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Dynamical evolution of intermediate-mass black holes and their observable signatures in the nearby Universe

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ABSTRACT

We investigate the consequences of a model of the assembly and growth of massive black holes (MBHs) from primordial seeds, remnants of the first generation of stars in a hierarchical structure formation scenario. Our model traces the build-up of MBHs from an early epoch, and follows the merger history of dark matter haloes and their associated holes via Monte Carlo realizations of the merger hierarchy, from early times to the present time, in a Λ cold dark matter cosmology. The sequence of minor and major mergers experienced by galactic haloes in their hierarchical growth affects the merger history of MBHs embedded in their nuclei. So, if the formation route for the assembly of supermassive black holes dates back to the early universe, a large number of black hole (BH) interactions is inevitable. The coalescence time-scales of binary black holes can be long enough for a third BH to fall in and interact with the central binary. These BH triple interactions lead typically to the final expulsion of one of the three bodies and to the recoil of the binary. Also, asymmetric emission of gravitational waves in the last stages of the BH merging can give a recoil velocity to the centre of mass of the coalescing binary. This scenario leads to the prediction of a population of intermediate-mass black holes (IMBHs) wandering in galaxy haloes at the present epoch. We compute the luminosity distribution produced by these IMBHs accreting from their circumstellar medium. We find that in a Milky Way-sized galaxy they are unable to account for sources with luminosities $\gtrsim 10^{39}$ erg s^{-1}, unless they carry a baryonic remnant from which they are able to accrete for a long time. We also find that, for typical spiral galaxies, the bright end of the point-source distribution correlates with the mass of the galaxy and the most luminous sources are expected to be found in the disc.

Key words: black hole physics – galaxies: kinematics and dynamics – cosmology: theory – X-rays: general.

1 INTRODUCTION

Observations of the centres of nearby galaxies indicate that most host a supermassive black hole (SMBH; Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000); supermassive black holes (SMBHs) seem to be unequivocally linked to galactic bulges, their masses scaling with the bulge luminosity and stellar velocity dispersion. In cold dark matter (CDM) bottom-up cosmogonies, mergers of galaxies are a central part of the galaxy formation process in the hierarchical structure formation picture, with major mergers (i.e. those between comparable-mass systems) expected to result in the formation of elliptical galaxies (Barnes 1988).

Volonteri, Haardt & Madau (2003; VHM03) and Volonteri, Madau & Haardt (2003; VMH03) have assessed a model for the assembly of SMBHS at the centre of galaxies that trace their hierarchical build-up, assuming that the first seed black holes (BHs) had intermediate masses, $m_\bullet \approx 150$ M$_\odot$ and formed in (mini)haloes collapsing at $z \sim 20$ from high-σ density fluctuations. These pre-galactic holes evolve in a hierarchical fashion, following the merger history of their host haloes. During a merger event, BHs approach each other owing to dynamical friction and form a binary system. Stellar dynamical processes drive the binary to harden and eventually coalesce.

The lifetime of black hole (BH) binaries can be long enough (Begelman, Blandford & Rees 1980; Quinlan & Hernquist 1997; Milosavljevic & Merritt 2001; Yu 2002) that following another galactic merger a third BH can fall in and disturb the evolution of

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the central system (VHM03). The three BHs are likely to undergo a complicated resonance scattering interaction, leading to the final expulsion of one of the three bodies (gravitational slingshot) and to the recoil of the binary. Any slingshot, in addition, modifies the binding energy of the binary, typically creating more tightly bound systems (VHM03).

Another interesting gravitational interaction between BHs happens during the last stage of coalescence, when the leading physical process for the binary evolution becomes the emission of gravitational waves. If the system is not symmetric (e.g. BHs have unequal masses or spins) there would be a recoil as a result of the non-zero net linear momentum carried away by gravitational waves in the coalescence (gravitational rocket). The coalesced binary would then be displaced from the galactic centre, leaving straightaway the host halo or sinking back to the centre owing to dynamical friction.

Historically, the possibility of these gravitational interactions between BHs has been envisaged even before the CDM-hierarchical picture has become popular. Slingshots have been proposed, as a contrast to the unified (twin beam) theory (e.g. Blandford & Rees 1974) to explain the nature of double radio sources (Saslaw, Valtonen & Aarseth 1974; Mikkola & Valtonen 1990; Valtonen & Heinämäki 2000): ejected BHs can produce extended radio lobes by interacting with the intergalactic medium in the areas of the lobes.

Slingshots and rockets were both involved when trying to explain the nature of galactic dark haloes as composed of BHs (Hut & Rees 1992; Xu & Ostriker 1994). Both processes basically give BHs a recoil velocity, that can even exceed the escape velocity from the host halo and spread BHs outside galactic nuclei (VHM03). So, the outlined scheme predicts, along nuclear SMBHs hosted in galaxy bulges, a number of wandering BHs that are the result of rockets, slingshots and mergers with a dynamical friction time-scale longer than the Hubble time, so at $z = 0$ the BHs are still on their way to the galactic centre. Note that most of the wandering BH's masses are in an intermediate range between stellar mass BHs and supermassive ones.

In this paper, we improve the modelling of the dynamical interactions between galactic haloes, and between BHs and their host haloes. In particular, we include the lengthening of the dynamical friction time-scale of infalling satellites as a result of tidal interactions with the potential of the primary halo and follow the orbital decay of every single satellite, determining its position within the primary at any given time. We also trace step-by-step the trajectories of BHs ejected from galaxy centres following an energetic BH interaction; this enables us to keep track of the position and velocity of all wandering intermediate-mass black holes (IMBHs) as a function of cosmic time.

The population of wandering IMBHs in local galaxies that our model predicts will have some observational consequences. In particular, as a result of accretion from their surrounding interstellar medium (ISM), these BHs will appear as bright X-ray sources. We compute here the luminosity distribution expected from such sources and relate it to current observations. In particular, we discuss whether and under what conditions these IMBHs can make up a substantial fraction of a population of ultraluminous X-ray sources (ULXs), characterized by luminosities $L_X \gtrsim 10^{39}$ erg s^{-1}, which has been recently identified in large *Chandra* surveys (e.g. Colbert et al. 2004). The properties of this population as a whole (see Fabbiano 1989, for a review) hint that we might be actually observing a heterogeneous population, where super-Eddington luminosities could for example be the result of a photon-bubble instability (Begelman 2002) or could be apparent as a result of strong beaming (King et al. 2001). A contribution to the high-end tail of the X-ray point-source luminosity distribution could also be the result of young millisecond pulsars (Perna & Stella 2004). However, accreting IMBHs constitute an obvious candidate for the ULXs, as it has been often suggested (e.g. Colbert & Mushotzky 1999; Miller & Hamilton 2002; Schneider et al. 2002; Cropper et al. 2004). Part of our study here is therefore a detailed investigation of the present-day observational properties of the population of IMBHs formed in minihaloes at high redshifts and evolved during the process of galaxy formation.

The paper is organized as follows: in Section 2, we summarize the main features of our cosmological scenario of BH growth; the dynamical evolution of SMBH binaries is discussed in Section 3. The dynamical evolution of satellite BHs is studied in Section 4, while Section 5 describes the accretion model. Section 6 is dedicated to the observational consequences of these IMBHs in present-day galaxies and Section 7 discusses our results in the context of previous work in the field; finally, in Section 8, we summarize our work.

2 ASSEMBLY AND MERGERS OF SMBHs

We briefly summarize here the main features of our scenario for the hierarchical growth of SMBHs in a ΛCDM cosmology (see VHM03 for a thorough discussion). In our model, pre-galactic seed holes form with intermediate masses ($m_\bullet = 150\ \mathrm{M}_\odot$) in (mini)haloes collapsing at $z = 20$ from rare 3.5σ peaks of the primordial density field (VHM03; Madau & Rees 2001). The assumed bias assures that almost all haloes above $10^{11}\ \mathrm{M}_\odot$ actually host a BH at all epochs.

The merger history of dark matter (DM) haloes and associated BHs is followed by cosmological Monte Carlo realizations of the merger hierarchy from early times until the present in a ΛCDM cosmology. The dynamical evolution of the BH population is followed in detail with a semi-analytical technique. In this paper, we focus on the properties of two sets of haloes with $M = 2 \times 10^{12}\ \mathrm{M}_\odot$ and $M = 10^{13}\ \mathrm{M}_\odot$ respectively, creating 30 merger trees of the former and 10 of the latter and averaging the results. For the smaller halo, we will also consider a case in which seed holes are more numerous and populate the 3σ peaks instead.

In order to follow the history of haloes and massive black holes (MBHs), we adopt a two-component model for galaxy haloes. The DM is distributed according to a Navarro, Frenk & White (1997; NFW) profile . During the merger of two halo + BH systems of comparable masses, dynamical friction against the DM background drags in the satellite hole towards the centre of the newly merged system, leading to the formation of a bound BH binary. When two haloes of mass M and M_s merge, the satellite (less massive) progenitor (mass M_s) is assumed to sink to the centre of the more massive pre-existing system on the dynamical friction (against the DM background) time-scale, which depends on the orbital parameters of the infalling satellite, which we take from van den Bosch et al. (1999).

The fate of the infalling halo has been investigated recently (Taffoni et al. 2003) in an NFW profile. Dynamical friction appears to be very efficient for major mergers with (total) mass ratio of the progenitors, $P = M_s/M > 0.1$. In each major merger, the more massive hole accretes at the Eddington rate a gas mass that scales with the fifth power of the circular velocity of the host halo: the normalization is fixed a posteriori in order to reproduce the observed local $m_{\rm BH}$–σ_* relation (Ferrarese 2002) and the observed luminosity function of optically selected quasars in the redshift range $1 < z < 5$.

Satellites of intermediate mass ($0.01\ M_h < M_{s,0} < 0.1\ M_h$) suffer severe mass losses by the tidal perturbations induced by the gravitational field of the primary halo. Tidal perturbations cause the progressive stripping of the satellite and, as the magnitude of

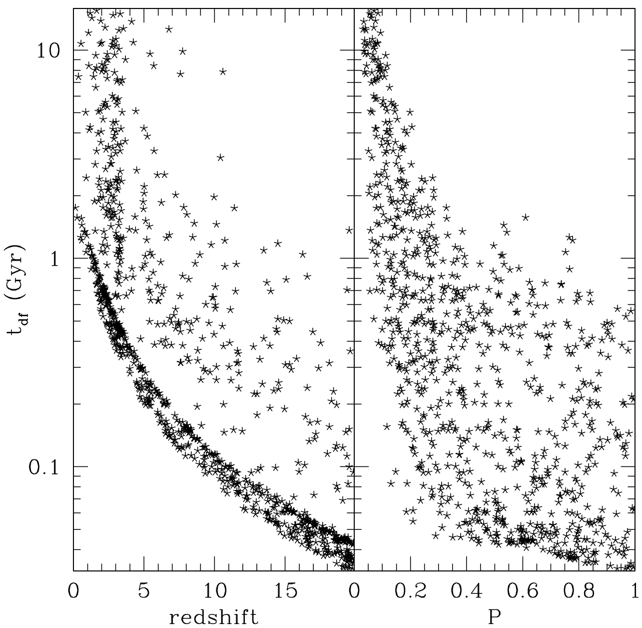

Figure 1. Dynamical friction time-scale of the haloes hosting massive black holes (MBHs) as a function of redshift (left panel) and mass ratio (right panel). Note at low redshift ($z < 5$) the sharp division in time-scale for major and minor mergers, the former characterized by time-scales shorter than 2 Gyr, the latter can be longer than the Hubble time.

the frictional drag depends on the mass of the satellite, this progressive mass loss increases the decay time. After a Hubble time, satellites have typical masses ∼1–10 per cent of their initial mass. The lightest satellites ($P < 0.01$) seem to be almost unaffected by orbital decay, so they survive and keep orbiting on rather circular, peripheral orbits.

We adopt the relations suggested by Taffoni et al. (2003) for the orbital decay of satellites in an NFW halo. Fig. 1 shows the evolution of the dynamical friction time-scales with redshift and the dependence on the mass ratio for haloes both hosting MBHs.

3 BLACK HOLE BINARY DYNAMICAL EVOLUTION

The subsequent evolution of a BH binary is determined by the initial central stellar distribution. The binary will initially shrink by dynamical friction from distant stars acting on each BH individually. However, as the binary separation decays, the effectiveness of dynamical friction slowly declines because distant encounters perturb only the binary centre of mass but not its semimajor axis. The BH pair then hardens via three-body interactions, i.e. by capturing and ejecting at much higher velocities the stars passing by within a distance of the order of the semimajor axis of the binary. The merger time-scale is computed adopting a simple semi-analytical scheme that qualitatively reproduces the evolution observed in *N*-body simulations (Merritt 2000; VHM03; VMH03). The binary evolution is slowed down as a result of the declining stellar density, with a hardening time that becomes increasingly long as the binary shrinks. If the hardening continues sufficiently far, gravitational radiation losses finally take over and the two BHs coalesce in less than a Hubble time.

We have adopted a simplified description of the BH coalescence process, ignoring for instance the depopulation of the loss cone (e.g. Yu 2002) and the loss of orbital angular momentum to a gaseous disc (Armitage & Natarajan 2002; Escala et al. 2004).

3.1 Gravitational rocket

When the binary semimajor axis is such that the time-scale for hardening by stellar scatterings equals the time-scale for shrinking by emission of gravitational waves, the latter process takes over. At this point, if the holes have unequal masses, or spin, the binary recoils as a result of the non-zero net linear momentum carried away by gravitational waves in the coalescence (gravitational rocket).

The recoil velocity has still large uncertainties and we adopt here the results from recent calculations by Favata, Hughes & Holz (2004). They estimate the recoil velocity as a function of the binary mass ratio $q = m_2/m_1$ (with BH masses $m_1 \geqslant m_2$) and the spin parameter during final plunge and coalescence. We adopt here the expression they suggest for estimating upper limits for the recoil, converting it into estimates of the binaries recoil velocity, $v_{\rm CM}$, following the procedure described in Merritt et al. (2004).

If the recoil velocity of the coalescing binary exceeds the escape speed $v_{\rm esc}$, the holes will leave the galaxy altogether. If instead $v_{\rm CM} < v_{\rm esc}$, we assume that the binary is kicked out to a radius $r_{\rm max}$ such that the total energy is conserved, i.e. we solve for $r_{\rm max}$ the equation $(m_1 + m_2)\, v_{\rm CM}^2 = 2[|\phi_0| - |\phi(r_{\rm max})|]$, where ϕ_0 is the galactic potential at the initial location of the binary and $\phi(r_{\rm max})$ is the potential at the apocentre.

3.2 Gravitational slingshot

The dynamical evolution of SMBH binaries may be disturbed by a third incoming BH, if another major merger takes place before the pre-existing binary has had time to coalesce or a wandering BH can reach the centre owing to dynamical friction (e.g. Hut & Rees 1992; Xu & Ostriker 1994). If the incoming hole reaches the sphere of influence of the central binary, the three BHs are likely to undergo a complicated resonance scattering interaction, leading to the final expulsion of one, typically the lightest, of the three bodies (gravitational slingshot).

Typically an encounter with an intruder of mass $m_{\rm int}$ smaller than both binary members leads to a scattering event, where the binary recoils by momentum conservation and the incoming lighter BH is ejected from the galaxy nucleus. By contrast, when the intruder is more massive than one or both binary components, the probability of an exchange is extremely high: the incoming hole becomes the member of a new binary and the lightest BH of the original pair gets ejected (Hills & Fullerton 1980).

All triple interactions are followed along the merger tree, adopting the same scheme described in VHM03.

In all cases, we have estimated the recoil velocities conserving the binary energy and momentum and estimated the apocentre $r_{\rm max}$ solving the equation $(m_1 + m_2)\, v_{\rm CM}^2 = 2[|\phi_0| - |\phi(r_{\rm max})|]$. Dynamical friction time-scales have been calculated by the Chandrasekhar dynamical friction time-scale for circular orbits, so they are presumably upper limits to these time-scales (thus giving an upper limit on the number of wandering BHs), as the ejection probably occurs on eccentric orbits.

In Fig. 2, the distribution of BH recoil velocities is plotted in units of the stellar velocity dispersion, ranging from 5 to 200 km s^{-1} depending on redshift and halo mass. As a rule of thumb, if the recoil velocity is smaller than the velocity dispersion, the BH remains in the proximity of the centre and the orbital decay is fast (Madau & Quataert 2004). Fig. 2 shows that the ejection of all three BHs is

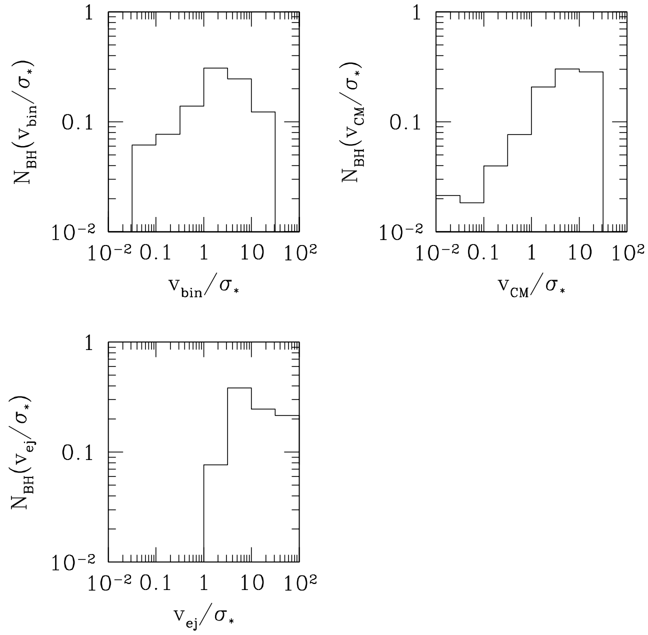

Figure 2. Distribution of black hole (BH) recoil velocities (in units of the stellar velocity dispersion). Binaries, either following a triple interaction (upper left panel) or a rocket (upper right panel), have a broad velocity distribution, while almost all single black holes (BHs) have high recoil velocities, typically larger than the escape velocity.

therefore not a likely outcome under the assumptions of our BH growth model (see VHM03 for a thorough discussion).

Clearly, most of the single holes either escape their host haloes or are slung to the periphery of the galaxy with consequently long dynamical friction time-scales. Most of the binaries recoil instead within the core and fall back to the centre soon afterwards, with $t_{df} < 0.01$ Gyr.

Note that triple interactions are rare events, in the whole history of a Milky Way (MW) sized halo with its satellites, on average only $\sim$3 slingshots happen, in the case of seed holes in 3.5σ peaks.

4 DYNAMICAL EVOLUTION OF OFF-NUCLEAR BLACK HOLES

The assumptions underlying our scenario lead to the prediction of a population of massive BHs wandering in galaxy haloes, as a result of the processes described above.

During the evolution and mass growth of DM haloes, we track the position of all wandering BHs, following the modifications of the galactic potential as a result of mergers. In case of minor mergers, the potential varies slightly, so the orbits of the wandering BHs evolve smoothly, while in the case of major mergers the potential of both interacting systems changes abruptly, causing larger modifications to the BH orbits. Although numerical simulations with resolution high enough to follow the dynamical evolution of IMBHs in galactic mergers are not available, we can rely on simulations studying the mixing of particles in major mergers (White 1980; Nipoti et al. 2003), assuming that during a merger a BH follows the evolution of other particles. On average, particles that were at a given radius (normalized at the half mass radius) in one of the galaxies before the merger, are found at a similar radius (normalized to the new half mass radius) in the merger remnant.

To track the orbital evolution of wandering BHs during galactic mergers, we adopt the following scheme.

(i) Minor mergers: we let the wandering BHs in the more massive progenitor be unperturbed, while the wandering BHs in the satellite galaxy are assumed to decay with their host.

(ii) Major mergers: each wandering BH outside the core is placed in the new halo at a distance conserving the same ratio with the virial radius as it had in its parent system. If a wandering BH is instead inside the core, it is assumed to reach the centre of the newly formed halo within the same merging time-scale of the haloes (see Section 2).

5 DETECTING INTERMEDIATE-MASS BLACK HOLES IN LOCAL GALAXIES

5.1 Naked wandering BHs

As our first model of IMBHs in present-day galaxies, we assume that all BHs are naked, i.e. that the BHs left over by minor mergers have been completely stripped of their envelope. We embed all wandering BHs in a galactic disc/bulge/halo model (Springel & White 1999) and determine the corresponding density of the medium in the surrounding of the BHs at their respective positions. We assume that a fraction m_d of the initial halo mass is into a thin stellar disc with an exponential surface density,

$$\rho_d(R, z) = \frac{\Sigma_0}{2z_0} \exp\left(-\frac{R}{R_d}\right) \mathrm{sech}^2\left(\frac{z}{z_0}\right). \quad (1)$$

Here, $M_d = m_d M$ is the total mass of the disc and R_d is its scale radius. We adopt $m_d = 0.05$, while the disc scalelength is determined through the fitting formula provided in Shen et al. (2003) for the Petrosian half-light (or mass) radius:

$$R_d = 0.17 M_d^{0.14} \left(1 + M_d/3.98 \times 10^{10}\right)^{0.25}. \quad (2)$$

Most spiral galaxies seem to be consistent with a constant vertical scalelength with a value of $z_0 \simeq 0.2 R_d$. Bulges are modelled with a spherical Hernquist (1990) profile of the form

$$\rho_b(r) = \frac{M_b}{2\pi} \frac{r_b}{r(r_b + r)^3}. \quad (3)$$

In analogy to the treatment of the disc, we assume that the bulge mass is a fraction $m_b = 0.02$ of the halo mass and that the bulge scale radius r_b is a fraction $f_b = 0.1$ of that of the disc, i.e. $r_b = f_b R_d$. We have then assumed that the gas traces the baryons, the gas fraction (of the total baryonic mass) is 20 per cent in the disc and 4 per cent in bulge and halo (Fukugita, Hogan & Peebles 1998; Bell & de Jong 2000).

To model an elliptical galaxy (in the case $M = 10^{13}\, M_\odot$), we have considered the Hernquist profile only, assuming that the baryonic content of the galaxy is a fraction 0.1 of the halo mass. For the elliptical, we have then assumed that the gas fraction is 1 per cent (Mathews & Brighenti 2003).

5.2 Accretion model

In this section, we discuss how we estimate the luminosities of off-nuclear BHs resulting from the process of accretion from the surrounding medium.

Let ρ be the density of the medium in the surroundings of a BH and let c_s be its sound speed. The accretion rate on to a BH of mass

$M_{\rm BH}$ can be estimated using the Bondi–Hoyle formula (Bondi & Hoyle 1944),

$$\dot{M}_{\rm Bondi} = \frac{\lambda\, 4\pi\, G^2\, M_{\rm BH}^2\, \rho}{\left(v^2 + c_{\rm s}^2\right)^{3/2}}, \tag{4}$$

where v is the velocity of the BH with respect to the medium and λ is a parameter on the order of 1. The BH radial velocities are computed by integrating the Chandrasekar formula (Binney & Tremaine 1987) as a function of the initial conditions, while the sound speed velocity, $c_{\rm s} \sim 10(T/10^4\ {\rm K})^{1/2}$ km s^{-1}, depends on the local temperature at the BH location, which is discussed later in this section.

The bolometric luminosity of the BH can be written as

$$L_{\rm bol} = \eta \dot{M} c^2, \tag{5}$$

where η represents the fraction of the accreted mass that is radiated away. The nature of the accretion process, and the consequent value of η in BHs is rather uncertain. Active galactic nuclei (AGNs) accrete through accretion discs with a high efficiency ($\eta \sim 0.1$). Their luminosities are close to their Eddington values. At the other end of the luminosity function, are the SMBHs at the centres of our own and nearby galaxies, whose luminosities can be as low as $\sim 10^{-9}$–10^{-8} of their Eddington values (e.g. Loewenstein et al. 2001). Low luminosities could be the result either of low efficiencies with $\dot{M} \sim \dot{M}_{\rm Bondi}$, or of relatively high efficiencies with $\dot{M} \ll \dot{M}_{\rm Bondi}$ (or also of a combination of both low accretion rates and low efficiencies). Both scenarios have been suggested in the literature. Narayan & Yi (1995a) found that, when the accretion rate decreases below some critical value $\dot{m} \sim 0.1\alpha^2$ (α being the viscosity parameter in the disc), the thin disc switches to an advection dominated accretion flow, characterized by a low radiative efficiency, as a result of the inability of the electrons in the plasma to cool (see also Rees et al. 1982; Begelman & Celotti 2004). On the other hand, an accretion rate at values below the Bondi rate could be the result of the presence of winds (or outflows; Narayan & Yi 1995b; Blandford & Begelman 1999). This scenario appears to be supported by observations of both accreting BHs (Loewenstein et al. 2001), as well as old, accreting neutron stars (Perna et al. 2003).

In this work, when considering a model for the X-ray luminosity from accretion on to the IMBHs similar to that in SMBHs, we will adopt an empirical approach and simply assume that the X-ray luminosity is a fraction $\eta_{\rm X}$ of the accretion luminosity, with $\eta_{\rm X}$ calibrated on X-ray observations of SMBHs. This approach is similar to the one adopted by Agol & Kamionkowski (2002), in their calculations of the X-ray luminosity from isolated, stellar-mass BHs in the MW (they parametrized their results in terms of the X-ray accretion efficiency).

As a second model, we consider an optically thick, geometrically thin accretion disc, as in the standard Shakura–Sunyaev (SS; Shakura & Sunyaev 1973) formulation. Radiation is emitted locally with a blackbody spectrum of temperature

$$T(r) = \left(\frac{3 G M_{\rm BH} \dot{M}}{8\pi r^3 \sigma}\right)^{1/4} \left[1 - \left(\frac{r_{\rm in}}{r}\right)^{1/2}\right]^{1/4}. \tag{6}$$

The emitted spectrum (per unit frequency) from the whole surface of the disc is given by

$$L_\nu = 2\pi \frac{h\nu}{c^2} \int_{r_{\rm in}}^{r_{\rm max}} \frac{r\, {\rm d}r}{{\rm e}^{h\nu/kT(r)} - 1}. \tag{7}$$

We take $R_{\rm in} = 3R_S$ and $R_{\rm max} = 1000\,R_S$, where $r_{\rm s} = 2GM_{\rm BH}/c^2$ is the Schwarzschild radius of the BH; this yields an efficiency $\eta \sim 0.06$. As described in the previous sections, our simulations allow us to identify whether the BHs are in the halo, bulge or disc of the galaxy. For those in the halo and bulge, we assume that the temperature is the virial temperature of the accreting ISM. This is $T_{\rm vir} = 5.8 \times 10^5$ K for the galaxy of mass 2×10^{12} M$_\odot$ and $T_{\rm vir} = 2.3 \times 10^6$ K for the galaxy of mass 10^{13} M$_\odot$. In our Galaxy, we know that the disc is composed of several phases (e.g. Bland-Hawthorn & Reynolds 2000), from cold ($T \sim 100$ K), to warm ($T \sim 8000$ K), to hot ($T \sim 10^6$ K). Modelling the various phases is beyond the scope of this paper essentially because, while some information on these phases is available for our Galaxy, no such studies have been possible for other galaxies. Moreover, as a result of the process of radiative feedback (Blaes, Warren & Madau 1995), the gas in the vicinity of the BH will be heated by the ionizing radiation produced by accretion. The amount of heating and cooling depends on a number of factors, such as the density of the medium, its metallicity, the velocity of the BH, the accretion efficiency. For a medium made of H and He only, the ratio between the total heating rate and the initial energy density of the gas at the accretion radius is $\sim 2 \times 10^5 \eta\, v_{40}^{-2} T_4^{-1}$ (Agol & Kamionkowski 2002), where $T_4 = T_4 10^4$ K and $v = v_{40} 40$ km s^{-1} is the BH velocity. For BHs with velocities smaller than a few tens of km s^{-1}, heating is important even for very low accretion efficiencies. Once H and He are ionized, the opacity drops substantially and the heating rate becomes much longer than the accretion rate, leaving the gas at a temperature of around 2×10^4 K (Blaes et al. 1995; Agol & Kamionkowski 2002). We will take this to be the temperature of the accreting gas in the disc, assuming that, if there is a hot phase, this does not generally dominate. Note that, in those cases where the velocity of the BH is sufficiently high that dynamical heating is not important (and therefore the gas is actually cooler than assumed), the velocity of the BH dominates over that of the sound speed in the expression for the accretion rate, hence making the precise value of the temperature of the gas unimportant for our calculations.

For any BH, the density of the accreting material is determined at its location in the galaxy according to the model described in Section 6.1. For satellites, we also consider the possibility that they might accrete from a remnant core as described in Section 5.4.

6 RESULTS AND IMPLICATIONS FOR ULXs

At a given time, a galaxy not only contains off-centre BHs slingshot or rocketed, but can also have BHs, possibly embedded in the remnant of their original host, still on their way to the centre following a minor merger.

Fig. 3 shows the evolution with redshift of the mass function of wandering BHs in a $M = 2 \times 10^{12}$ M$_\odot$ halo, assuming that seed holes form in 3σ density peaks at $z = 20$. Fig. 4 shows instead the mass function of wandering BHs in a $M = 2 \times 10^{12}$ M$_\odot$ halo at $z = 0$, for the case of seed holes in 3.5σ peaks and in 3σ peaks. Note that most of the wandering BH masses are in an intermediate range between stellar mass BHs and supermassive ones. The upper end of the mass distribution of IMBHs, as well as their total number, is an increasing function of the galaxy mass. This can be seen by comparing Fig. 4 (top panel) and Fig. 5, which shows the mass function of wandering BHs in a $M = 10^{13}$ M$_\odot$ halo at $z = 0$, for the case of seed holes in 3.5σ peaks.

Figs 6 and 7 show the corresponding radial distributions of these BHs. Typically, BHs in satellite remnants dwell in the outskirts of galaxies, while those caused by slingshots or rockets have a broader distribution and can be found even in the inner regions. Interestingly, there is not a correlation between BH masses and radial distance (Fig. 8). Naively, more massive BHs would be expected in inner

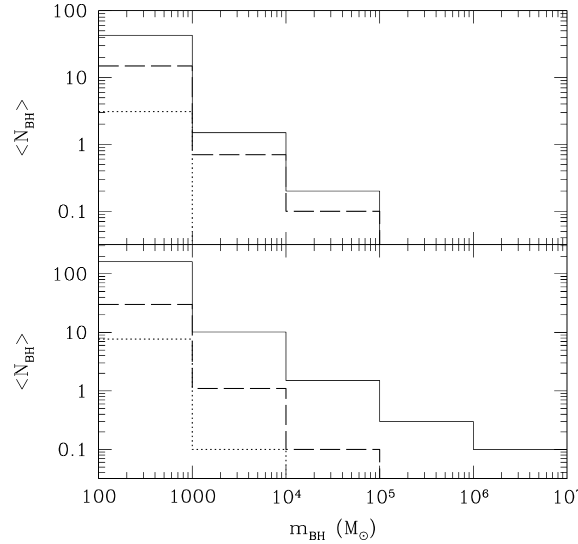

Figure 3. Mass function of wandering black holes (BHs) at different redshifts, averaged over 30 Monte Carlo realizations of an $M = 2 \times 10^{12}$ $M_{\odot}$ halo assuming that seed BHs form in 3σ density peaks at $z = 20$. Upper panel: BHs in satellite remnants. Lower panel: BHs displaced from the centre as a result of slingshots or rockets. Solid line: $z = 0$. Dashed line: $z = 2$. Dotted line: $z = 5$.

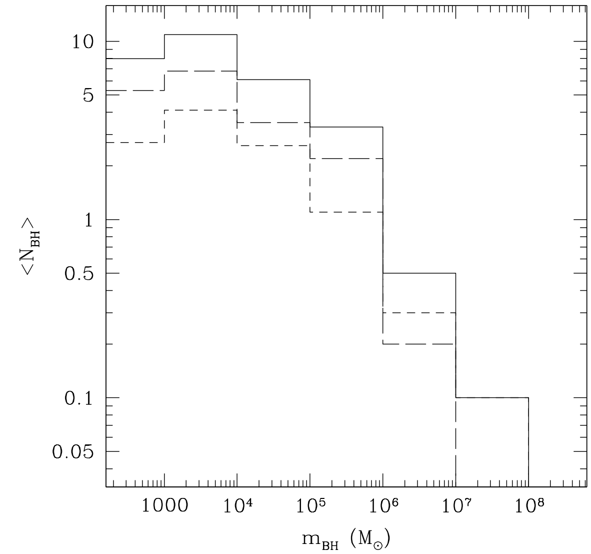

Figure 5. Mass function of wandering black holes (BHs) at z=0, averaged over 10 Monte Carlo realizations of an $M = 10^{13}$ $M_{\odot}$ halo. Solid line: total mass function. Long dashed line: BHs displaced from the centre as a result of slingshots or rockets. Short dashed line: BHs in satellite remnants.

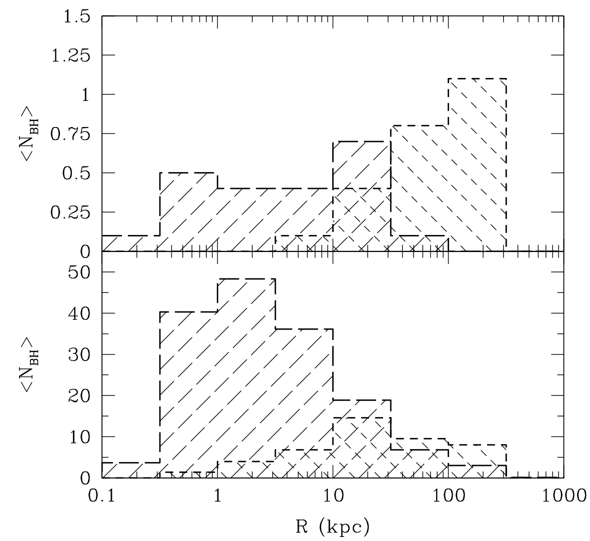

Figure 6. Radial distribution of wandering black holes (BHs) at $z = 0$, averaged over 30 Monte Carlo realizations of an $M = 2 \times 10^{12}$ $M_{\odot}$ halo. Upper panel: seed BHs form in 3.5σ peaks. Lower panel: seed BHs form in 3σ peaks. Long dashed line: BHs displaced from the centre as a result of slingshots or rockets. Short dashed line: BHs in satellite remnants.

regions, as a result of the inverse dependence of orbital decay time-scale on the mass. On the other hand, the shortness of the orbital decay time-scale for the more massive BHs implies that very few of these are expected in the inner regions because, once they sink to the inner regions, they quickly sink further to the very centre and merge with the central BH or are re-ejected. Larger holes, however, appear only at later times, so that the time elapsed from their initial interaction with the galaxy is short. Fig. 8 shows also the density of gas surrounding the same BHs.

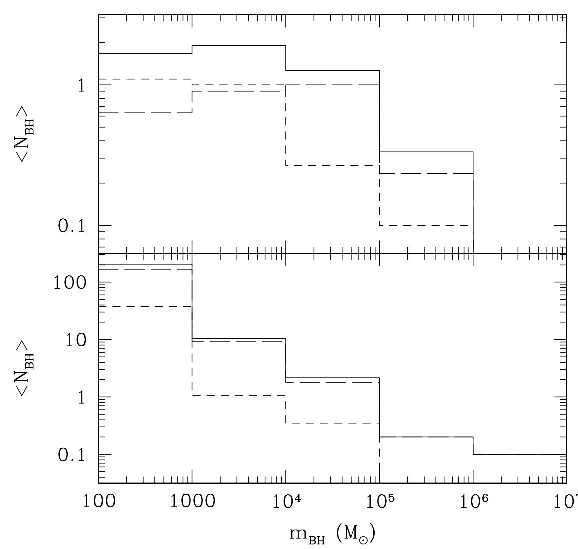

Figure 4. Mass function of wandering black holes (BHs) at $z = 0$, averaged over 30 Monte Carlo realizations of an $M = 2 \times 10^{12}$ $M_{\odot}$ halo. Upper panel: seed BHs form in 3.5σ peaks. Lower panel: seed BHs form in 3σ peaks. Solid line: total mass function. Long dashed line: BHs displaced from the centre as a result of slingshots or rockets. Short dashed line: BHs in satellite remnants.

Resulting luminosities are shown in Figs 9, 10 and 11. For the bolometric luminosities, we show results for an efficiency $\eta = 0.1$ (more typical of AGNs) and for $\eta = 10^{-5}$ (more representative of the dormant SMBHs in local galaxies), while X-ray luminosities are shown for the disc model and for an X-ray efficiency[1] $\eta_X = 10^{-6}$.

For our galaxy model with mass $M = 2 \times 10^{12}$ $M_{\odot}$ and accretion from the local ISM, we find (see Fig. 9) that there are no sources

[1] The SMBH in the Galactic Centre has an X-ray efficiency of $\sim 4 \times 10^{-8}$–2×10^{-6} in the 2–10 keV band (Baganoff et al. 2001). For BHs at the other end of the mass spectrum (i.e. the stellar-mass BHs), Agol & Kamionkowski (2002) used a best-guess estimate of $\eta_X \sim 10^{-5}$.

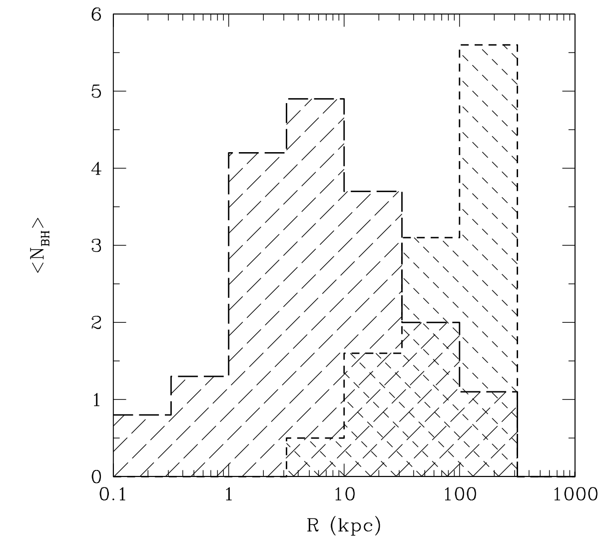

Figure 7. Radial distribution of wandering black holes (BHs) at $z = 0$, averaged over 10 Monte Carlo realizations of an $M = 10^{13}$ M$_\odot$ halo. Long dashed line: BHs displaced from the centre as a result of slingshots or rockets. Short dashed line: BHs in satellite remnants.

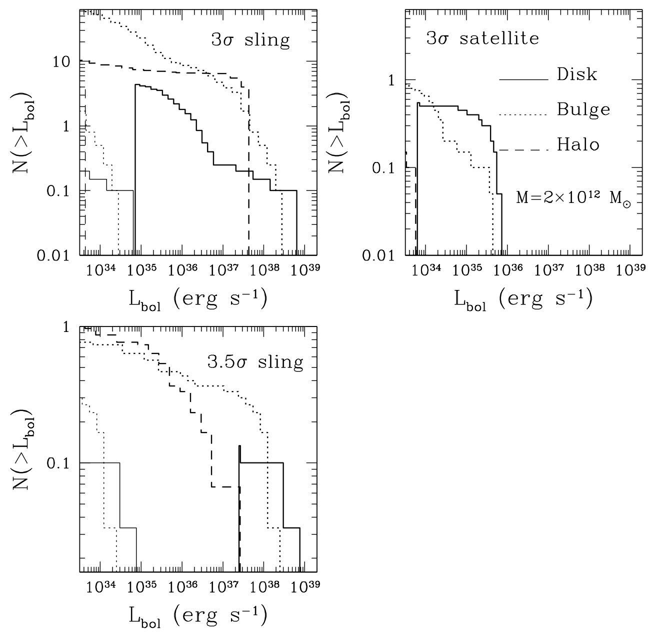

Figure 9. Cumulative distribution of the bolometric luminosity for IMBHs accreting from the local interstellar medium (ISM) in a spiral galaxy of mass $M = 2 \times 10^{12}$ M$_\odot$. Thick lines refer to an accretion efficiency $\eta = 0.1$, while thin lines are computed with $\eta = 10^{-5}$. The contribution from the three galaxy components (disc, bulge and halo) is separately shown. The standard deviation among the various Monte Carlo realizations at the upper end tail of the distribution is 0.3 for the 3σ sling case, 0.22 for the 3σ satellites and 0.18 for the 3.5σ sling.

with bolometric luminosity larger than $\sim 10^{39}$ erg s^{-1}, even for a large efficiency of 0.1. Clearly, these sources cannot contribute to the ultraluminous X-ray sources, with $L_X \gtrsim 10^{39}$ erg s^{-1}, observed in local galaxies. We find the X-ray luminosity to be at most a few $\times 10^{38}$ erg s^{-1} (see Fig. 10), if accretion proceeds at high efficiency through an SS disc. We need to stress that, although we find some very massive slung BHs at typical ISM densities (see Fig. 8), they have rather large velocities, and this suppresses the accretion rate and prevents these sources from exhibiting very large X-ray luminosities. It should also be noted that, although the number of BHs is largest in the halo and smallest in the disc, the bright end of the luminosity function is dominated by the BHs in the disc when accretion is solely from the ISM. This is a result of the typically larger densities and lower temperatures of the disc. If the accretion mode of these BHs were similar to the one in the Galactic Centre, the bright

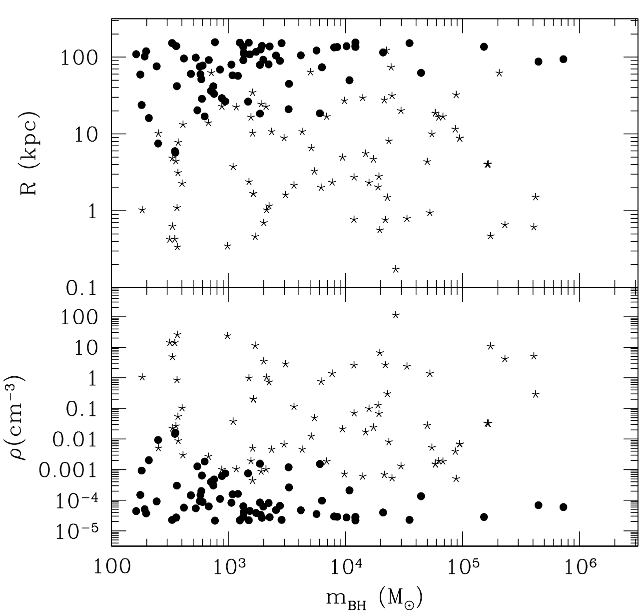

Figure 8. Gas density (lower panel) and radial distance (upper panel) of black holes (BHs) as a function of their mass, for all 30 Monte Carlo realizations of an $M = 2 \times 10^{12}$ M$_\odot$ halo, with seed BHs in 3.5σ peaks. Filled dots: BHs in satellite remnants. Stars: wandering BHs as a result of slingshots or rockets.

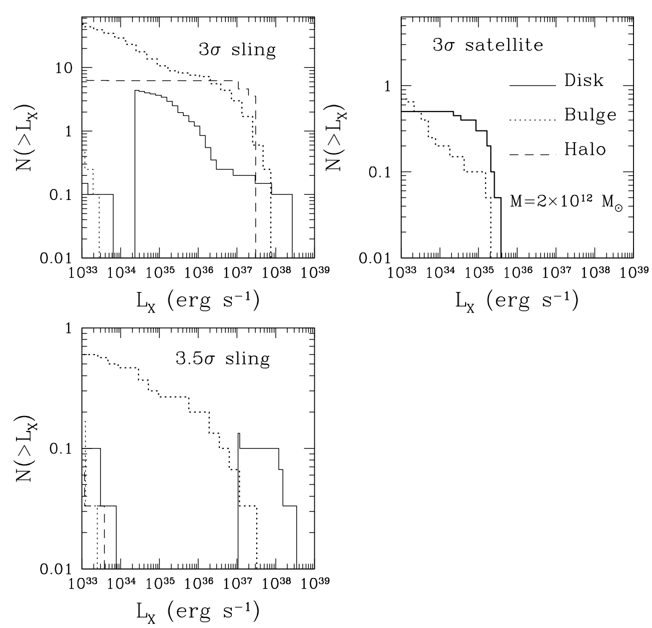

Figure 10. Cumulative distribution function for the X-ray luminosity (0.1–10 keV band) of IMBHs accreting from the local interstellar medium (ISM) through a Shakura–Sunyaev (SS) disc (thick lines) and for an X-ray efficiency of 10^{-6} (thin lines). The galaxy, of mass 2×10^{12} M$_\odot$, is assumed to be a spiral, and the contribution from the disc, bulge and halo is separately shown.

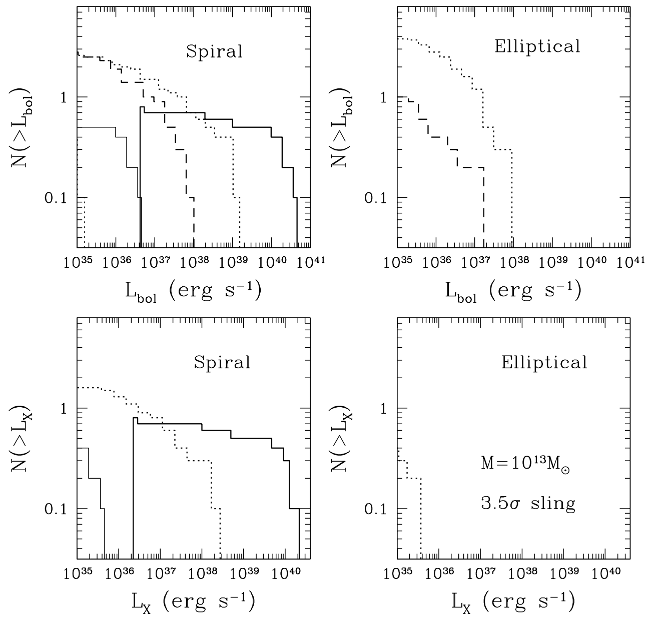

Figure 11. The upper panels show the bolometric luminosity distribution for a galaxy of mass $M = 10^{13}$ $M_\odot$ in a spiral (left) and elliptical (right) model. Thick lines are computed assuming an efficiency of 0.1, while thin lines of 10^{-5}. For the same galaxy models, the bottom panels show the X-ray luminosity (0.1–10 keV band) assuming that accretion proceeds through a Shakura–Sunyaev (SS) disc (thick lines) and for an X-ray efficiency of 10^{-6} (thin lines). Line types refer to the same galaxy components as in Figs 9 and 10. The standard deviation among the various Monte Carlo realizations at the upper end tail of the distribution is 0.31 for the spiral and 0.48 for the elliptical.

end of X-ray luminosity would barely reach the $\sim 10^{34}$ erg s^{-1} level, several orders of magnitude below the Eddington limit for a solar mass BH.

In our model in which local IMBHs are formed through mergers of smaller BHs during the galaxy assembling process, bigger galaxies are more likely to harbour more massive wandering BHs (compare Figs 3 and 4). Given the scaling of the accretion rate with $M^2_{\rm BH}$, this implies that, the larger the galaxy mass, the more luminous will be the sources associated with accreting IMBHs. This is shown in Fig. 11, where the bolometric luminosity function is computed for a galaxy of $M = 10^{13}$ $M_\odot$. Both a spiral and an elliptical galaxy model are considered. If the accretion efficiency is high ($\eta \sim 0.1$), a spiral galaxy has a 10 per cent probability of hosting a source with $L_{\rm X} \gtrsim 10^{40}$ erg s^{-1}. This is however not the case for an elliptical galaxy, where the lower ISM densities suppress the accretion emission. No ULXs resulting from IMBHs are expected even in a very massive elliptical galaxy and for a high accretion efficiency.

6.1 Dressed wandering BHs

All the previous results have been produced under the assumption that the BHs left over by minor mergers have been completely stripped of their envelope and accrete from their surrounding ISM (the naked BHs scenario). However, it is possible that, during the merger process, BHs are not completely stripped of their surrounding core of material. Following tidal stripping, a bound core can remain, enveloping the central BH. Mayer & Wadsley (2003) have performed high-resolution N-body/smoothed particle hydrodynamics simulations that follow the evolution of small disc satellites falling into the potential of a much larger halo. Tidal shocks remove most of the outer dark and baryonic mass. In addition, ram pressure affects the gaseous component, stripping it even more severely. After a Hubble time, approximately 30 per cent of the stars have been stripped and 80–90 per cent of the gas disc has been removed, leaving a system resembling a gas-poor dwarf spheroidal. A reasonable value for the gas density in satellite remnants is the typical gas density $\rho \sim 10^{-3}$ cm^{-3} found in dwarf galaxies of the local group (Grebel, Gallagher & Harbeck 2003). The density scatter is large, varying by approximately 3 orders of magnitude from one system to another. An optimistic upper limit for the gas densities was adopted by Islam, Taylor & Silk (2004a,b). Their estimate assumes that all the baryons in the satellite remnants are under the form of gas and that the baryon content equals the cosmological baryon fraction. In this case, for a standard ΛCDM cosmology, the gas density in the remnants is of order $\rho \sim 8 \times 10^{-2}$ cm^{-3}.

Given the uncertainties involved in the estimates of the density of these possible remnant cores, we prefer to just give some indicative results within the context of this scenario. In particular, we find that approximately 10 per cent of the galaxies with mass $\sim 2 \times 10^{12}$ $M_\odot$ will have a source with bolometric luminosity of $L_{\rm bol} \gtrsim 1.5 \times 10^{39}(\eta/0.1)(\rho/0.1\ {\rm cm}^{-3})$ erg s^{-1} for the 3σ peaks and $L_{\rm bol} \gtrsim 2 \times 10^{41}(\eta/0.1)(\rho/0.1\ {\rm cm}^{-3})$ erg s^{-1} for the 3.5σ peaks. It should also be noted that, if the BHs do accrete from a remnant core, then the luminosity function of the BHs will be independent of their location and therefore the most luminous ones are likely to be found in the halo, where their number is the largest.

7 COMPARISON WITH PREVIOUS WORK

Our results are much more pessimistic than previous investigations involving IMBH remnants of the first stars (Islam, Taylor & Silk 2003; Islam et al. 2004a,b). Although the hierarchical framework is similar, this paper and the Islam et al. papers rely on different assumptions about the abundance of primordial seeds, and about the dynamical and mass growth history of MBHs. First, their preferred model assumed seed holes, of $m_\bullet = 260\,M_\odot$, in 3σ peaks at $z = 24.6$, leading to a number of seeds almost 3 orders of magnitude larger than that in our reference model (3.5σ peaks at $z = 20$). Secondly, their merger efficiency is much larger, because they assume that any MBH coming within 1 per cent of the virial radius of the host halo actually merges with the central BH. Finally, they ignore the mass growth of MBHs as a result of the accretion of gas, in a luminous phase as quasars, thus requiring a large number of MBH mergers in order to reproduce the observed local $m_{\rm BH}$–σ_* relation. In our model, instead, it is gas accretion, following galactic major mergers, which determines the mass of SMBHs today, with mergers playing a secondary role, thus requiring a much smaller number of seeds to reproduce the observed SMBH masses.

As a result, our predictions for the number of X-ray sources in a galaxy of given mass generally fall below the predictions of Islam et al. (2004b), when similar estimates for the density and temperature of the core remnant are adopted.[2]

8 SUMMARY AND DISCUSSION

In this paper, we have studied the dynamical evolution with cosmic time of a population of IMBHs wandering in galactic haloes,

[2] Note that we consider the possibility of BHs accreting from a baryonic remnant only for the satellites, whose mass distribution has an upper end cut-off, which is smaller than that of the sling BHs (see Figs 3 and 4).

in the context of popular hierarchical structure formation theories. We follow the merger history of DM haloes and associated SMBHs via cosmological Monte Carlo realizations of the merger hierarchy from the end of the dark ages to the present in a ΛCDM cosmology. MBHs form as the end product of the first generation of stars and then evolve in a hierarchical fashion following the fate of their host haloes. Along the merger history of DM haloes, the BHs embedded in their inner regions sink to the centre of coalescing larger and larger galactic structures owing to dynamical friction, accrete a fraction of the gas in the merger remnant to become supermassive and form a binary system. Stellar dynamical processes drive the binary to harden and eventually coalesce. The dynamical evolution of SMBH binaries may be disturbed by a third incoming BH, if another major merger takes place before the pre-existing binary has had time to coalesce. The three BHs are likely to undergo a complicated resonance scattering interaction, leading to the recoil of the binary and of the single BH, thus creating a population of wandering BHs. Other coalescing binary BHs become wandering as a result of the non-zero net linear momentum carried away by gravitational waves if a binary is asymmetric. BHs retained within the potential well of the host halo are then bound to slowly travel back towards the galactic centre under the effect of dynamical friction. The population of wandering BHs comprises also another class of holes, those originally hosted by haloes, which are small compared with the primary halo. In this case, the wandering holes can, or cannot, be still surrounded by the remnants of their old host.

Our simulations have allowed us to estimate the number of BHs, their mass distribution and position within the galaxy. The total number of wandering IMBHs correlates with the mass of the galaxy at $z = 0$ and the BHs have typically larger masses. As a result, the number of point sources resulting from IMBHs is also expected to correlate with the mass of the galaxy and so the luminosity of the brightest sources. To zeroth order, no correlation is expected in our scenario of IMBH formation and the star formation rate (SFR) in the galaxy at $z = 0$, as the mass function and positions of the BHs within the galaxy are essentially determined by its past merger history. However, if a galaxy has a high SFR, then it is likely to also have a larger filling fraction of dense molecular clouds, which would significantly enhance the accretion rate if a BH happened to wander inside them. In the scenario recently proposed by Krolik (2004), BHs can be formed from primordial abundance gas or from stellar mergers[3] and these mechanisms would make them to preferentially populate the disc of galaxies, therefore making them brighter, especially if they move for most of the time inside dense regions.

In our scenario of BH formation in minihaloes and growth through subsequent galaxy merging, we find that, if the wandering IMBHs do not carry any substantial baryonic core with them, then an MW sized galaxy is not likely to harbour sources with $L \gtrsim 10^{39}$ erg s^{-1}. On the other hand, about 10 per cent of spiral galaxies with mass $\sim 10^{13}$ M$_\odot$ would likely have a source with luminosity $\gtrsim 10^{40}$ erg s^{-1}. The brightest sources are expected to be found in the disc, as a result of its typical lower temperature and larger density than the bulge and the halo. No ULXs are expected in ellipticals, even of large mass ($\sim 10^{13}$ M$_\odot$), as a result of their average lower density and the lack of a cooler, dense disc, which boosts the emission. At sub-Eddington luminosities, the luminosity function of the naked IMBH population in a typical, MW-sized galaxy is well below the observed point-source population in *Chandra* surveys (Colbert et al. 2004). This is not surprising, as this point-source population in the sub-Eddington range is dominated by high mass X-ray binaries (Grimm, Gilfanov & Sunyaev 2003).

Our results imply that, in order to produce ULXs from IMBHs in MW-type galaxies (and ellipticals for that matter), it is necessary that the wandering IMBHs are not completely stripped of their baryonic core and this remnant material feeds the accretion at a rate higher than what would be allowed from the ISM alone. Even allowing a high efficiency of ~ 0.1, a density $\gtrsim 0.01$ cm^{-3} is required in order for a few per cent of MW-type galaxies to host a source with luminosity $\gtrsim 10^{40}$ erg s^{-1}. However, the density cannot be significantly higher than that. In our models, the high tail of the mass distribution of IMBHs extends to $\sim 10^6$–10^8 M$_\odot$ and the observational lack of sources with luminosities $\gtrsim 10^{44}$ erg s^{-1} implies that these IMBHs must accrete at sub-Eddington rates.

In this paper, however, we have investigated the luminosity that IMBHs can attain in normal, quiescent galaxies. Starbursting galaxies, such as the Antennae (Zezas & Fabbiano 2002) or the Cartwheel galaxy (Gao et al. 2003) show a much larger population of ULXs compared with quiescent galaxies of the same size. In particular, in the Cartwheel galaxy these sources are found in the outer star-forming ring, believed to be created by radially expanding density waves caused by a plunging merger. Note that all these sources are at a distance larger than ~ 10 kpc from the centre of the galaxy, so in our scheme for a quiescent spiral, they would be found in the low-density, gas-poor galactic halo. The density waves expanding outwards, though, provide a temporary high-density environment that may supply fuel for an IMBH to accrete and shine at high luminosities, higher also than those predicted for IMBHs travelling in galactic discs.

[3] For studies of stellar merging see also Portegies Zwart & McMillan (2002) and Gürkan, Freitag & Rasio (2004); note that the formation of IMBHs by runaway stellar merging is possible only in young, compact clusters.

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