Massive black hole remnants of the first stars in galactic haloes

Raty R. Islam,* James E. Taylor and Joseph Silk

Astrophysics, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH

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ABSTRACT

We investigate the possibility that present-day galactic haloes contain a population of massive black holes (MBHs) that form by hierarchical merging of the BH remnants of the first stars. Some of the MBHs may be large enough or close enough to the centre of the galactic host that they merge within a Hubble time. We estimate to what extent this process could contribute to the mass of the supermassive black holes observed in galactic centres today. Many MBHs will not reach the centre of the main halo, however, but continue to orbit within satellite subhaloes. Using a semi-analytical approach that explicitly accounts for dynamical friction, tidal disruption and encounters with the galactic disc, we follow the dynamics of the satellites and their MBHs and determine the abundance and distribution of MBHs in present-day haloes of various masses. Considering two different accretion scenarios, we also compute the bolometric luminosity function for the MBHs.

Key words: galaxies: formation – galaxies: haloes – galaxies: nuclei – cosmology: theory.

1 INTRODUCTION

The presence of supermassive black holes (SMBHs) at the centres of most galaxies appears by now firmly established. SMBHs have estimated masses in the range $10^6$–$10^9 M_{\odot}$ and various correlations have been observed between the mass of SMBHs and the properties of the galactic bulge hosting them. The first of these to be established were correlations between the mass of the SMBH, $M_{\text{smbh}}$, and the mass $M_{\text{bulge}}$ or luminosity $L_{\text{bulge}}$ of the galactic bulge (Magorrian et al. 1998; Kormendy & Gebhardt 2000; Laor 2001). More recently, a tighter correlation was found between $M_{\text{smbh}}$ and the bulge velocity dispersion, $\sigma_{\text{bulge}}$, at some fiducial distance from the centre (Gebhardt et al. 2000; Merritt & Ferrarese 2001). An equally tight correlation has also been determined between $M_{\text{smbh}}$ and the bulge’s light profile, as parametrized by a shape index, $n$ (Graham et al. 2001).

Because these correlations extend well beyond the direct dynamical influence of the SMBH, it seems likely that there is a close link between the formation of SMBHs and the formation of their host galaxy. A recent analysis finds that the masses of SMBHs appear to be correlated with the host circular velocity even beyond the optical radius (Ferrarese 2002). If this is confirmed, it indicates that the SMBHs are linked to properties of the host dark matter halo. This might be the strongest hint yet that there must be a hierarchical merging component to the growth of SMBHs, as the properties of haloes are primarily determined in the context of their hierarchical build up.

Most models put forward to account for the correlations assume a close link between galaxy and SMBH formation as a starting point, although they subsequently proceed along either or both of two routes to explain how the SMBHs grow in mass. One way is to consider that the SMBH mass increases mainly by the merging of smaller precursors. This requires SMBH precursors to have been present in galaxies from very early on (Madau & Rees 2001, hereafter MR01; Menou, Haiman & Narayanan 2001; Schneider et al. 2002). This might allow the observed correlations to be set up over a long period of time with a potentially large number of mergers through the dynamical interactions between the merging galaxies and SMBH precursors. However, BH merging by itself might ultimately be highly inefficient especially for low-mass BH binary systems, for which it would be extremely difficult to progress from a mutually bound configuration to the stage where emission of gravitational radiation draws the binary constituents to final coalescence.

Another mechanism considered is growth mainly by gas accretion within the host bulge. In this case, a strong non-gravitational interaction between the growing SMBH and the bulge has to be invoked. An example of this is the radiative feedback of an accreting SMBH that changes the gas dynamics in the bulge so as to effectively control its own gas supply and establish a relation between $M_{\text{smbh}}$ and $\sigma_{\text{bulge}}$ (Silk & Rees 1998). A similar route is followed by models that tie $M_{\text{smbh}}$ to the amount and properties of gas in the bulge (Adams, Graff & Richstone 2001). The latter itself may depend on the previous merging of the galaxy with others and so provides a way of combining SMBH mass growth through both mergers and accretion (Haehnelt & Kauffmann 2000).

As an example of the merger-only scenario, it has been shown that the merging of the massive black hole (MBH) remnants of the first stars in the Universe could account for the inferred overall abundance of SMBHs today (Schneider et al. 2002).
However, gas accretion during the optically bright quasi-stellar object (QSO) phase may be able to account for most of the present-day SMBH mass density (Yu & Tremaine 2002), although this process alone would probably not allow ordinary stellar mass BHs to become as large as the most massive SMBHs observed today \( M_{\text{mbh}} \gtrsim 10^9 \, M_\odot \) (see e.g. Richstone et al. 1998). Even if stellar mass BHs were accreting at the Eddington limit, there would not be enough time for the required mass increase to occur. The presence of MBH seeds prior to the QSO phase and/or subsequent merging of MBHs therefore appears to be necessary.

In this paper we explore this idea further to determine an upper limit on the mass to which SMBHs can grow through mergers of lower mass precursors and, more importantly, what the implications are for the presence of a remnant population of lower mass MBHs in the galactic halo. In doing so we assume efficient merging between MBHs, but we also consider the effect of relaxing this assumption. As the ‘seeds’ in the merging hierarchy, we consider MBHs of some mass \( M_{\text{seed}} \) that are remnants of the first stars in the Universe, forming within high-\( \sigma \) density peaks at redshifts of \( z \sim 24 \). We use Monte Carlo merger trees to describe the merging of haloes and then follow the dynamical evolution of merged/accreted satellite haloes and their central MBHs within larger hosts, explicitly accounting for dynamical friction, tidal stripping, and disc encounters. A key prediction is that \( \sim 10^3 \) MBHs in the mass range \( 1-1000 \times M_{\text{seed}} \) should be present within the galactic halo today as a result of this process.

We start by describing the origin of seed MBHs in Section 2. In Section 3, we explain how the subsequent merging of their haloes could lead to a build-up of a population of MBHs in present-day galactic haloes, as well as contributing to the mass of a central SMBH. Ways of detecting the population of halo MBHs, particularly via their X-ray emission, are described in Section 4. We conclude with a summary of our findings in Section 5.

2 PRIMORDIAL STAR FORMATION AND MASSIVE BLACK HOLES

A number of recent semi-analytical (Hutchings et al. 2002; Fuller & Couchman 2000; Tegmark et al. 1997) and numerical (Bromm, Coppi & Larson 2002; Abel, Bryan & Norman 2000) investigations suggest that the first stars in the Universe were likely created inside molecular clouds that fragmented out of the first baryonic cores inside dark matter haloes at very high redshifts. For common \( \Lambda \)CDM cosmologies in particular these objects are found to have a mass \( M_{\text{min}} \approx 3 \times 10^5 \, h^{-1} \, M_\odot \) and to have collapsed at redshift \( z \sim 24 \). In linear collapse theory this corresponds to collapse from 3\( \sigma \) peaks in the initial matter density field. This is because the mass contained in overdensities corresponding to 3\( \sigma \) peaks at this redshift is just about twice as massive, i.e. around \( 500 \, M_\odot \), and that most of them end up in the SMBH today. For less massive seed MBHs, growth through gas accretion will have to play an important role in achieving the present-day SMBH mass density. For the actual local mass density contained in SMBHs Merritt & Ferrarese (2001) obtain \( \rho_\ast \approx 5 \times 10^5 \, M_\odot \, \text{Mpc}^{-3} \).

This means that, in order for the SMBH to have grown primarily by mergers of lower mass MBHs, the mass of the initial seed MBHs need to be just about twice as massive, i.e. around \( 500 \, M_\odot \), and that most of them end up in the SMBH today. For less massive seed MBHs, growth through gas accretion will have to play an important role in achieving the present-day SMBH mass density. Especially, the assumption that all MBHs merge to form the SMBHs, is inappropriate and the dynamics of individual MBHs needs to be examined in more detail as we describe in the next section.

3 HIERARCHICAL MERGING OF PRIMORDIAL BLACK HOLES

3.1 Modelling halo growth

While the basic properties of the seed MBHs are determined by the physics of the first baryonic objects, as outlined above, the extent to which they merge to form the present-day SMBH depends on their subsequent dynamical evolution after their respective host haloes have merged. To track this evolution we use a semi-analytical code (Taylor & Babul 2003; see also Taylor 2001 and Taylor & Babul 2001) which combines a Monte Carlo algorithm to generate halo merger trees with analytical descriptions for the main dynamical processes – dynamical friction, tidal stripping, and tidal

1 At or above the cooling mass the corresponding virial temperature, to which the baryons are heated, is high enough for cooling to proceed on a timescale that is smaller than the gravitational infall timescale. The latter is the condition for fragmentation to occur.
heating – that determine the evolution of merged remnants within a galaxy halo.

Starting with a halo of a specific mass at the present day, we trace the merger history of the system back to a redshift of 30, using the algorithm of Somerville & Kolatt (1999). Computational considerations limit the mass resolution of the tree to \( \approx 3 \times 10^{-5} \) of the total mass; below this limit we do not trace the merger history fully. For the more massive haloes, this resolution limit is larger than \( M_{\text{min}} \) and many of the branchings of the merger tree drop below the mass resolution limit before they reach \( z = 24 \), so that we cannot always track the formation of individual BHs. To overcome this problem, if systems over \( M_{\text{min}} \) appear in the merger tree after primordial BHs have started forming at \( z = 24 \), we determine how likely they are to contain one or more primordial BHs, based on the frequency of 3\( \sigma \) peaks, and we populate them accordingly. In the most massive trees, haloes at the resolution limit are likely to contain several primordial BHs. In this case, we assume that the BHs have merged to form a single object, in keeping with the assumption of efficient merging discussed below.

Within the merger trees, we then follow the dynamical evolution of BHs forward in time to the present day, using the analytic model of satellite dynamics developed in Taylor & Babul (2001). Merging subhaloes are placed on realistic orbits at the virial radius of the main system, and experience dynamical friction, mass loss and heating as they move through their orbits. The background potential is modelled by a smooth Moore profile \( (\rho \propto r^{-1.5}(r^{-1.5} + r^{-1.5})) \), which grows in mass according to its merger history, and changes in concentration following the relations proposed by Eke, Navarro & Steinmetz (2001). We give this profile a constant-density core of radius 0.1 \( r_s \), to account for the possible effects of galaxy formation in disrupting the dense central cusp.

Within this potential, the formation of a central galaxy with a disc and a spheroidal component is modelled schematically, by assuming that a third of the gas within the halo cools on the dynamical time-scale to form a galactic disc, and that major mergers disrupt this disc and transform it into a spheroid with some overall efficiency. We choose as the disruption criterion that the disc collide with an infalling satellite of mass equal to or greater than its own, and we set the efficiency with which disc material is then transferred to the spheroid to 0.25. This choice of parameters is required to limit the formation of spheroids and thus to produce a reasonable range of morphologies in isolated present-day 10\(^{12} \) \( M_\odot \) systems, as discussed in Taylor & Babul (2002). We do not expect the results for halo BHs to depend strongly on these parameters, although they may have some effect on the properties of the central BHs. Finally, the evolution of haloes in side branchers of the merger tree is followed more approximately, by assuming that the higher-order substructure (that is subhaloes within subhaloes) merges over a few dynamical times, causing its BH component to merge as well, while the unmerged substructure percolates down to a lower level in the tree. We will discuss the details of this model in a forthcoming work (Taylor & Babul 2003): here it serves only as a backdrop for the dynamical calculations of BH evolution.

The semi-analytical code tracks the positions of all the primordial BHs that merge with the main system and the amount of residual dark matter from their original halo that still surrounds them, if any. We classify systems as ‘naked’ if their surrounding subhalo has been completely stripped by tidal forces, and ‘normal’ otherwise. Our orbital calculations cannot follow the evolution of systems down to arbitrarily small radii within the main potential, so if BHs come within 1 per cent of the virial radius of the centre of the potential (roughly 3 kpc for a system such as the present-day Milky Way), we assume they have ‘fallen in’ and stop tracking their orbits. Black holes contained in satellites which disrupt the disc in major mergers are also assumed to fall into the centre of the potential during its subsequent rearrangement. Clearly, this assumes that BH merging in the centre of the main system is completely efficient, so it will produce a conservative upper limit on how many BHs merge with the central SMBH. We discuss the effect of relaxing these assumptions below.

Using the semi-analytical code, we generate sets of different realizations for seed BH masses of 260 and 1300 \( M_\odot \), and for final halo masses of 1.6 \( \times 10^{10} \), 1.6 \( \times 10^{11} \), 1.6 \( \times 10^{12} \) and 1.6 \( \times 10^{13} \) \( M_\odot \).

### 3.2 Central SMBHs

The assumption that MBHs within a kpc or so from the host centre merge efficiently can be used to determine an upper limit on the mass of central SMBHs. Although MBH merging may proceed much less efficiently, we give examples of a range of processes that can lead to rapid merging of MBHs in the galactic context.

If the mass of only the MBHs is considered, their orbital decay time-scale in the host can be longer than a Hubble time. However, MBHs typically remain associated with stars and gas from their original satellite, which increases their effective mass by a factor of at least 100 to 1000 and lowers the orbital decay time-scale accordingly, allowing even relatively light MBHs (\( M_\bullet > 10^3 \) \( M_\odot \)) to spiral into the host central region (\( \approx \)kpc) within a Hubble time (Yu 2002). This is true even if the satellite itself may have actually lost most of its mass (\( \geq 99 \) per cent) due to tidal stripping inside the host halo, and is thus classified as ‘naked’ in our treatment. This implies that only at high redshifts could seed mass MBHs have travelled to the host centre, as they would have then entered the correspondingly smaller host halo at smaller distances from the centre.

It seems then that dynamical friction can deliver MBHs to the host central regions efficiently where they then form binaries with any MBH already at the centre. The evolution of a MBH binary system in stellar background has been studied extensively (Begelman, Blandford & Rees 1980; Quinlan 1996; Milosavljevic & Merritt 2001; Yu 2002) and the ‘hardening’ stage of binary evolution has been singled out as the ‘bottle neck’ on the way to the final merger (Milosavljevic & Merritt 2001; Yu 2002). With dynamical friction no longer significant and orbital decay due to gravitational wave emission not yet important, the only way for the binary MBHs to reduce their orbital axis is by interaction with stars in their vicinity, which can take significantly longer than a Hubble time.

However, the presence of gas may be of crucial importance in this context (Milosavljevic & Merritt 2001). High densities of gas between the binary MBHs could allow for a much faster evolution and eventual merger of the binary. Several scenarios have been suggested for this, such as a massive gas disc around the binary (Gould & Rix 2000) or massive gas inflow (see e.g. Begelman et al. 1980) in the wake of major mergers. Hydrodynamical simulations of galaxy mergers, for instance, find that up to 60 per cent of the total gas mass of two merging Milky-Way-sized galaxies can end up within a region only a few hundred parsec across, which is about half the bulge scale radius (Barnes & Hernquist 1996; Naab & Burkert 2001; Barnes 2002).

Here we assume that during major mergers the gas infall will actually lead to all MBHs binaries merging. We also neglect the possibility of triple BH interactions and sling-shot ejections. Fig. 1 shows the relation between the mass of the galactic bulge and the central SMBH if the latter grows purely through mergers...
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Figure 1. Mass of central SMBH versus bulge mass of host galaxy at $z = 0$. From bottom left to top right, the symbols are for bulges in haloes with masses $1.6 \times 10^{10}, 1.6 \times 10^{11}, 1.6 \times 10^{12}$ and $1.6 \times 10^{13} M_\odot$. The upper and lower data sets are for seed MBH masses of 260 and 1300 $M_\odot$, respectively. The observational relation between $M_{\text{bulge}}$ and $M_{\text{smbh}}$ is shown by the dashed grey line. The solid line represents the linear relationship between SMBH and bulge mass as determined by observations (Magorrian et al. 1998) and here is only shown to give an upper limit on the allowed masses for the SMBHs and also the mass of the seed MBHs provided $M_{\text{smbh}} \propto M_{\text{seed}}$. For instance, in the extreme case where the seed MBH mass is equal to the total baryonic mass ($\sim 1.3 \times 10^4 M_\odot$) of the 3$\sigma$ haloes within which they first formed, the resulting SMBH masses are essentially ruled out by the observed relation. For both seed masses we are considering, growth through gas accretion is required to match the observations. We also note that a power-law best fit, between the SMBH and bulge mass for both seed masses, yields an index $\sim 0.9$, i.e. less than 1, as would be the case for a linear relationship. This means that for larger bulges a slightly smaller fraction of the total mass contained in MBHs merges with the SMBH, and therefore a relatively larger amount has to be acquired through gas accretion to achieve a linear relationship. Larger bulges will have typically formed inside correspondingly more massive host galaxies/haloes which collapse at higher redshifts, which implies that more gas must have been available then to be accreted by the central SMBH. This trend seems plausible also in the light of results from star formation and quasar activity at high redshifts.

3.3 Abundance of MBHs in galactic haloes

In Fig. 2 we show the average abundance of MBHs within the virial radius of the primary host halo and we also identify the abundance due to naked MBHs.

Compared to the mass of the bulge, disc and halo the seed MBH masses are small and so do not significantly affect the evolution of the substructure within the host. For this reason we find that, except for the high mass end, the MBH mass functions for the two different MBH seed masses are essentially the same but are offset from one another along the ordinate (representing the actual MBH mass) by a constant factor that is more or less equal to the ratio of the initial seed MBH masses. Based on this, the solid line in Fig. 2 represents the inferred mass function for a seed MBH with a mass of $1.3 \times 10^4 M_\odot$, which is the case where the entire primordial cloud collapses into the BH. Because the different seed MBH masses only become important at the high mass end, this scaling just reflects the one-to-one correspondence between number and mass of 3$\sigma$ haloes and their seed MBHs. In the following, our analysis will therefore focus on the case of 260 $M_\odot$ seed mass MBHs unless stated otherwise.

Figure 2. Mass function of MBHs in the halo averaged over 30 realizations with error bars corresponding to 1$\sigma$ variance. In the left panel, the mass function is shown for the $1.6 \times 10^{12} M_\odot$ halo for all MBHs as well as only naked MBHs. Upper and lower data sets are for $M_{\text{seed}} = 260$ and $1300 M_\odot$, respectively. The right panel shows the mass functions for $M_{\text{seed}} = 260 M_\odot$ and all final halo masses.
we see that it is very similar for the different masses. It also becomes clear that by far most of the MBHs in the inner part of the host centre is more uncertain, $N \sim \mathcal{M}_{\star}^{-0.79\pm0.04}$. The total number of MBHs in the halo is given in Table 1. For Milky-Way-sized haloes, for instance, we would expect some 1400 to 1500 MBHs to orbit within the galactic halo. We found that the number of MBHs in the galactic disc out to about two disc scale radii is less than 0.2 per cent of the total number of MBHs for all final halo masses. Part of the reason for this low number is that many of the MBHs in the disc are orbiting at small distances of less than 1 per cent of the host virial radius and are therefore counted as having fallen to the centre as their dynamics cannot be traced accurately any longer, as mentioned above. Conversely, the high mass end implies that apart from the central SMBH there will be one or two other MBHs of about a tenth of its mass orbiting in the halo.

Fig. 3 shows the number of MBHs as a function of distance from the host centre in the $1.6 \times 10^{12} M_\odot$ halo. We have only plotted the case $M_{\star,\text{seed}} = 260 M_\odot$ as it is essentially the same for the two different seed MBH masses. The left panel indicates that the relative distribution of MBHs with distance from the halo centre is remarkably similar for the different masses of MBHs. It also becomes clear that by far most of the MBHs in the inner part of the halo are naked; that is, they have no associated satellite halo. In the right panel we have plotted the cumulative radial distribution and we see that it is very similar for the different final halo masses when scaled to their respective virial radii. Apart from the different halo masses that account for different normalization of the abundance of MBHs, the difference in shape, especially for the $1.6 \times 10^{10} M_\odot$ halo, likely reflects the higher concentration of the halo potential.

In Table 2 we have listed the average abundance of MBHs in local Earth centred volumes. Virtually all of these will be seed BHs that have not yet merged and, in the absence of any growth process other than hierarchical merging, their mass will be equal to that of the initial seed BHs. The total mass contained in halo MBHs is shown in Table 3 and compared with the average mass of the central SMBH. Regardless of seed MBH mass we find that, on average, the central SMBH has about 30 to 50 per cent of the mass that is contained in lower mass MBHs in the galactic halo.

Within the variance quoted we expect the average number and mass abundance of MBHs, particularly in the $1.6 \times 10^{12} M_\odot$ halo as shown above, to be representative for Milky-Way-sized galaxies in currently favoured ΛCDM cosmologies.

3.4 Constraints on MBH IMF

The above results for the two different seed MBH masses give some indication of the effect of other changes in the masses and numbers of seed MBHs in the primordial haloes.

We have seen above that the MBH mass functions are shifted along the $M_{\text{halo}}$ axis in proportion to the mass of the seed MBHs. This mass, however, cannot be higher than the total baryonic mass contained in the original $3\sigma$ haloes. This translates into the solid grey line shown in Fig. 2, and thus any mass for a single seed MBH between 260 and $1.3 \times 10^4 M_\odot$ will lead to a present-day MBH mass function between the upper and lower ones shown.

By conservation of mass, if the primordial halo contains more than one MBH of different masses in the range $260 M_\odot < M_{\text{MBH}} < 13\ 000 M_\odot$ then the resulting mass function will again lie between the bottom and the top ones shown, but will have a different slope. If initially one or more MBHs are present with masses lower than $260 M_\odot$, the present-day mass function will correspondingly extend to lower masses, but will otherwise still be limited by the top mass function. This means that, even though we had initially made a fairly specific choice for the MBH IMF in the primordial haloes, any general form for the MBH IMF is expected to lead to results within the limits provided by the mass functions shown, if there is at least one seed MBH of $260 M_\odot$ or larger.

We need to stress that the above depends on the assumption that all MBHs falling to within 1 per cent of the virial radius merge efficiently in all haloes merging along the way to produce the final host halo. We consider the implications of less efficient or no merging of MBHs in the next section.

If the only, or at least most significant, source of seed MBHs is that forming in the $3\sigma$ haloes then the total mass contained in halo MBHs can be used to normalize the IMF of seed MBHs, to which it is related by the background cosmology. The latter determines the average merger history of haloes and thus the average number of $3\sigma$ haloes ending up in more massive haloes later on. Note that this is not much affected by the merger efficiency of MBHs as the present-day MBH mass function is dominated by seed MBHs that have not merged, and that contribute a similar amount to the total mass contained in halo MBHs as the few very massive MBHs that have resulted from multiple mergers of seed MBHs.

3.5 MBH merger efficiency

Up to now we have considered any MBH as having merged with the central MBH, when it comes within 1 per cent (hereafter referred to as the merger region) of the virial radius of the host halo at that time. There are various ways in which the actual merger efficiency could be lower than this, and so our results above only provide an upper limit on how much the MBH merger process can contribute to the mass of central and halo MBHs.

One major source of inefficiency is, of course, the time it takes for any MBH to spiral into another and typically more massive MBH at the centre of their common host, and how likely it is then for the two to merge. One does not necessarily imply the other – at early times haloes are smaller, i.e. at the first encounter the two central MBHs within any two haloes will start out much closer and so are more likely to spiral to the common centre of the halo merger remnant in a relatively short time. Because there are more low-mass haloes this might then give rise to configurations consisting of more

Table 1. Total number of MBHs in halo averaged over 30 trees with associated variance.

| Halo mass (M_\odot) | M_{\star,\text{seed}} = 260 M_\odot | M_{\star,\text{seed}} = 1300 M_\odot |
|----------------------|--------------------------|--------------------------|
| 1.6 \times 10^{10}   | 88 \pm 22                | 72 \pm 16                |
| 1.6 \times 10^{11}   | 330 \pm 50               | 420 \pm 70               |
| 1.6 \times 10^{12}   | 1560 \pm 550             | 1370 \pm 340             |
| 1.6 \times 10^{13}   | 1130 \pm 100             | 1430 \pm 310             |

\nonumber 2 \text{ Strictly the masses of two merging BHs are not conserved, but will be lower by a few per cent, as gravitational waves can radiate away some of the BH rest mass energy. In the following we assume that this effect only changes our results by a negligible amount, although the mass loss through gravitational radiation accumulated in many mergers for some MBHs may become significant.}
Figure 3. Radial distribution of MBHs for the case of 260-\(M_\odot\) seed MBHs. The left panel shows the differential distributions for all (top set of curves) MBHs and those with masses above 10^4 \(M_\odot\) (middle) and 10^5 \(M_\odot\) (bottom) for the 1.612-\(M_\odot\) halo. The same but only for ‘naked’ MBHs is shown by the dotted lines. The total number of MBHs within a given distance from the host centre is shown on the right for all final halo masses where distances have been scaled to the virial radius of the respective halo.

Table 2. Abundance of MBH in Earth-centred volumes at 8.5 kpc from the galactic centre in the Milky-Way-sized halo (1.6 × 10^{12} \(M_\odot\)). We give the average over 30 trees with their respective variance.

| \(M_\odot\), seed \(M_\odot\) | Distance from Earth \(\Delta r\) (kpc) | 2.0 | 2.5 | 3.0 |
|--------------------------|-----------------------------|-----|-----|-----|
| 0.260 \(M_\odot\)       | 1.12 ± 0.6                  | 2.16 ± 1.12 | 3.64 ± 1.67 |
| 1.300 \(M_\odot\)       | 1.07 ± 0.53                 | 2.21 ± 1.09 | 3.94 ± 1.89 |

Table 3. SMBH mass and total mass contained in halo MBH averaged over 30 trees.

| Model  | \(M_\odot\), seed \(M_\odot\) | \(\Sigma M_{\text{MBH}} \ [M_\odot]\) | \(M_{\text{SMBH}} \ [M_\odot]\) |
|--------|-----------------------------|-----------------------------|-----------------------------|
| 1.6 × 10^{10} | 260 \(M_\odot\) | (4.9 ± 0.9) × 10^4 | (1.7 ± 0.7) × 10^4 |
| 1.6 × 10^{11} | 260 \(M_\odot\) | (3.4 ± 1.5) × 10^5 | (1.9 ± 1.0) × 10^5 |
| 1.6 × 10^{12} | 260 \(M_\odot\) | (2.5 ± 0.7) × 10^6 | (9.2 ± 6.2) × 10^5 |
| 1.6 × 10^{13} | 260 \(M_\odot\) | (5.7 ± 0.8) × 10^6 | (1.7 ± 0.9) × 10^6 |
| 1.6 × 10^{13} | 1300 \(M_\odot\) | (2.3 ± 0.7) × 10^7 | (9.0 ± 3.5) × 10^6 |
| 1.6 × 10^{14} | 260 \(M_\odot\) | (2.6 ± 0.5) × 10^8 | (8.4 ± 4.6) × 10^7 |

than two MBHs and thus the possibility of sling-shot ejections. In other words some fraction of MBHs, although having travelled to the centre quickly, might eventually end up being expelled rather than merging. This has implications for the most massive trees. Haloes at the resolution limit in these trees have a mass above \(M_{\text{min}}\) and therefore might appear in the tree with several seed MBHs which we have thus far assumed have merged to form one MBH (cf. Section 3.2). This may no longer be the case if sling-shot ejections occur. Assuming that in this case the lightest MBHs are ejected, however, this should not significantly reduce the mass of the central MBH.

We can also ask what happens if those MBHs that have crossed into the merger region of the host do not actually merge at all but keep orbiting on only mildly radial orbits with associated long orbital decay time-scales. We will subsequently refer to this as the ‘no-merger’ scenario. The first and most crucial consequence of this is that a SMBH grown through hierarchical mergers of these MBHs would not exist in the first place. Instead the SMBH mass would simply add to the total mass contained in halo MBHs. In Fig. 4 we show the mass function of MBHs that have fallen into the merger region, and which in the no-merger scenario would just remain orbiting there. Their total number is about a quarter that of the MBHs in the haloes as given in Table 1.
4 DETECTIONS

4.1 X-rays

An abundance of MBHs as determined above should be detectable in various ways. First and foremost, we expect these MBHs to be sources of X-rays. These could arise as a result of accretion from the interstellar medium (ISM) as it moves through the host halo (Fujita et al. 1998). This effect is only expected to be large for MBHs travelling through the disc or bulge at relatively low speeds. However, above we have seen that by far most MBHs are actually in the halo and not in either the bulge or disc. In this case, the number of significant MBH X-ray sources is therefore expected to be rather low.

We have estimated this using the Bondi–Hoyle (Bondi & Hoyle 1944; Bondi 1952) mass accretion rate and the standard radiative efficiency for thin disc accretion, $\eta = 0.01$. The resulting bolometric luminosity function is shown in Fig. 5. Depending on the accretion model, e.g. advection or convection dominated accretion flows (ADAF or CDAF; Manmoto, Mineshige & Kusunose 1997; Ball, Narayan & Quataert 2001), X-rays will account for 5 to 30 per cent of this luminosity. Most of the very luminous sources are ‘naked’ MBHs, i.e. in tidally stripped satellites, which implies that they must be orbiting at relatively small distances from the host centre and therefore in or close to the bulge region.

Another more likely scenario is that most MBHs will actually remain embedded in a dense baryonic core remnant of their original satellite halo. If this core had formed within a satellite before it entered the host, then it is likely to survive in the host gravitational tidal field even though most of satellite’s dark matter may be tidally stripped. Our calculations indicate that with this ‘portable fuel supply’ travelling along with the MBH, accretion rates can be much higher. In particular, we have assumed that the core is a constant density sphere with a radius that is about 10 per cent the virial radius of the original satellite and contains all its baryonic mass. Applying the Bondi–Hoyle accretion formula to this with a smaller radius of the original satellite and contains all its baryonic mass.

Figure 5. Bolometric luminosity function for MBHs accreting from the halo ISM. Results are shown for the $1.6 \times 10^{12} M_\odot$ halo and all as well as only naked MBHs. Upper and lower data sets are for $M_{*,\text{seed}} = 260$ and $1300 M_\odot$, respectively. The left panel shows the luminosity functions for $M_{*,\text{seed}} = 260 M_\odot$ and all final halo masses. In all cases the radiative efficiency is $\eta = 0.001$.
in fact be the only way to detect of the order of 100–1000 MBHs in the central kpc. Detection by gravitational waves, in comparison, is more straightforward. Detection rates for hierarchically merging central SMBHs could be calculated out to redshifts larger than 100, if MBHs did exist there (Haehnelt 1994; Menou et al. 2001) and depend sensitively on the merger history and abundance and distribution of seed BHs. In principle, MBHs falling into the centre and merging with the central SMBH will produce gravitational wave events in addition to those arising from mergers between central SMBHs in the wake of major halo mergers. In fact, in our model the number of MBH–central SMBH mergers is expected to be higher than this, because between any two galaxy mergers with corresponding mergers of their central SMBHs there are a number of MBHs that fall to the centre and coalesce with the central SMBH. The latter have a lower gravitational wave amplitude because of the very different masses of MBH and SMBH, and detection of these events is therefore limited to lower redshifts. But detection should still cover the range up to $z \sim 20$, which is where the haloes of the seed MBHs in our model would undergo their first mergers.

5 SUMMARY AND DISCUSSION

We have used a semi-analytical approach to track the merger history of MBHs and their associated dark matter haloes, as well as the subsequent dynamical evolution of the MBHs within the new merged halo. In particular, we have looked at the possibility that MBHs, which are the remnants of massive Population III stars, forming in low-mass haloes at redshifts $z \sim 24$, could hierarchically build up to contribute to the present-day abundance of central galactic SMBHs. If this is the case, then a number of remnant MBHs are expected to orbit inside galactic haloes. Although our analysis has been carried out for one of the currently favoured $\Lambda$CDM cosmological models, we expect our findings to hold for any model that provides for hierarchical structure formation such as CDM models in general, but notably excluding warm dark matter and other models with a cut-off or discontinuity at some specific scale in their corresponding cosmological matter power spectrum.

The main findings of our analysis are:

(i) For Milky-Way-sized galaxies, of the order of $10^3$, MBHs that have not reached the host centre are expected to orbit within the halo. Around 1/3 of these will be seed mass MBHs, 85 per cent of these MBHs with masses up to $10 \times M_{\text{seed}}$.

(ii) For a seed MBH mass of $260 \, M_\odot$ ($1300 \, M_\odot$) some 5 to 8 (2 to 3) MBHs with masses above $10^5 \, (10^6) \, M_\odot$ are expected in the halo of Milky-Way-sized galaxies.
(iii) Hierarchical merging of seed MBHs with masses of $M_\bullet \sim 10^2 M_\odot$ forming in haloes collapsing from $3\sigma$ peaks in the matter density field at $z \sim 24$ can contribute up to 10 per cent to the present-day mass density contained in the SMBH. Another mechanism for the SMBH to gain mass, such as gas accretion, appears inevitable.

(iv) Depending on the size of a baryonic core remnant around the MBHs, they could be significant sources of X-rays and possibly account for the ultraluminous off-centre X-ray sources that have been found in a number of galaxies. Accretion from the host ISM is probably not important.

We find that the mass functions for all seed MBH masses considered are essentially the same and only shifted along the mass axis proportional to the mass of the seed MBHs. This is because it is the mass of the satellite haloes and not that of the MBHs that dominates their dynamical evolution in a host halo.

Our findings are consistent with the results of another recent investigation by Volonteri et al. (2003). We find that the total mass density in a Milky-Way-sized galactic halo is about a factor of 10 higher than their value inferred from the density function of ‘wandering’ BHs in galactic haloes. This is what we would expect on the basis of the difference in seed BH masses and the height of the peaks where initial collapse occurred (their $3\sigma$ versus our $3\sigma$).

Furthermore, we find the mass of a central SMBH in a Milky-Way-sized halo to be $1.7 \times 10^5 M_\odot$. Accounting for the difference in seed MBH masses used, this agrees to within a factor of 2 with the central SMBH mass of $\sim 5 \times 10^5 M_\odot$ for a galaxy-sized halo ($\sigma \sim 100 \text{ km s}^{-1}$) as implied by their $M_\bullet - \sigma$ relation (with no gas accretion). This also happens to coincide with the mass determined for the SMBH in the Milky Way, although the Milky Way SMBH is known to lie significantly below the observed $M_\bullet - \sigma$ relation.

However, the slightly non-linear $M_\bullet - M_{\text{gal}}$ correlation corresponds to a $M_\bullet - \sigma$ relation whose logarithmic slope ($\sim 4.0$) does not match the much flatter one Volonteri et al. determined ($\sim 2.9$) for $3\sigma$ collapse and no gas accretion. We believe this to be primarily a result of the different assumptions made about the MBH merger process. In particular, the inclusion of triple BH interactions and slingshot ejections, that they find, would probably lead to even lower central SMBH masses in our analysis.

While the fiducial model of Volonteri et al. is based on the collapse of $3.5\sigma$ peaks and a seed MBH mass of $150 M_\odot$, we consider $3\sigma$ peaks and a higher mass for the seed MBHs, both of which imply a higher mass density in MBHs at high redshift. This in turn means that less gas accretion on to MBHs is needed to match the $M_\bullet - M_{\text{gal}}$ that is actually observed in nearby galaxies. In any case, even for our lightest seed MBH mass considered, any resulting central galactic SMBH in our analysis would need to accrete at least 50–100 times its own initial mass to match the observed relation. This agrees with a number of studies – see, for example, Yu & Tremaine (2002) and references therein – that find the present-day SMBH mass density to be consistent with the amount of gas accreted during the optically bright QSO phase. On the other hand, gas accretion during the QSO phase alone cannot explain growth from stellar mass BHs to the most massive SMBHs ($\gtrsim 10^9 M_\odot$). Even if stellar mass BHs are accreting at the Eddington limit, the QSO phase would not last long enough to accommodate the required number of e-folding times for the BHs to grow to SMBH size. The need for intermediate mass seed BHs and/or some merging of MBHs/SMBHs is therefore necessary to explain the presence of the most massive SMBHs.

Our numerical results depend on a number of parameters that are not yet well constrained, notably the exact height of the fluctuations in the matter density field that are supposed to collapse to form the first baryonic objects and the IMF of metal-poor stars forming inside these. While the former could possibly be determined better by improved numerical simulations, we have shown that, particularly for the abundance of MBHs in the halo, our results hold qualitatively for a wide range of different IMFs.

If the halo MBHs could be uniquely identified by their X-ray emission or otherwise, then within the context of our model they could also be used to tag (remnants of) the substructure orbiting in a galactic halo. In this way they would complement counts and location of dwarfs and star clusters as measures of the substructure in the galaxy and the halo.

Our results for the growth and present-day mass of the central SMBHs do depend sensitively on how efficiently MBHs merge at the host centre. Here we have taken the view that, during major mergers, any MBHs orbiting within the core region of the host will be dragged towards the central SMBH quickly, aided by the massive inflow of gas. Due to the increased non-homogeneity, violent dynamical evolution and departure from spherical symmetry during this phase, analytical estimates of dynamical time-scales presumably overestimate the time required for MBHs to travel to the centre.

However, a more detailed analysis of this process will be required for the calculation of event rates of mergers between central and inspiralling MBHs and the accompanying gravitational wave emission.

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