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Citation
O’Leary, Ryan M., and Abraham Loeb. 2009. “Star Clusters around Recoiled Black Holes in the Milky Way Halo.” Monthly Notices of the Royal Astronomical Society 395 (2): 781–86. https://doi.org/10.1111/j.1365-2966.2009.14611.x.

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Star clusters around recoiled black holes in the Milky Way halo

Ryan M. O’Leary* and Abraham Loeb*

Department of Astronomy, Harvard University, 60 Garden St., Cambridge, MA 02138, USA

Accepted 2009 February 9. Received 2009 January 7; in original form 2008 September 24

ABSTRACT

Gravitational wave emission by coalescing black holes (BHs) kicks the remnant BH with a typical velocity of hundreds of km s\(^{-1}\). This velocity is sufficiently large to remove the remnant BH from a low-mass galaxy but is below the escape velocity from the Milky Way (MW) galaxy. If central BHs were common in the galactic building blocks that merged to make the MW, then numerous BHs that were kicked out of low-mass galaxies should be freely floating in the MW halo today. We use a large statistical sample of possible merger tree histories for the MW to estimate the expected number of recoiled BH remnants present in the MW halo today. We find that hundreds of BHs should remain bound to the MW halo after leaving their parent low-mass galaxies. Each BH carries a compact cluster of old stars that populated the core of its original host galaxy. Using the time-dependent Fokker–Planck equation, we find that the present-day clusters are \(\lesssim 1\) pc in size, and their central bright regions should be unresolved in most existing sky surveys. These compact systems are distinguishable from globular clusters by their internal (Keplerian) velocity dispersion greater than 100 km s\(^{-1}\) and their high mass-to-light ratio owing to the central BH. An observational discovery of this relic population of star clusters in the MW halo would constrain the formation history of the MW and the dynamics of BH mergers in the early Universe. A similar population should exist around other galaxies and may potentially be detectable in M31 and M33.

Key words: black hole physics – gravitational waves – galaxies: kinematics and dynamics – galaxies: nuclei.

1 INTRODUCTION

During the final coalescence of two black holes (BHs), gravitational waves (GWs) are emitted unisotropically and carry away linear momentum, thus kicking the merger BH remnant in the opposite direction (Peres 1962; Bekenstein 1973; Fitchett 1983). The resulting kick velocity of typically hundreds of km s\(^{-1}\) depends on the mass ratio of the BHs as well as the spin and orientation of the binary before coalescence (Baker et al. 2006; Campanelli et al. 2007a,b; Tichy & Marronetti 2007). Such kicks can alter both the population of nuclear BHs in galactic bulges (Madau & Quataert 2004; Libeskind et al. 2006; Schnittman 2007; Volonteri 2007; Blecha & Loeb 2008) as well as the core of stars in the bulge itself (Gualandris & Merritt 2008). The discovery of a remnant population of recoiled BHs in the present-day Universe can provide a new window into the merger statistics and spin distribution of the BHs (Libeskind et al. 2006; Volonteri 2007), as well as test general relativity in the strong regime.

Recoiling BHs may be detected through their unique flaring (Lippai, Frei & Haiman 2008; Schnittman & Krolik 2008; Shields & Bonning 2008) or observed as spatially and kinematically offset quasars (Madau & Quataert 2004). If the BH binary was surrounded by an accretion disc, the ejected remnant BH would carry the disc with it and shine as a quasar (Loeb 2007). A search for spectral shifts in the broad lines of quasars relative to the narrow emission lines of their parent galaxies resulted mainly in upper limits (Bonning, Shields & Salvatier 2007), and possibly one suggested candidate (Komossa, Zhou & Lu 2008) for an ejected quasar. Unfortunately, these quasars lose their source of gas for accretion and have short lifetimes (Loeb 2007; Blecha & Loeb 2008; Volonteri & Madau 2008).

Past studies of the observational consequences of GW recoil have generally focused on massive BHs with a mass \(M_\bullet \gtrsim 10^7\) M\(_\odot\). Such BHs reside in the most massive galaxies, and require the greatest and rarest kick velocities in order to escape their parent galaxies (Schnittman & Buonanno 2007). But since the kick velocity from BH mergers is independent of the total mass of the system, the dynamical consequences are most prominent for less massive BHs which tend to reside in low-mass galaxies with shallower potential wells and lower escape velocities (Madau & Quataert 2004; Volonteri & Perna 2005; Baker et al. 2006; Libeskind et al. 2006; Volonteri 2007; Tanaka & Haiman 2008). In fact, most BHs with \(M_\bullet \lesssim 10^5\) M\(_\odot\) will likely be kicked out of their parent galaxies as...
a result of major mergers (Baker et al. 2006). During the hierarchi-
ical build-up of the Milky-Way (MW) galaxy, mergers of low-mass
galaxies were common and should have resulted in a population of
freely floating BHs (Volonteri & Perna 2005). Since the gravita-
tional potential of an overdense region does not evolve dramatically
during the growth of cosmological structure (Loeb 2006), the region
that eventually collapsed to make the MW was able to trap those
BHs with the most common kick velocities (≤500 km s⁻¹) even
before the MW had formed. Each of the ejected BHs carries with it
a star cluster that used to populate the core of its parent galaxy
(Gualandris & Merritt 2008; Komossa et al. 2008). In this paper,
we examine the observational signatures of the ejected star clusters
which are expected to be floating in the MW halo. The discovery of
a relic population of the star clusters attached to recoiled BHs would
provide a new window for cosmology, allowing one to constrain the
merger history of the MW as well as the formation history of the
first population of massive BHs.

Previous studies have looked at populating the MW halo with
recoiling BHs as analysed again here (Madau & Quataert 2004;
Volonteri & Perna 2005; Libeskind et al. 2006), through three body
encounters (Volonteri & Perna 2005), as well as a variety of other
processes. Other sources of wandering BHs are the remnants of
Population III stars (Islam, Taylor & Silk 2003; Zhao & Silk 2005)
as well as the direct collapse of baryons into a BH (Bertone, Zentner
& Silk 2005; Mapelli, Ferrara & Rea 2006). In both of these cases,
however, the BH either is presently located in the centre of a galaxy
or is ‘naked’ without any stellar companions. Such BHs are only
likely to be located by their interaction with the matter that surrounds
them (Islam, Taylor & Silk 2004b; Bertone, Zentner & Silk 2005;
Mii & Totani 2005; Volonteri & Perna 2005). Additionally, dwarf
galaxies may be tidally stripped of their outer stars, leaving behind
a BH surrounded by a massive cluster of stars similar to some globular
clusters (Zinnecker et al. 1988; Bassino, Mazzio & Rabolli 1994).

In contrast, the new source of BHs presented in this paper uniquely
have a population of bound stars that are only a fraction of the mass
of the central BH.

In Section 2, we consider the formation history of the MW to
estimate the number and distribution of ejected BHs that may be
found in its halo today. We then follow the long-term evolution of
the star clusters that are attached to them in Section 3. In Section 4,
we discuss the observational signatures of these systems. Finally,
Section 5 summarizes our main results and their implications.

2 THE MERGER HISTORY OF THE MW
AND EJECTED BHs IN THE HALO

In the standard cosmological context of hierarchical galaxy forma-
tion (Springel et al. 2008a), the MW formed from an overdense
region of the universe with a present-day virial mass $M_{\text{gal}} \approx 1-2 \times 10^{12} M_\odot$ (Klypin, Zhao & Somerville 2002; Li & White 2008).
The threshold for cooling by atomic transitions limits the minimum
mass of star forming galaxies at high redshifts to $M_{\text{gal}} \sim 10^9 M_\odot$
(Wyithe & Loeb 2006). If the earliest population of star-forming
galaxies had BHs at their centre, then their shallow potential would
be insufficient to retain the recoiling BHs after mergers with a BH
mass ratio $q \equiv (M_{\text{gal}} / M_{\text{bh}}) \gtrsim 0.1$. Nevertheless, since most kicks
are modest (≤500 km s⁻¹), the ejected BHs remain confined to the
MW.

We estimate the number of BHs in the MW halo, $N_{\text{bh}}$, by
analysing a large statistical ensemble of possible merger tree his-
tories for the MW using analytic models for the distribution of
kick velocities and galaxy profiles. In particular, we generate ≥10³
Monte Carlo realizations of the merger history of the MW galaxy
with the merger tree code made publicly available by Parkinson,
Cole & Helly (2008). This code follows a modified form of the
extended Press & Schechter (1974) formalism and is normalized
to match the Millennium run numerical simulation (Springel et al.
2005; Cole et al. 2008). We assume that the MW has a mass of
1.5 × 10^{12} M_\odot and restrict our simulations to formation scenarios
in which the MW undergoes no major mergers ($q > 1/3$) since a
redshift $z = 1$ (Diemand, Kuhlen & Madau 2007).

We determine the properties of the halo from its circular velocity
at the virial radius (Barkana & Loeb 2001),

$$v_c = 24 \left( \frac{M_{\text{gal}}}{10^9 h^{-1} M_\odot} \right)^{1/3} \left( \frac{\Omega_m}{\Omega_\Lambda} \right)^{1/6} \left( \frac{\Delta_c}{18\pi^2} \right)^{1/6} \left( \frac{1 + z}{10} \right)^{1/2} \text{km s}^{-1} ,$$

where $\Delta_c = 18\pi^2 + 82d - 39d^2$, $d = \Omega_m - 1$, $\Omega_m = (\Omega_m(1 + z)^3/\Omega_m(1 + z)^3 + \Omega_\Lambda)$, evaluated at the merger redshift $z$ and we adopt the values for the cosmological density parameters, $\Omega_m$ and $\Omega_\Lambda$, used in the Millennium run (Springel et al. 2005). In each
galaxy, we assume that the dark matter follows an Navarro-Frenk-
White (NFW) radial profile (Navarro, Frenk & White 1996) with a
concentration parameter $c = 4$ out to the virial radius, as expected
for a newly formed dark matter halo (Wechsler et al. 2002). In this
case, the escape velocity from the galaxy’s centre is $v_{\text{esc}} \approx 2.8 v_c$.
We scale the stellar velocity dispersion of the bulge in the low-mass
galaxies similarly to the MW and adopt $\sigma = v_c / 2$. The BH mass
in the centre of each galaxy is then dictated by the observed $M_\bullet - \sigma$
relation (Tremaine et al. 2002):

$$M_\bullet = 8.1 \times 10^7 M_\odot \left( \frac{\sigma}{100 \text{ km s}^{-1}} \right)^4 .$$

We assume that the merger of the BHs is efficient, occurring before
a third BH is introduced into the system, and that the remnant
BH mass is $M_{\text{bh, final}} = M_{\text{bh,1}} + M_{\text{bh,2}}$. Although the $M_\bullet - \sigma$
relation was initially determined from the analysis of more massive BHs,
Barth, Greene & Ho (2005) and Greene & Ho (2006) have found that
it consistently extends to active galactic nuclei with BHs with masses
∼10^8 M_\odot, even without classical bulges (Greene, Ho &
Barth 2008).

For each merger tree, we randomly assign a kick velocity from
analytic models of the kick velocity distribution of Schnittman &
Buonanno (2007) assuming that all the BHs have the same spin
with two different values: $a = 0.1$ and 0.9. A BH is ejected from
its host galaxy if its kick velocity is larger than the escape velocity,
v_{k} > v_{\text{esc}}$, and remains in the larger potential of the MW if the
final velocity is less than the escape velocity of the MW halo,
v_{ej} = \sqrt{v_k^2 - v_{\text{esc}}^2} \lesssim 500 \text{ km s}^{-1}$. Although the MW escape velocity
evolves by tens of percent as the MW halo assembles,¹ we neglect
this evolution in our analysis.

In our realizations of the MW merger tree, there were an average
of ≈1500 galaxy mergers for each run. Of these, ≈700 were major
mergers with $q > 0.1$. For BHs with spin $a = 0.9$ ($a = 0.1$),
GW recoil ejected ≈570 (∼440) BHs from their parent galaxy and
$N_{\text{bh, parent}} \approx 330$ (∼440) remained within the MW halo. In all of our
simulations, the average kick velocity, even for the most massive
BHs ejected, is comparable to or less than the present day velocity

¹ The gravitational potential does not evolve during the linear growth of
perturbations at redshifts $z \gtrsim 1$, and is only modestly enhanced in the final
collapse of galaxy haloes (Loeb 2006).
The cumulative distribution of ejected star clusters in the MW halo would be visible to the depth of Sloan Digital Sky Survey (SDSS). The mass distribution of the ejected BHs has approximately equal number per log $M_\star$ interval, with $dN_{\text{BH}}/dM_\star \propto M_\star^{-1}$.

dispersion of the halo $\lesssim 200$ km s$^{-1}$. Thus, we expect that most of the BHs trace the distribution of the dark matter in the halo. This is consistent with the results of Libeskind et al. (2006) who used $N$-body simulations to follow the kicked BHs in MW halo. The BHs which were not ejected from their host galaxies settle back into the core of galaxies owing to dynamical friction, however, the vast majority of these galaxies have since merged to form the MW.

In Fig. 1, we plot the cumulative flux distribution of the remnant BHs, assuming that the BHs follow the present-day NFW profile of the MW with $c = 12$ and $r_{\text{vir}} = 200$ kpc (Klypin et al. 2002; Li & White 2008). We determine the luminosity from equation (6) in Section 3, and report the flux in units of the flux from the Sun if it were at a distance of 1 kpc, $f_{\text{NFW} \text{- kpc}}$, and also the apparent bolometric magnitude (top axis). Assuming that these clusters lose little mass, we expect that nearly all remnant BHs with mass $M_\star \gtrsim 2 \times 10^5 M_\odot$ in the MW halo would be visible to the depth of Sloan Digital Sky Survey (SDSS).

In all our models, we find the mass distribution of the ejected BHs to scale roughly as $dN_{\text{BH}}/dM_\star \propto M_\star^{-1}$ (with the $a = 0.1$ case showing a slightly steeper distribution on the high-mass end of BHs). The most massive BH present in the halo is $6.3^{+5.2}_{-2.7} \times 10^5 M_\odot$ for $a = 0.9$ and $1.7^{+0.8}_{-0.5} \times 10^6 M_\odot$ for $a = 0.1$, where the quoted uncertainty represents the one standard deviation. The closest BH that has an apparent magnitude $< 21$th, the approximate depth of SDSS, has an average mass of $\sim 3 \times 10^5 M_\odot$ and is $\sim 1$ kpc away. For the typical distances and masses of the BHs, dynamical friction is negligible over the age of the universe. For example, the dynamical friction time-scale of a $\sim 10^5 M_\odot$ BH is $\gtrsim 10^9$ yr at even $\sim 1$ kpc from the galactic centre (Binney & Tremaine 1987).

![Figure 1. The cumulative distribution of ejected star clusters in the MW halo. Plotted is the flux distribution associated with BHs masses greater than $10^3 M_\odot$ (black), $10^4 M_\odot$ (blue) and $10^5 M_\odot$ (red), in our models with BH spin $a = 0.1$ (solid) and $a = 0.9$ (dashed) lines, plotted in units of the flux of the Sun at a distance of 1 kpc ($f_{\text{NFW} \text{- kpc}}$). The top axis is labelled with the apparent bolometric magnitude of the clusters. Nearly all BHs with $M_\star \gtrsim 2 \times 10^5 M_\odot$ have apparent magnitudes greater than 21, the rough magnitude limit of SDSS. The mass distribution of the ejected BHs has approximately equal number per log $M_\star$ interval, with $dN_{\text{BH}}/dM_\star \propto M_\star^{-1}$.](https://academic.oup.com/mnras/article-abstract/395/2/781/1746998)
frame of the BH, all stars receive kicks with a reflex velocity $-v_k$. Stars with total energies $\geq -m_*v_k^2/2$ will become unbound to the BH. In the Keplerian potential of the BH, this roughly corresponds to stars at $r \geq r_k = \sqrt{\frac{GM_*}{v_k^2}} = (\sigma/v_k)^2 r_i$. The total number of stars that remain bound the BH is then

$$N_\alpha \approx \frac{2M_*}{m_*} \left( \frac{\sigma}{v_k} \right)^{2-\alpha}.$$  \hspace{1cm} (6)

For $\alpha = 1.75$, the total number of stars that remain bound for a minimally ejected BH with $v_k = 5.6\sigma$, is then $\sim 4 \times 10^4 (M_* / 10^3 M_\odot)$. The actual number of stars may be less due to the ejection of stars by the BH binary inspiral (Merritt & Szell 2006; Merritt et al. 2007). These stars will mainly remain within a radius $r_k \approx (\sigma/v_k)^2 r_i \ll 1$ pc, and have a $\alpha = 4$ profile for $r \gg r_k$ (Komossa & Merritt 2008). Given the short relaxation time-scale of the star cluster and the lack of a source of new stars, the star cluster will expand.

We determine the long-term evolution of the ejected cluster by numerically solving the time dependent, angular momentum averaged, Fokker–Planck equation for stars around a central massive object (Bahcall & Wolf 1976, 1977):

$$\frac{\partial g(x, \tau)}{\partial \tau} = -x^3 \frac{\partial^2}{\partial x^2} \frac{g(x)}{R(x)} - J(x), \hspace{1cm} (7)$$

where $x = -E/(m_*\sigma^2)$ is the dimensionless energy, $\tau = t/t_i$ is the dimensionless time, $g(x, \tau) = 1/[(2\alpha)^3/2 \sigma^2] f(E)$ is the dimensionless distribution function of the stars, $Q(x)$ is the rate stars flow to energies larger than $x$, and $R(x)$ is the tidal disruption rate of stars by the BH (Komossa & Merritt 2008). In these units, $Q(x) = \int_{-\infty}^{\alpha} \frac{dy}{\sqrt{2\pi}} e^{-(x+y)^2/2}$ and $R(x) = \frac{\int_{-\infty}^{\alpha} dx}{\ln J(x)/J(x)}$, \hspace{1cm} (8)

where $J(x) = G M_* \sigma^{-1}(2x)^{-1/2}$ is the angular momentum of a circular orbit at a radius $r \approx r_i/(2x)$ and $J(x)$ is the maximum angular momentum for the star to be destroyed or consumed by the BH. For a star of radius $r_i$, $J(x) = G M_* \sigma^{-1} x_{\sigma}^{-1/2} [2(x + x_{\sigma})]^{-1/2}$, where $x_{\sigma} \approx (M_* / m_*)^{1/3} r_i / R$. We assume that far from the BH, the stars initially follow a Maxwellian distribution with dispersion $\sigma_x$. In dimensionless units, the distribution function of the unbound stars is just $g(x) = \exp(x)$ for $x > 0$. For a power-law distribution function with $g(x) \propto x^p$, the density profile of the stars will also follow a power-law $n_x \propto r^{-4p}$, with $\alpha = -p - 3/2$.

We have performed two sets of calculations, first for a binary that merges because of stellar relaxation and then for a gas rich merger. For the first case, we evolved the system for one relaxation time-scale, at which point the system has reached steady state, and then we removed all unbound stars by setting $g(x) = 0$ for $x > 0$. The initial kick on the system breaks the spherical symmetry assumed here. However, after a relaxation time-scale, we expect the system to reach spherical symmetry again. To represent the kick on the bound stars, we scale the distribution function of stars as $g(x) \rightarrow g(x) x^{\gamma} / \left(1 + x^{\gamma} \right)$, where $\gamma = x_i/(v_k/\sigma_x)^2$. This yields an asymptotic density profile with $n \rightarrow r^{-4}$ for $r \gg r_k$, as expected immediately after the kick (Komossa & Merritt 2008). To examine the evolution of the star system if the BHs coalesce through a gas rich merger (Callegari, Mayer & Kazantzidis 2008), we adopt $g(x) \propto x^{1-\gamma/2} / (1 + x^{\gamma/2})$, normalized by the same number density and relaxation time-scale used in equation (3). This yields $\alpha \sim 1$ for $r \leq r_h$ and $\alpha \sim 4$ for $r \gg r_h$, as expected following a merger (Merritt & Szell 2006; Merritt et al. 2007). This run results in $\sim 10$ per cent of the number of bound stars as with $\alpha = 1.75$. Its importance, however, is uncertain given the short relaxation time-scales for these systems.

Shortly after the GW recoil kicks the BH, the star cluster expands as a result of two-body relaxation and evolves until the relaxation time-scale of the cluster becomes comparable to the age of the system. Fig. 2 shows the evolution of the projected number of stars interior to a radius $r$ for a BH with mass $10^3 M_\odot$ for both $\alpha = 1.75$ and $\alpha = 1$ density profiles. Since our simulations indicate little mass loss, the condition that the relaxation time-scale of the system (equation 3) be comparable to the age of the Universe implies that the cluster should expand by a factor of order $(t_\tau/t_f)^{1/2} \sim 10$. Even then, the present day cluster size is less than the initial radius of influence of the BH, $r_i \ll 1$ pc, and much smaller than the tidal radius of the system, distinguishing them from globular clusters with a similar stellar mass (owing to the gravitational binding provided by the central BH).

In our simulations, there is very little mass loss due to the tidal disruption of stars or the ejection of stars from the system. Since the cluster expands so rapidly, the rate of tidal disruption of stars rapidly decreases, and is much lower than the rate associated with a comparable BH in the nucleus of a galaxy.

Our simulations only treat the evolution of the cluster due to many small-angle scatterings (two-body relaxation), and does not include the strong scattering that might occur in a dense stellar environment. Such scatterings would launch stars on eccentric orbits that take them outside of the cluster to about the tidal radius, thus enhancing the mass loss from the system. The existence of a halo of such stars provides an additional signature unique to the compact star clusters associated with recoiled BHs. We also ignore the effects of resonant relaxation, which can deplete the number of stars both before and after the ejection of the BH (Rauch & Tremaine 1996; Rauch & Ingalls 1998). Although resonant relaxation has been approximately accounted for in equation (7) by averaging over angular momentum (Hopman & Alexander 2006a), a full multidimensional accounting for angular momentum is best suited for these clusters.

4 OBSERVING EJECTED SYSTEMS

Size and Structure. Based on the results in Section 2, we estimate that there should be $\sim 300$ recoiled BHs in the MW halo. Equation (6) implies that these BHs are surrounded by $\sim 4 \times 10^3 (M_* / 10^3 m_*)$ stars with a half mass radius, $r_h \lesssim 1$ pc. At the typical distance to the most massive recoiled BH, $\sim 100$ kpc, the cluster will have a typical angular size $\lesssim 1$ arcsec, below the resolution limit of most existing sky surveys. Thus, the cluster will appear as a point source and might be confused as a single foreground star with unusual colours. The closest clusters are $\sim 1$ kpc away and may be a few arcmin in size. However, these clusters surround the smallest BHs ($\sim 10^3 M_\odot$) with the fewest number of stars, and their present day distribution is uncertain owing to strong encounters between the stars in the cluster as well as stars in the disc. To date, no star cluster has been identified in the MW with such a small size; the smallest star cluster discovered has a size of $\sim 3$ pc (Koposov et al. 2007). Clusters at distances of tens of kpc could in principle be distinguished from point sources by comparing their extended image to the point-spread-function of the telescope. In comparison, the stellar mass of globular clusters and the tidally stripped cores of dwarf galaxies completely outweighs the total mass of any central BH in such systems. By measuring the total mass of stars, one can approximately determine how large the kick velocity may have been.
Recoiled BHs in the Milky Way

Colour. A recoiled star cluster can be distinguished from single foreground stars by its anomalous colour. The cluster is likely old, \(~1\)–\(10\) Gyr, and to first order should have colours similar to globular clusters of a similar age and metallicity.

Spectra. The velocity dispersion profile of the ejected star clusters should be Keplerian. The unusually large width of their spectral lines (greater than 100 km s\(^{-1}\)) can be used to distinguish these clusters from foreground stars, which possess much lower rotational velocities.

The compact star clusters around ejected BHs are distinguishable from cores of globular clusters by their internal (Keplerian) velocity dispersion of order 100 km s\(^{-1}\) and their high mass-to-light ratio owing to the central BH.

Proper motion. The most massive systems that reside near the virial radius of the galaxy and have a relatively small proper motion. Nevertheless, future surveys like GAIA\(^3\) Pan-STARRS\(^4\) and LSST\(^5\) could aim to measure the proper motion of such clusters, and be used in conjunction with expected cluster colours to distinguish the clusters from foreground stars. The expected proper motion of these clusters is \(~10^{-3}\) arcsec yr\(^{-1}\).

The local group. Given the constrained distances to M31 and M33, colour–magnitude diagrams could be used to identify candidate star clusters around ejected BHs, and spectroscopic follow-up could reveal the high dispersions expected from the stars very near the BH. At the distance of M31, a cluster with \(r_\odot \sim 0.5\) pc would have an angular size of \(~0.1\) arcsec, and could in principle be resolved by HST\(^6\), JWST\(^7\) or ground-based telescopes with adaptive optics.

Gas accretion. A faint radio glow from the central BH may also be detectable as it accretes material from stellar winds in the surrounding cluster of stars (Loeb 2004). Rarely, these BHs may accrete gas from the interstellar medium or molecular clouds as they pass through the disc of the galaxy (Fujita et al. 1998; Islam et al. 2003; Mii & Totani 2005; Volonteri & Perna 2005; Mapelli et al. 2006); however, for the number of BHs expected in the MW, such a scenario is unlikely to be observed (Volonteri & Perna 2005).

Dark matter annihilation. The recoiled BHs may be surrounded by a dense cusp of dark matter, which was adiabatically compressed by the baryonic condensation and BH growth in its parent low-mass galaxy. These high-density cusps can dramatically increase the rate of dark matter annihilation and may be visible through the relativistic by products of the annihilation (Bertone et al. 2005; Zhao & Silk 2005; Springel et al. 2008b).

5 SUMMARY AND DISCUSSION

Based on a large statistical ensemble of merger tree histories for the MW, we have found that hundreds of GW recoiled BHs should reside within the MW halo today. The BHs have a mass \(M_\odot \gtrsim 10^5 M_\odot\), and should be surrounded by a cluster of stars that were tightly bound to the BH when it was ejected. The most massive BH weighs \(~1\)–\(6 \times 10^5 M_\odot\), and is surrounded by a compact star cluster \(~1\) pc in size with a stellar velocity dispersion of hundreds of km s\(^{-1}\). High-resolution adaptive optics imaging along with spectroscopy of the star clusters can constrain the distance and mass of the BH in the centre of the cluster based on orbits of individual stars for the closest clusters (Eisenhauer et al. 2005; Ghez et al. 2005).

The number of recoiled BHs in the MW is most sensitive to the fraction of low mass galaxies that harboured BHs in their centres, as well as to the merger history of such galaxies during the formation of the MW. We emphasize that most of these galactic ‘building blocks’ were made at high redshifts and were disrupted during the assembly process of the MW; hence, they likely had different properties than the remaining dwarf satellites of the MW today. The future discovery of the population of ejected star clusters will provide a unique probe of the early history of the MW, as well as the distribution and evolution of low-mass BHs. It would also open

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\(^3\) http://www.esa.int/esaSC/
\(^4\) http://pan-starrs_ifa.hawaii.edu/
\(^5\) http://www.lsst.org/
\(^6\) http://www.stsci.edu/hst/
\(^7\) http://www.stsci.edu/jwst/
a new window to exploring the low-mass end of the population of nuclear BHs in high-redshift galaxies. Merritt et al. (2008), whose work we learned of after submission of this manuscript, arrived at a similar conclusion independently, with a slight different application to the nearby Virgo cluster.

ACKNOWLEDGMENTS

We thank the GALFORM team for making their merger tree code available. This work is supported in part by NASA grant NNX08AL43G, by FQXi and by Harvard University funds.

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