Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 24 February 2013 (MN LaTeX style file v2.2)

Star clusters around recoiled black holes in the Milky Way halo

Ryan M. O'Leary⋆ and Abraham Loeb†
Harvard University, Department of Astronomy, 60 Garden St., Cambridge, MA 02138, USA

24 February 2013

ABSTRACT

Gravitational wave emission by coalescing black holes (BHs) kicks the remnant BH with a typical velocity of hundreds of $\mathrm{km\,s^{-1}}$. 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 present-day clusters are $\lesssim 1\,\mathrm{pc}$ 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 one hundred km $\mathrm{s^{-1}}$ 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: galaxies:kinematics and dynamics–galaxies:nuclei–black hole physics–gravitational waves–star clusters

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 $\mathrm{km\,s^{-1}}$ 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. 2007b,a; Tichy & Marronetti 2007). Such kicks can alter both the the population of nuclear BHs in galactic bulges (Madau & Quataert 2004; Libeskind et al. 2006; Volonteri 2007; Schnittman 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 et al. 2008; Shields & Bonning 2008; Schnittman & Krolik 2008) or observed as spatially and kinematically offset quasars (Madau & Quataert 2004). If the BH binary was surrounded by an accretion disk, the ejected remnant BH would carry the disk 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 et al. 2007) and possibly one suggested candidate (Komossa et al. 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

⋆ E-mail:roleary@cfa.harvard.edu
† E-mail:aloeb@cfa.harvard.edu

recoil have generally focused on massive BHs with a mass $M_\bullet \gtrsim 10^7\,\mathrm{M}_\odot$. 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 $M_\bullet \lesssim 10^5\,\mathrm{M}_\odot$ will likely be kicked out of their parent galaxies as a result of major mergers (Baker et al. 2006). During the hierarchical 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 gravitational 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 ($\lesssim 500$ 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 et al. 2003; Zhao & Silk 2005) as well as the the direct collapse of baryons into a BH (Bertone et al. 2005; Mapelli et al. 2006). In both of these cases, however, the BH either is presently located in the center of a galaxy or is "naked" without any stellar companions. Such BHs are likely to only be located by their interaction with the matter that surrounds them (Islam et al. 2004c,b; Volonteri & Perna 2005; Mii & Totani 2005; Bertone et al. 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 et al. 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 § 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 § 3. In § 4 we discuss the observational signatures of these systems. Finally, § 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 formation (Springel et al. 2008) the MW formed from an overdense region of the universe with a present-day virial mass $M_{\rm vir} \approx 1\text{–}2\times10^{12}\,\mathrm{M}_\odot$ (Klypin et al. 2002; Li & White 2008). The threshold for cooling by atomic transitions limits the minimum mass of star forming galaxies at high redshifts to $M_{\rm gal} \sim 10^8\,\mathrm{M}_\odot$ (Wyithe & Loeb 2006). If the earliest population of star-forming galaxies had BHs at their center, then their shallow potential would be insufficient to retain the recoiling BHs after mergers with a BH mass ratio $q \equiv (M_{\bullet,1}/M_{\bullet,2}) \gtrsim 0.1$. Nevertheless, since most kicks are modest ($\lesssim 500\,\mathrm{km\,s^{-1}}$), the ejected BHs remain confined to the MW.

We estimate the number of BHs in the MW halo, $N_{\rm BH}$, by analyzing a large statistical ensemble of possible merger tree histories for the MW using analytic models for the distribution of kick velocities and galaxy profiles. In particular, we generate $\gtrsim 10^3$ Monte-Carlo realizations of the merger history of the MW galaxy with the merger tree code made publicly available by Parkinson et al. (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 $1.5\times10^{12}\,\mathrm{M}_\odot$, and restrict our simulations to formation scenarios in which the MW undergoes no major mergers ($q > 1/3$) since a redshift $z = 1$ (Diemand et al. 2007).

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

$$v_{\rm c} = 24\left(\frac{M_{\rm gal}}{10^8 h^{-1}\,\mathrm{M}_\odot}\right)^{1/3}\left(\frac{\Omega_m}{\Omega_m^z}\frac{\Delta_c}{18\pi^2}\right)^{1/6}\left(\frac{1+z_{\rm merge}}{10}\right)^{1/2}\mathrm{km\,s^{-1}}, \quad (1)$$

where $\Delta_c = 18\pi^2 + 82d - 39d^2$, $d = \Omega_m^z - 1$, $\Omega_m^z = (\Omega_m(1+z)^3/(\Omega_m(1+z)^3 + \Omega_\Lambda)$, evaluated at the merger redshift z and we adopt the values for the cosmological density parameters, Ω_m and Ω_Λ, used in the Millennium run (Springel et al. 2005). In each galaxy, we assume that the dark matter follows an NFW radial profile (Navarro et al. 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 center is $v_{\rm esc} \approx 2.8 v_{\rm c}$. We scale the stellar velocity dispersion of the bulge in the low-mass galaxies similarly to the MW and adopt $\sigma_\star = v_{\rm c}/2$. The BH mass in the center of each galaxy is then dictated by the observed $M_\bullet$–$\sigma_\star$ relation (Tremaine et al. 2002)

$$M_\bullet = 8.1\times10^6 M_\odot\left(\frac{\sigma_\star}{100\,\mathrm{km\,s^{-1}}}\right)^4. \quad (2)$$

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 $M_{\bullet,\rm final} = M_{\bullet,1} + M_{\bullet,2}$. Although the $M_\bullet$–$\sigma_\star$ relation was initially determined from the analysis of more massive BHs, Barth et al. (2005) and Greene & Ho (2006) have found that it consistently extends to active galactic nuclei with BHs with masses $\sim 10^5\,\mathrm{M}_\odot$, even without classical bulges (Greene et al. 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 the kick velocity is larger than the escape velocity, $v_k > v_{\rm esc}$, and remains in the larger potential of the MW if the final velocity is less than the escape velocity of the MW halo, $v_{\rm ej} = \sqrt{v_{\rm k}^2 - v_{\rm esc}^2} \lesssim 500\,{\rm km\,s^{-1}}$. 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 $a = 0.9$ ($a = 0.1$) gravitational wave recoil ejected ≈ 570 (≈ 440) BHs from their parent galaxy, and $N_{\rm BH} \approx 330$ (≈ 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 dispersion of the halo $\lesssim 200\,{\rm km\,s^{-1}}$. 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 Milky Way.

In Figure 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 $r_{\rm vir} = 200\,{\rm kpc}$ (Klypin et al. 2002; Li & White 2008). We determine the luminosity from Eq. (6) in § 3, and report the flux in units of the flux from the Sun if it were at a distance of 1 kpc, $f_{\odot,{\rm kpc}}$, and also the apparent bolometric magnitude (top axis). Assuming that these clusters lose little mass, we expect that nearly all remnant BHs with mass $M_\bullet \gtrsim 2 \times 10^3\,{\rm M_\odot}$ in the MW halo would be visible to the depth of *Sloan Digital Sky Survey* [2] (SDSS).

In all our models, we find the mass distribution of the ejected BHs to scale roughly as ${\rm d}N_{\rm BH}/{\rm d}M_\bullet \propto M_\bullet^{-1}$ (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 $6.3^{+5.7}_{-2.8} \times 10^5\,{\rm M_\odot}$ for $a = 0.9$, and $1.7^{+0.8}_{-0.5} \times 10^5\,{\rm M_\odot}$ for $a = 0.1$, where the quoted uncertainty represents the one standard deviation. The closest BH that has an apparent magnitude $< 21^{\rm m}$, the approximate depth of SDSS, has an average mass of $\sim 3 \times 10^3\,{\rm M_\odot}$ and is $\sim 1\,{\rm kpc}$ 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 timescale of a $\sim 10^5\,{\rm M_\odot}$ BH is $\gtrsim 10^{11}\,{\rm yr}$ at even $\sim 1\,{\rm kpc}$ from the galactic center (Binney & Tremaine 1987).

Given the assumptions used here and the uncertainties in the lower limit for the BH mass, our results are consistent with the findings of previous analyses of BHs in the MW halo, even though only a few papers (i.e., Volonteri & Perna 2005; Libeskind et al. 2006) explicitly account for GW recoil. Previous studies that focused on BHs that formed in the smallest overdensities in the early universe ($\sim 10^6\,{\rm M_\odot}$ at $z \gtrsim 20$) found that there may be up to $10^3 - 10^4$ BHs with masses $\gtrsim 10^2\,{\rm M_\odot}$ (Islam et al. 2004a; Zhao & Silk 2005; Bertone et al. 2005; Mapelli et al. 2006). Volonteri & Perna (2005) and Libeskind et al. (2006) used more conservative estimates for the threshold of forming seed BHs, and accounted for the growth of the BH owing to accretion. They concluded that there are more likely only $\sim 10^2$ such BHs in the halo. Here, we sidestepped the issue of how and when the seed BHs formed, and assumed that all galaxies (with mass $\gtrsim 10^8\,{\rm M_\odot}$) have a central BH that follows the $M_\bullet - \sigma_\star$ relationship, which consistently extends to the lowest mass BHs observed (Greene & Ho 2006). With these conditions for the BH mass, our results are most consistent with Volonteri & Perna (2005) and Libeskind et al. (2006), however we do not follow the evolution of BHs with mass $\lesssim 10^3\,{\rm M_\odot}$.

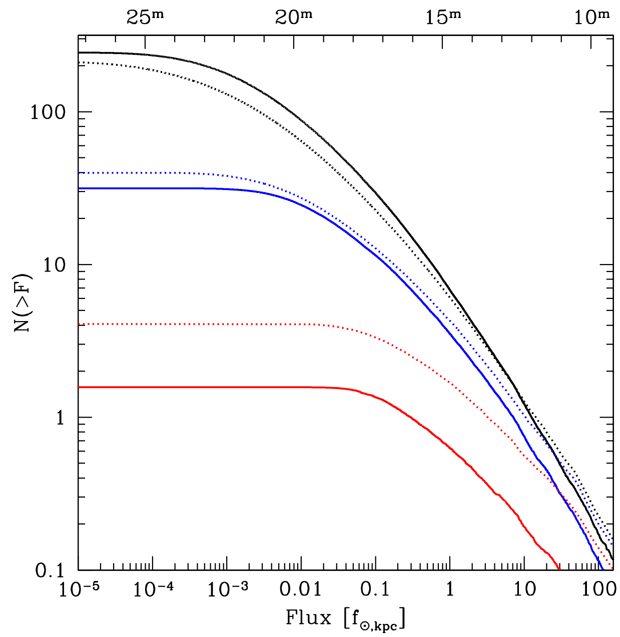

Figure 1. The cumulative distribution of ejected star clusters in the MW Halo. Plotted is the flux distribution associated with BHs masses greater than $10^3\,{\rm M_\odot}$ (black), $10^4\,{\rm M_\odot}$ (blue), and $10^5\,{\rm M_\odot}$ (red), in our models with BH spin $a = 0.1$ (solid) and $a = 0.9$ (dashed) lines, plotted in units of the flux of the Sun at a distance of 1 kpc ($f_{\odot,{\rm kpc}}$). The top axis is labelled with the apparent bolometric magnitude of the clusters. Nearly all BHs with $M_\bullet \gtrsim 2 \times 10^3\,{\rm M_\odot}$ have apparent magnitudes greater than 21, the rough magnitude limit of SDSS. The mass distribution of the ejected BHs has approximately equal number per $\log M_\bullet$ interval, with ${\rm d}N_{\rm BH}/{\rm d}M_\bullet \propto M_\bullet^{-1}$.

3 STRUCTURE AND EVOLUTION OF EJECTED STAR CLUSTERS

The number of stars that remain bound to the ejected BH will depend on the stellar distribution immediately before merger and the magnitude of the kick from GWs. The stellar distribution is determined by the relaxation timescale at the radius of influence of the BH binary, $r_i = GM_\bullet/\sigma_\star^2$,

[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 halos (Loeb 2006).
[2] http://www.sdss.org

(Bahcall & Wolf 1976)

$$t_r = \frac{3(2\pi\sigma_\star^2)^{3/2}}{32\pi^2 G^2 m_\star^2 n_\star \ln\Lambda}, \quad (3)$$

where $\sigma_\star$ is the stellar velocity dispersion after the galaxies merge, $m_\star$ is the average stellar mass, $n_\star$ is the number density of stars at r_i, and $\ln\Lambda \approx \ln(M_\bullet/M_\star)$ is the Coulomb logarithm. From the $M_\bullet$–$\sigma_\star$ relation (Eq. 2) the relaxation timescale can be written as

$$t_r \approx 10^9 \left(\frac{M_\bullet}{10^5\,\mathrm{M}_\odot}\right)^{5/4} \mathrm{yr}, \quad (4)$$

if we assume that $m_\star = 1\,\mathrm{M}_\odot$, and that the total mass in stars interior of r_i is $\sim 2M_\bullet$. Within a relaxation timescale, the stars form a density cusp within the radius of influence around the central BH, with $n_\star(r) \propto r^{-\alpha}$, where $\alpha = 1.75$ for a population of equal mass stars and $\alpha \approx 1.5 - 2.0$ for varying mass distributions of the stars and compact remnants (Bahcall & Wolf 1976, 1977; Freitag et al. 2006; Hopman & Alexander 2006b). If the BHs coalesce on a time much shorter than the relaxation timescale of the stars owing to a gas rich merger, then the stellar density profile is likely much shallower with $\alpha \approx 1$ due to the scattering off the inspiraling binary (Merritt & Szell 2006; Merritt et al. 2007). However, new stars might form out of the gas and introduce a new cusp of stars. In either case, however, the relaxation timescale of the stellar systems is much shorter than a Hubble time, and the present-day distribution of stars is different than its initial condition.

Assuming that the stars follow a power-law density profile and that the total stellar mass within r_i is $2M_\bullet$, the stellar density profile before the BH ejection is

$$n_\star(r) = \frac{M_\bullet}{m_\star}\frac{3-\alpha}{2\pi r_i^3}\left(\frac{r}{r_i}\right)^{-\alpha}. \quad (5)$$

The kick is imparted to the BH merger remnant on a timescale much shorter than the dynamical time of the star cluster. In the frame of the BH, all stars receive kicks with a reflex velocity $-v_k$. Stars with total energies $\gtrsim -m_\star v_k^2/2$ will become unbound to the BH. In the Keplerian potential of the BH, this roughly corresponds to stars at $r \gtrsim r_k = \sqrt{GM_\bullet/v_k^2} = (\sigma_\star/v_k)^2 r_i$. The total number of stars that remain bound the the BH is then,

$$N_{\rm cl} \approx \frac{2M_\bullet}{m_\star}\left(\frac{v_k}{\sigma_\star}\right)^{2a-6}. \quad (6)$$

For $\alpha = 1.75$ the total number of stars that remain bound for a minimally ejected BH with $v_k = 5.6\sigma_\star$ is then $\sim 4\times 10^3 (M_\bullet/10^5\mathrm{M}_\odot)$. 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 $r_k \approx (\sigma_\star/v_k)^2 r_i \ll 1\,\mathrm{pc}$, and have a $\alpha = 4$ profile for $r \gtrsim r_k$ (Komossa & Merritt 2008). Given the short relaxation timescale 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)

$$\frac{\partial g(x,\tau)}{\partial\tau} = -x^{5/2}\frac{\partial}{\partial x}Q(x) - R(x), \quad (7)$$

where $x = -E/(m_\star\sigma_\star^2)$ is the dimensionless energy, $\tau = t/t_r$ is the dimensionless time, $g(x,\tau) = [(2\pi\sigma_\star^2)^{3/2} n_\star^{-1}]f(E)$ 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,

$$Q(x) = \int_{-\infty}^{x_{\rm td}} \mathrm{d}y[\max(x,y)]^{-3/2}\left(g(x)\frac{\partial g(y)}{\partial y} - g(y)\frac{\partial g(x)}{\partial x}\right). \quad (8)$$

and

$$R(x) = \frac{g(x)^2}{\ln[J_c(x)/J_{\rm LC}]}, \quad (9)$$

where $J_c(x) = GM_\bullet\sigma_\star^{-1}(2x)^{-1/2}$ is the angular momentum of a circular orbit at a radius $r \approx r_i/(2x)$, and $J_{\rm LC}$ is the maximum angular momentum for the star to be destroyed or consumed by the BH. For a star of radius $R_\star$ $J_{\rm LC} = GM_\bullet\sigma^{-1}x_{\rm td}^{-1}(2(x+x_{\rm td}))^{1/2}$, where $x_{\rm td} \approx (M_\bullet/m_\star)^{-1/3} r_i/R_\star$. We assume that far from the BH the stars initially follow a Maxwellian distribution with dispersion $\sigma_\star$. 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 $n_\star \propto r^{-\alpha}$, 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 timescale, 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 timescale 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 $g(x) \rightarrow g(x)z^{2.5}/(1+z^{2.5})$, where $z = x/(v_k/\sigma_\star)^2$. This yields an asymptotic density profile with $n \propto r^{-4}$ for $r \gtrsim r_k$, 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 et al. 2008), we adopt $g(x) \propto x^{-1/2}z^3/(1+z^3)$, normalized by the same number density and relaxation timescale used in Eq. (3). This yields $\alpha \sim 1$ for $r \lesssim r_k$ and $\alpha \sim 4$ for $r \gtrsim r_k$, as expected following a merger (Merritt & Szell 2006; Merritt et al. 2007). This run results in $\sim 10\%$ the number of bound stars as with $\alpha = 1.75$. Its importance, however, is uncertain given the short relaxation timescales 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 timescale of the cluster becomes comparable to the age of the system. Figure 2 shows the evolution of the projected number of stars interior to a radius r for a BH with mass $10^5\,\mathrm{M}_\odot$ for both $\alpha = 1.75$ and $\alpha = 1$ density profiles. Since our simulations indicate little mass loss, the condition that the relaxation timescale of the system (Eq. 3) be comparable to the age of the Universe implies that the cluster should expand by a factor of order $(t_h/t_r)^{1/3} \sim 10$. Even then, the present day cluster size is less than the initial radius of influence of the BH, $r_i \lesssim 1\,\mathrm{pc}$, 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

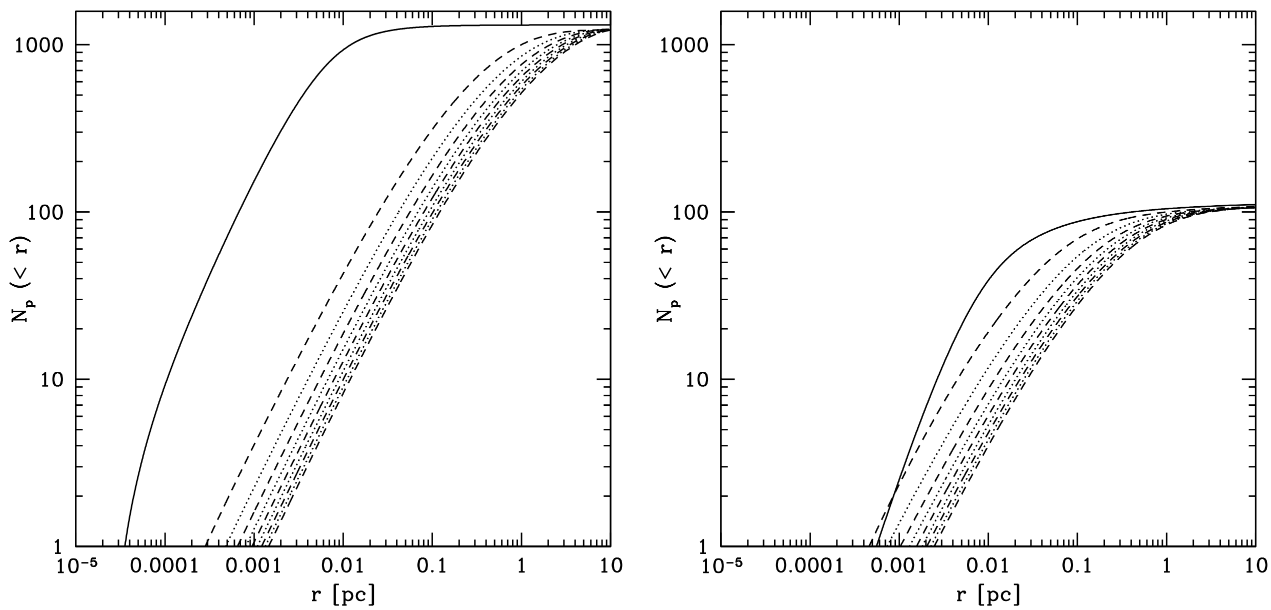

Figure 2. The total number of projected stars interior to r, $N_p(< r)$, for $M_\bullet = 10^5 \mathrm{M}_\odot$ and $\alpha = 1.75$ (left) and $\alpha = 1$ (right). The solid line corresponds to the cluster immediately after being ejected from its parent galaxy with $v_k = 5.8\sigma_\star$,normalized to have the same number density at the radius of influence. The alternating dashed and dotted lines correspond to the projected number of stars after every $10t_r \approx 650\,\mathrm{Myr}$. Immediately after ejection, the cluster rapidly expands until its relaxation time becomes comparable to the age of the Universe, with very little mass loss. n For a $10^5\,\mathrm{M}_\odot$ BH, the circular velocity of the stars is $\approx 66\,\mathrm{km\,s^{-1}}(r/0.1\,\mathrm{pc})^{-1/2}$.

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 relaxaation, which can deplete the number of stars both before and after the ejection of of the BH (Rauch & Tremaine 1996; Rauch & Ingalls 1998). Although resonant relaxation has been approximately accounted for in Eq. 7 by averaging over angular momentum (Hopman & Alexander 2006a), a full multidimensional analysis accounting for angular momemtum is best suited for these clusters.

4 OBSERVING EJECTED SYSTEMS

Size and Structure: Based on the results in § 2, we estimate that there should be ~ 300 recoiled BHs in the MW halo. Equation (6) implies that these BHs are surrounded by $\sim 4 \times 10^3 (M_\bullet/10^5 m_\star)$ stars with a half mass radius, $r_h \lesssim 1\,\mathrm{pc}$. At the typical distance to the most massive recoiled BH, $\sim 100\,\mathrm{kpc}$, 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 colors. The closest clusters are $\sim 1\,\mathrm{kpc}$ away and may be a few arcmin in size. However, these clusters surround the smallest BHs ($\sim 10^3\,\mathrm{M}_\odot$) 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 disk. 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 $\sim 3\,\mathrm{pc}$ (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 outweights 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.

Color: A recoiled star cluster can be distinguished from single foreground stars by its anomalous color. The cluster is likely old, $\sim 1-10\,\mathrm{Gyr}$, and to first order should have colors 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 (greather than one hundred 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 one hundred 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 colors to distinguish the clusters from foreground stars. The expected proper motion of these clusters is $\sim 10^{-3}$ arcsec yr^{-1}.

The Local Group: Given the constrained distances to M31 and M33, color-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 $r_{\rm h} \sim 0.5\,{\rm pc}$ would have an angular size of $\sim 0.1\,{\rm arcsec}$, 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 black hole 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 disk 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 (Zhao & Silk 2005; Bertone et al. 2005; Springel et al. 2008).

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 $M_\bullet \gtrsim 10^3\,{\rm M}_\odot$, 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 $\sim 1-6\times10^5\,{\rm M}_\odot$, and is surrounded by a compact star cluster $\lesssim 1\,{\rm pc}$ 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 center of the cluster based on orbits of individual stars for the closest clusters (Ghez et al. 2005; Eisenhauer et al. 2005).

The number of recoiled BHs in the MW is most sensitive to the fraction of low mass galaxies that harbored BHs in their centers, 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 Milky Way, as well as the distribution and evolution of low mass BHs. It would also open a new window to exploring the low-mass end of the population of nuclear BHs in high-redshifts galaxies. Merritt et al. (2008), whose work we learned of after submission of this manuscript, arrived at a similar conclusion independently, with a slightly different application to the nearby Virgo cluster.

[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/

ACKNOWLEDGEMENTS

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.

REFERENCES

Bahcall J. N., Wolf R. A., 1976, ApJ, 209, 214
Bahcall J. N., Wolf R. A., 1977, ApJ, 216, 883
Baker J. G., Centrella J., Choi D.-I., Koppitz M., van Meter J. R., Miller M. C., 2006, ApJ, 653, L93
Barkana R., Loeb A., 2001, Physics Reports, 349, 125
Barth A. J., Greene J. E., Ho L. C., 2005, ApJ, 619, L151
Bassino L. P., Muzzio J. C., Rabolli M., 1994, ApJ, 431, 634
Bekenstein J. D., 1973, ApJ, 183, 657
Bertone G., Zentner A. R., Silk J., 2005, PhRvD, 72, 103517
Binney J., Tremaine S., 1987, Galactic dynamics. Princeton, NJ, Princeton University Press, 1987, 747 p.
Blecha L., Loeb A., 2008, MNRAS, 390, 1311
Bonning E. W., Shields G. A., Salviander S., 2007, ApJ, 666, L13
Callegari S., Mayer L., Kazantzidis S., 2008, arXiv:0811.0615, Submitted to ApJL
Campanelli M., Lousto C., Zlochower Y., Merritt D., 2007a, ApJ, 659, L5
Campanelli M., Lousto C. O., Zlochower Y., Merritt D., 2007b, Physical Review Letters, 98, 231102
Cole S., Helly J., Frenk C. S., Parkinson H., 2008, MNRAS, 383, 546
Diemand J., Kuhlen M., Madau P., 2007, ApJ, 657, 262
Eisenhauer F., Genzel R., Alexander T., Abuter R., Paumard T., Ott T., et al. 2005, ApJ, 628, 246
Fitchett M. J., 1983, MNRAS, 203, 1049
Freitag M., Amaro-Seoane P., Kalogera V., 2006, ApJ, 649, 91
Fujita Y., Inoue S., Nakamura T., Manmoto T., Nakamura K. E., 1998, ApJ, 495, L85+
Ghez A. M., Salim S., Hornstein S. D., Tanner A., Lu J. R., Morris M., Becklin E. E., Duchêne G., 2005, ApJ, 620, 744
Greene J. E., Ho L. C., 2006, ApJ, 641, L21
Greene J. E., Ho L. C., Barth A. J., 2008, ApJ, 688, 159
Gualandris A., Merritt D., 2008, ApJ, 678, 780
Hopman C., Alexander T., 2006a, ApJ, 645, 1152
Hopman C., Alexander T., 2006b, ApJ, 645, L133
Islam R. R., Taylor J. E., Silk J., 2003, MNRAS, 340, 647

Islam R. R., Taylor J. E., Silk J., 2004a, MNRAS, 354, 427
Islam R. R., Taylor J. E., Silk J., 2004b, MNRAS, 354, 443
Islam R. R., Taylor J. E., Silk J., 2004c, MNRAS, 354, 629
Klypin A., Zhao H., Somerville R. S., 2002, ApJ, 573, 597
Komossa S., Merritt D., 2008, ApJ, 683, L21
Komossa S., Zhou H., Lu H., 2008, ApJ, 678, L81
Koposov S., de Jong J. T. A., Belokurov V., Rix H.-W., Zucker D. B., Evans N. W., Gilmore G., Irwin M. J., Bell E. F., 2007, ApJ, 669, 337
Li Y.-S., White S. D. M., 2008, MNRAS, 384, 1459
Libeskind N. I., Cole S., Frenk C. S., Helly J. C., 2006, MNRAS, 368, 1381
Lippai Z., Frei Z., Haiman Z., 2008, ApJ, 676, L5
Loeb A., 2004, MNRAS, 350, 725
Loeb A., 2006, astro-ph/0603360
Loeb A., 2007, Physical Review Letters, 99, 041103
Madau P., Quataert E., 2004, ApJ, 606, L17
Mapelli M., Ferrara A., Rea N., 2006, MNRAS, 368, 1340
Merritt D., Mikkola S., Szell A., 2007, ApJ, 671, 53
Merritt D., Schnittman J. D., Komossa S., 2008, arXiv:0809.5046
Merritt D., Szell A., 2006, ApJ, 648, 890
Mii H., Totani T., 2005, ApJ, 628, 873
Navarro J. F., Frenk C. S., White S. D. M., 1996, ApJ, 462, 563
Parkinson H., Cole S., Helly J., 2008, MNRAS, 383, 557
Peres A., 1962, Physical Review, 128, 2471
Press W. H., Schechter P., 1974, ApJ, 187, 425
Rauch K. P., Ingalls B., 1998, MNRAS, 299, 1231
Rauch K. P., Tremaine S., 1996, New Astronomy, 1, 149
Schnittman J. D., 2007, ApJ, 667, L133
Schnittman J. D., Buonanno A., 2007, ApJ, 662, L63
Schnittman J. D., Krolik J. H., 2008, ApJ, 684, 835
Shields G. A., Bonning E. W., 2008, ApJ, 682, 758
Springel V., Wang J., Vogelsberger M., Ludlow A., Jenkins A., Helmi A., Navarro J. F., Frenk C. S., White S. D. M., 2008, MNRAS, 391, 1685
Springel V., White S. D. M., Frenk C. S., Navarro J. F., Jenkins A., Vogelsberger M., Wang J., Ludlow A., Helmi A., 2008,Nat, 456, 73
Springel V., White S. D. M., Jenkins A., Frenk C. S., Yoshida N., Gao L., Navarro J., Thacker R., Croton D., Helly J., Peacock J. A., Cole S., Thomas P., Couchman H., Evrard A., Colberg J., Pearce F., 2005, Nat, 435, 629
Tanaka T., Haiman Z., 2008, arXiv:0807.4702, submitted to ApJ
Tichy W., Marronetti P., 2007, PhRvD, 76, 061502
Tremaine S., Gebhardt K., Bender R., Bower G., Dressler A., Faber S. M., Filippenko A. V., Green R., Grillmair C., Ho L. C., Kormendy J., Lauer T. R., Magorrian J., Pinkney J., Richstone D., 2002, ApJ, 574, 740
Volonteri M., 2007, ApJ, 663, L5
Volonteri M., Madau P., 2008, ApJ, 687, L57
Volonteri M., Perna R., 2005, MNRAS, 358, 913
Wechsler R. H., Bullock J. S., Primack J. R., Kravtsov A. V., Dekel A., 2002, ApJ, 568, 52
Wyithe J. S. B., Loeb A., 2006, Nat, 441, 322
Zhao H., Silk J., 2005, Physical Review Letters, 95, 011301
Zinnecker H., Keable C. J., Dunlop J. S., Cannon R. D., Griffiths W. K., 1988, in Grindlay J. E., Philip A. G. D., eds, The Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies Vol. 126 of IAU Symposium, The Nuclei of Nucleated Dwarf Elliptical Galaxies - are they Globular Clusters?. pp 603–+