO}} = 8.2 \times 10^5 \, \text{M}_\odot \, \text{Mpc}^{-3} \, h^2 \), with a large fraction \( \sim 75 \) per cent due to MDOs in E and S0 galaxies. The remaining 20 per cent are due to MDOs in Sa/Sb galaxies and 5 per cent 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 Magorrian et al. (1998) are apparent from Fig. 1(b). The Magorrian et al. (1998) log Gaussian law predicts a large number density of BHs with mass larger than \( 10^8 \, \text{M}_\odot \) and yields a total mass density \( \rho_{\text{MDO}} \sim 3 \times 10^9 \, \text{M}_\odot \, \text{Mpc}^{-3} \, h^2 \), which is higher than the estimate of the local mass density of the accreted matter based on counts of optically selected AGNs, 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 \( M_{\text{MDO}} \) and the luminosity of the bulge of the host galaxies, is substantially below our determination and yields a lower total mass density \( \rho_{\text{MDO}} \sim 10^6 \, \text{M}_\odot \, \text{Mpc}^{-3} \, h^2 \). This is partly due to the adopted LF of E and S0 galaxies and partly to the fact that they neglected the broadness of the distribution of the ratio \( M_{\text{MDO}}/L_{\text{bulg}} \).

### 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 on to dormant BHs occurring at very low rates is possibly advection-dominated with low radiative efficiency (Rees et al. 1982; Abramowicz et al. 1988; Narayan & Yi 1995a,b). In this regime, a hot ion torus (\( T \sim 10^{12} \) K) forms, while the electrons, coupled to the ions only through two-body Coulomb effects, remain at much lower temperature (\( T \sim 10^9 \) K) and emit at radio frequencies via thermal synchrotron radiation. Fabian & 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 \( P_r \sim \nu^{2/3} \rho_{\text{BH}}^{1/3} M_{\text{BH}}^2 \) (e.g. Mahadevan 1997), where \( M \) is the mass accretion rate. The dependence on frequency is quite close to the relationship \( P_r \sim \nu^{2/3} \) found by Sree et al. (1994) for a sample of radio cores of E/S0 galaxies. However the ADAF model should be treated with some caution, since new high-resolution radio and submillimetre 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 \( \dot{M} \sim M_{\text{BH}}^2 \rho(\infty)/c_s(\infty)^2 \) the ADAFs yield radio powers \( P \sim M_{\text{BH}}^{2/3} \), 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, \( \rho \sim M_{\text{sph}}^{1/3} \) and \( c_s \sim M_{\text{sph}}^{1/4} \), we have \( P \sim M_{\text{BH}}^{2.4/3} \). Given that self-absorbed processes (e.g. jets) yield \( P \sim M_{\text{BH}}^{3} \), a relationship \( P \sim M_{\text{BH}}^{3} \) with \( 2.0 \leq \alpha \leq 2.2 \) is expected under rather general conditions.

Franceschini et al. (1998) found a significant correlation between the radio power of the cores \( P_{\text{core}} \) and the estimated BH mass in eight objects with \( P_{\text{core}} \sim M_{\text{BH}}^{2.0 \pm 0.6} \). 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 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 six objects with upper limits in the latter.

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

$$\log P_{\text{core}}^{5 \, \text{GHz}} = 19.5 + 2.2^{+0.55}_{-0.35} \log \left( \frac{M_{\text{BH}}}{10^8 M_\odot} \right),$$

with a slope close to that inferred theoretically for the exponent $\alpha$ (Fig. 2(a)). It is worth noticing that the same value of the slope has also been claimed 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 $\phi(P_t)$ of $P_t$ at 5 GHz down to $\log P_t = 19.6$. More recently, Slee et al. (1994) observed a large fraction of objects from the same sample at a higher angular resolution; this has provided the $P_t$ versus $P_{\text{core}}$ relationship: $\log P_{\text{core}} = 19.5 + 0.78(\log P_t - 19.5)$ for $\log P_t > 19.5$ 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) (Fig. 2(b)) 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 shown in Fig. 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 $\log M_{\text{BH}}$ versus $\log P_t$, taking into account its uncertainties in the normalization and in the slope. The errors turn out to be about $\pm 0.2$ dex. It is worth noticing that the core radio luminosity function exhibits a gentle slope and no exponential decline at least for powers $P \approx 10^{24}$ W Hz$^{-1}$. This ensures that the possible scatter in the $\log P_{\text{core}}$ versus $\log M_{\text{BH}}$ 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 $P_t \propto M_{\text{BH}}^{2.56}$. The resulting MF stays significantly below our estimate for $M_{\text{BH}} > 2 \times 10^5 M_\odot$ and the predicted total mass density is smaller by a factor of about 3, mainly because of the steeper adopted relationship $P_t - M_{\text{BH}}$.

In Fig. 3b 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, none of 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 also be found for $h = 0.5$. It is worth noticing that the OMFs derived by using the distribution of $\log x$ proposed by Magorrian et al. (1998) [see equations (1) and (2) and Fig. 1(b)] cannot be reconciled with the RMF.

### 3 THE LOCAL MASS FUNCTION OF THE DORMANT BLACK HOLES

The mass density associated with luminosities higher than $L$ is

$$\rho(L) = \frac{k_{\text{bol}}}{c^2 H_0} \int^\infty_0 \frac{1 + z}{(1 + z)^{1/2}} \left( 1 + \frac{\Omega}{1 + z} \right) dL,$$

where $L$ is the luminosity in a certain band and $k_{\text{bol}}$ 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 the rest mass of the accreted matter into energy, we adopt $\epsilon = 0.1$ unless otherwise stated. Putting $L = L_{\text{min}} \sim 10^{44}$ erg s$^{-1}$ (e.g. Pei 1995), we get the local total mass density $\rho_{\text{BH}}$. 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 on to AGNs 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 spheroid 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.

On the hypothesis of single short events, it is likely that the AGNs are observed in the highest state of activity; hence we can evaluate the mass of the BH associated with a luminosity $L$ (hereafter the bolometric luminosity) through the assumption $L = \lambda L_{\text{Edd}}$ and $L_{\text{Edd}} = M_{\text{BH}} c^2 / \eta E$. The constraint for the latter can be obtained as follows: if we assume $\lambda$ to be constant during the accretion, we get

$$ M_{\text{BH}}(t_{\text{obs}}) = M_{\text{BH}}(t_{\text{in}}) \exp \left( \frac{\lambda t_{\text{in}}}{\eta \tau_{\text{E}}} \right), $$

and

$$ L(t_{\text{obs}}) = \frac{\lambda c^2}{\eta E} M_{\text{BH}}(t_{\text{obs}}) \exp \left( \frac{\lambda t_{\text{in}}}{\eta \tau_{\text{E}}} \right), $$

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

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

$$ \int_0^L d\phi(L') dL' = \int_{-\infty}^{\log M_{\text{AMF}}(t_{\text{in}})} M_{\text{AMF}}(M_{*}) d \log M_{*}, $$

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

$$ \lambda(L) = L/L_{\text{E}} = 10^{\gamma (\log L - 49)}, \quad \gamma = 0.2, $$

which follows the findings that the most luminous QSOs radiate at about the Eddington limit, while low-luminosity AGNs, $L \sim 10^{44} \text{ erg s}^{-1}$, show $\lambda = L/L_{\text{E}} \sim 0.1-0.05$ (see Padovani 1989; Wandel 1998). Then, from equations (6) and (7) the MF of the relic BHs can be written as

$$ \phi(M_{\text{BH}}) d\log M_{\text{BH}} = \ln(10) \frac{\psi(\psi(L))}{1 - \gamma} \frac{d \log \psi(\psi(L))}{d \log(L)} d \log M_{\text{BH}}. $$

The next step is to insert into equations (3) and (8) the information on the luminosity function and its evolution. For the optically selected AGNs 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 as $k_{\text{bol}}(B) = 13$, on the basis of the spectra reported by Elvis et al. (1994). The total mass density turns out to be $\rho_{\text{BH}} = 2.0 \times 10^4 \text{ M}_\odot \text{ Mpc}^{-3}$, close to the estimate of Chokshi & Turner (1992), who however adopted $k_{\text{bol}}(B) = 16.5$.

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

Setti & Wolter (1989) suggested that these AGNs yield most of
the HXRB (recall that type I AGNs are well known to be minor contributors to the HXRB). Direct evidence comes from Fiore et al. (1998), who, in a survey with BeppoSAX in the 5–14 keV band, found about 150 sources corresponding to a surface density of 20 objects per square degree at the flux limit \( F = 6 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \). So far, only nine sources have been optically identified, five of which turn out to be QSOs and four ‘type II’ AGNs. The surface density implied by these detections can explain about 40 per cent 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

\[
\rho_{\text{BH}} = \frac{\rho_{\text{bol}}}{\Omega} = \frac{k_{\text{bol}}}{\epsilon_{\text{bol}}} \frac{(1 + z_e) L}{k(z_e) c},
\]

(9)

The intensity in the 2–50 keV band is \( I = 1.9 \times 10^{-6} \text{ erg s}^{-1} \text{ cm}^{-2} \), \( k_{\text{bol}} = 14.5 \) is the bolometric correction for the 2–50 keV band (see Elvis et al. 1994; Bassani, Capetti & Malaguti 1998), \( z_e \) is the effective emission redshift, which can be assumed to be \( z_e \sim 1 \), and \( k(z_e) \) is the k-correction for \( z = z_e \). The total associated mass density amounts to \( \rho_{\text{BH}} \sim 3 - 5 \times 10^{5} M_{\odot} \text{ Mpc}^{-3} \), 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 AGNs 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 type II AGNs. 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 an LF in the 0.3–3.5 keV band, while Celotti et al. (1995) used one referring to the 2–10 keV band. We adopt \( k_{\text{bol}} = 25 \) and \( k_{\text{bol}} = 38 \), respectively, on the basis of the spectra presented by Elvis et al. (1994). Both models assume luminosity evolution \( L(z) \sim (1 + z)^{k} \) 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

Figure 4. (a) The AMF derived by assuming \( \lambda = 1 \) (dotted curve) and \( \lambda = 0.2 \) (dashed curve). In both panels the solid curve and filled circles are defined as in Fig. 3. (b) The AMF derived according to equation (7) compared with the MF of the relic BHs by Cavaliere & Vittorini (1998) (dotted curve).

the shape of the HXRB and by the LF and the evolution of the soft X-ray selected AGNs compel the redshift distribution to be quite similar for both models. Let us notice that the results for the shape of the mass function and the mass density \( \rho_{\text{BH}}(X - \text{ray}) = 4.2 \times 10^{5} M_{\odot} \text{ Mpc}^{-3} \) are very similar for both models.

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

The local LF of AGNs in the X-ray bands do not extend below \( \sim 4 \times 10^{44} \text{ erg s}^{-1} \), so that our estimate includes only objects with \( L > 10^{44} \text{ erg s}^{-1} \) and with \( M_{\text{BH}} > 10^{5} M_{\odot} \), assuming \( \lambda = 0.1 \) 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 Fig. 4(a) we compare the MF derived from past activity, assuming \( \lambda = 1 \) and \( \lambda = 0.2 \), with 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 \( 10^{5} - 10^{10} M_{\odot} \). This suggests that the assumption of a constant \( \lambda = L/L_{E} \) is not adequate.

Instead, by using equation (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 to be in good agreement with the MF of the local MDOs (see Fig. 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 of MDOs resident in local galaxies and the mass function of the BHs inferred from the past activity of AGNs is based on very simple and sound hypotheses: (i) the nuclear activity is a single short event; (ii) the spectra of the AGNs do not greatly depend on redshift; (iii) the mass–radiation conversion efficiency of accretion $\epsilon = 0.1$; (iv) the HXRB is produced by absorbed AGNs; (v) $\lambda = L/L_{\gamma}$ 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 \( \lesssim 20 \) per cent of the HXRB, whose observed intensity implies $\rho_{\text{BH}}(X-\text{ray}) \sim 3-5 \times 10^5 M_\odot \text{Mpc}^{-3}$.

Let us comment that the idea that ADAF accretion would be responsible for the HXRB (Di Matteo & Fabian, 1997, see also Haehnelt & Rees 1993), which implies a quite larger $\rho_{\text{BH}}(X\text{-ray})$ and a different AMF with respect to the one we have derived, runs against the evidence from the new hard X-ray surveys, which have found that obscured objects are responsible for the emission of at least 20 per cent of the HXBR, yet at a rather bright flux limit (Fiore et al. 1998).

The MF computed using the distribution of the ratio $M_{\text{HII}}/M_{\text{sph}}$ obtained by Margonari et al. (1998) 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 log normal distribution of the $M_{\text{HII}}/M_{\text{sph}}$ ratio of Margonari et al. (1998) can match the AMF by assuming an efficiency $\epsilon \sim 0.02$, a factor of five 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 HXRB is only 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 X-ray bands). However, if the silent phase occurred before the bright one, the problem of BH formation at early times would become more intricate and $\lambda \ll 1$ is required at all luminosities. If it is postponed, then extreme obscuration is required.

The dependence on $\Omega_0$ of the mass functions is interesting. The shape of the AMF depends slightly on $\Omega_0$ while the corresponding total mass density of the accreted matter is independent of $\Omega_0$. On the other hand, the mass functions derived from the local radio power function and optical LFs strongly depend on $\Omega_0$, with $M_{\text{MDO}} \propto h^{-1}$ and $\Phi \propto h^3$ while the mass density in dormant BHs $\rho_{\text{BH}} \propto h^2$. With the present uncertainties in the derivation of the mass functions it is not possible to discriminate between different values of the Hubble constant. In order to counterbalance the decrease by a factor of about two of the total luminosity density resulting from the change from $H_0 = 70 \text{km s}^{-1} \text{Mpc}^{-1}$ to $H_0 = 50 \text{km s}^{-1} \text{Mpc}^{-1}$, the average ratio $M_{\text{HII}}/M_{\text{sph}}$ must be increased by the same factor. Thus the match between OMF and AMF is obtained with $\log x_0 = -2.35$ and $\sigma = 0.3$ in equation (1). The agreement with the RMF is obtained assuming $\log p_{\text{core}} = 19.2 + 2.0 \log (M_{\text{HII}}/10^9)$, 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 one significantly to reduce the uncertainties in the estimates 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 & Padovani 1988; Small & Blanford 1992; Haehnelt & Rees 1993; Cavaliere & Vittorini 1998). Cavaliere & Vittorini (1998) propose a scenario in which the energy output, at early times is governed by a 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 Fig. 4(b), is below our estimate in the mass range $10^7 M_\odot \lesssim M_{\text{BH}} \lesssim 10^8 M_\odot$. The derived total mass density is $\rho_{\text{BH}} = 3.2 \times 10^5 M_\odot \text{Mpc}^{-3}$, which falls short by a factor two of the total mass accreted on to type I and type II AGNs. The difference may result from 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 $\lambda = L/L_{\text{Edd}}$, but increasing from $\lambda \sim 0.1$ for $L \sim 10^{44} \text{erg s}^{-1}$ to $\lambda \sim 1$ for $L \gtrsim 10^{46} \text{erg s}^{-1}$, as found also by independent studies (see, for example, 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 AGNs of small and moderate mass are responsible for most of the HXRB. 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 authors found that a large fraction of the host galaxies are massive elliptical galaxies. These facts add complexity to the problem of AGN evolution. Not only coordination is required to mimic the luminosity evolution, but also a kind of coordination is required to pass from high-luminosity, high-redshift optically selected AGNs, preferentially hosted in E/S0 galaxies, to low-luminosity objects, such as the local Seyfert galaxies, hosted preferentially in Sa/Sab galaxies.

The discussion of these aspects in relation to the problem of BH formation will be presented in a subsequent paper (Monaco et al. 1998).

ACKNOWLEDGMENTS
We thank A. Cavaliere, F. La Franca and G. Fasano for helpful discussions and J. Magorrian for insightful and clarifying comments. We thank also an anonymous referee for comments that have helped to present our results better. P.M. has been supported by the EC Marie Curie TMR contract ERB FMB ICT961709.

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