WANDERING BLACK HOLES IN BRIGHT DISK GALAXY HALOS

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ABSTRACT

We perform SPH+N-body cosmological simulations of massive disk galaxies, including a formalism for black hole (BH) seed formation and growth, and find that satellite galaxies containing supermassive BH seeds are often stripped as they merge with the primary galaxy. These events naturally create a population of “wandering” BHs that are the remnants of stripped satellite cores; galaxies like the Milky Way may host 5–15 of these objects within their halos. The satellites that harbor BH seeds are comparable to Local Group dwarf galaxies such as the Small and Large Magellanic Clouds; these galaxies are promising candidates to host nearby intermediate-mass BHs. Provided that these wandering BHs retain a gaseous accretion disk from their host dwarf galaxy, they give a physical explanation for the origin and observed properties of some recently discovered off-nuclear ultraluminous X-ray sources such as HLX-1.

Key words: black hole physics – galaxies: evolution – galaxies: formation – galaxies: halos
Online-only material: color figure

1. INTRODUCTION

Recent evidence for the existence of intermediate-mass black holes (IMBHs) raises questions about how such objects might form and evolve. IMBH candidates exist in globular clusters (Ulvestad et al. 2007), nearby bulgeless galaxies (Filippenko & Ho 2003; Barth et al. 2004), and active galactic nuclei (Greene & Ho 2004). Additionally, off-nuclear ultraluminous X-ray sources (ULXs) have become increasingly promising IMBH candidates (Farrell et al. 2009; Jonker et al. 2010). A source of IMBHs may be the seeds of supermassive black holes (SMBHs) formed at high redshift; any seed that does not grow into an SMBH would today be observed as an IMBH. While the precise mechanism for seed black hole (BH) formation is unknown, there are several postulated theories. One possible mechanism for SMBH seed formation is the direct collapse of pristine, low angular momentum gas, which forms BHs with mass on the order of $10^4–10^6\ M_\odot$ (Koushiappas et al. 2004; Lodato & Natarajan 2006; Begelman et al. 2006). Another possibility is that the seeds are the remnants of Population III stars, with masses around $10^3–10^5\ M_\odot$ (Madau & Rees 2001; Volonteri et al. 2003). Alternatively, the first nuclear star clusters may collapse to form BHs of mass 1000–2000\ $M_\odot$ (Devecchi & Volonteri 2009).

We perform SPH+N-body simulations of massive disk galaxies to explore the evolution of seed BHs in a cosmological context. While previous works have addressed the growth of central SMBHs (Di Matteo et al. 2008; Okamoto et al. 2008; Booth & Schaye 2009), here we specifically focus on those which do not end up in galaxy centers. We include BH growth by gas accretion and merging as well as radiative feedback in order to form a fully self-consistent picture of BH growth and evolution. We find that the tidal stripping of galaxies containing SMBH seeds leads to a population of “wandering” BHs within the larger galaxy halo. Such a phenomenon has been predicted in the case of idealized simulations of merging galaxies (Governato et al. 1994; Kazantzidis et al. 2005), though fully cosmological simulations in the current $\Lambda$CDM paradigm are needed to test a suite of non-idealized scenarios. Wandering BHs may also be created by a gravitational slingshot from three-body BH interactions (Volonteri & Perna 2005), gravitational recoil, or a distribution of Population III star remnants which have not spiraled into the central BH (Schneider et al. 2002). In each of these cases, the timescale for dynamical friction is longer than a Hubble time (Taffoni et al. 2003), leaving a potentially substantial population of “wandering” IMBHs in galaxy halos.

The recent discovery of an off-nuclear IMBH candidate (Farrell et al. 2009) leads us to explore whether such an object can be explained by a “wandering” BH. The object HLX-1 is offset from the nucleus of its host spiral galaxy and exhibits an X-ray luminosity of $10^{42}\ erg\ s^{-1}$. This luminosity implies a lower limit to a BH mass of 500\ $M_\odot$, but the true mass may be much larger. We discuss under what circumstances HLX-1 would be observable. Preliminary results suggest that HLX-1 cannot be described by an isolated wandering BH, but a BH traveling with the remnant core of its parent galaxy may explain its observed properties.

2. SIMULATIONS

We use the N-body code GASOLINE (Wadsley et al. 2004; Stadel 2001), an smoothed particle hydrodynamics (SPH) tree code which incorporates star formation, gas cooling and hydrodynamics, and supernova feedback, and successfully models realistic galaxies. Studies of cosmological simulations with GASOLINE have produced galaxies that follow the mass–metallicity relation (Brooks et al. 2007) and the $\text{H}i$ Tully–Fisher relation (Governato et al. 2009), exhibit cold flow gas accretion (Brooks et al. 2009), and reproduce the distribution of damped Lyman alpha systems at high redshift (Pontzen et al. 2008). Additionally, Governato et al. (2010) have shown how high resolution and physically motivated supernova feedback allow for the formation of a bulgeless dwarf galaxy with a dark matter core. The ability to form realistic disk galaxies is critical to our analysis of BH physics, because of the need to accurately trace the angular momentum of in-spiraling gas, which comprises the disk and eventually fuels the BH as well as the star formation histories responsible for dispensing metals into the interstellar medium (ISM) via supernova feedback.
For this Letter, we have simulated four different Milky Way mass halos, which were selected from a uniform, 50 Mpc volume and re-simulated at a high resolution using the volume renormalization technique (Katz & White 1993). All simulations are run with gravitational softening $\epsilon = 0.3$ kpc, gas particle masses of $2.28 \times 10^5 M_\odot$, dark matter particle masses of $1.26 \times 10^5 M_\odot$, a Chabrier initial mass function (Chabrier 2003), and a Wilkinson Microwave Anisotropy Probe (WMAP) three-year cosmology (Spergel et al. 2007). Star formation and supernova recipes are described in detail in Stinson et al. (2006) and Governato et al. (2007); we adopt parameter values $\epsilon = 0.1$ and $eSN = 1.0$. Stars are allowed to form when gas reaches a threshold density of 1.0 amu cm$^{-3}$, which allows us the most physical representation of star formation given our resolution. While our dwarf galaxy satellites are not resolved to the level of Governato et al. (2010), for our purposes here this resolution is sufficient. Simulation properties are described in Table 1. Circular velocity $V_{\text{circ}}$ is measured using the width at 20% of the peak of the simulated H I line profile (see Governato et al. 2009). The disk scale length $r_s$ is determined by simultaneously fitting an exponential + Sérsic profile to the projected edge-on stellar surface density of the galactic disk.

| Run     | No. within $R_{200}$ | $M_{200}$ ($M_\odot$) | $V_{\text{circ}}$ (km s$^{-1}$) | $R_{200}$ (kpc) | $r_s$ (kpc) |
|---------|----------------------|------------------------|---------------------------------|----------------|------------|
| h239    | 7408639              | $8.32 \times 10^{11}$  | 247.7                           | 242.9          | 2.82       |
| h258    | 7347383              | $7.90 \times 10^{11}$  | 225.4                           | 238.8          | 3.81       |
| h277    | 6624914              | $7.09 \times 10^{11}$  | 262.7                           | 230.3          | 2.74       |
| h285    | 7373714              | $8.18 \times 10^{11}$  | 238.2                           | 241.5          | 2.24       |

We provide a dynamical mechanism to place massive BHs in galaxy halos, which is simply a consequence of hierarchical merging in the $\Lambda$CDM paradigm. Detecting these objects may help constrain the mechanism of seed BH formation, and we investigate a few scenarios in which a wandering BH may be observed as a ULX.

### 3. RESULTS

For our four simulated halos, we show the radial distribution of BHs at $z = 0$, defined as the distance between the halo center and the BH, in Figure 1. Each of the four galaxies has a central BH and between 5 and 15 “wandering” BHs whose distances range from 10 to 100 kpc. The vast majority of wandering BHs have grown in mass by less than 2% since their formation. A small number (5 out of 36 total) have undergone BH–BH mergers early in their lifetimes and thus have larger masses, but only one of these has experienced any substantial accretion events. In all cases, accretion is effectively quenched when the host galaxies are torn apart and the BHs are left to wander throughout the halo, and thus any BHs present here are at or within a few factors of their original seed mass.

Local Group dwarf galaxies are promising targets for IMBH searches (Van Wassenhove et al. 2010). In Figure 2, we show the masses of BH-hosting satellite galaxies before the stripping process has begun. This distribution peaks between $10^8$ and $10^{10} M_\odot$; at halo masses of $3 \times 10^9 M_\odot$ the satellites become increasingly dark. Since very few stars form in these halos, it is unlikely that we are underestimating the number hosting massive BH seeds, given our scenario. We estimate the absolute magnitudes of the satellites in these mass ranges using the STARBURST99 (Leitherer et al. 1999) code, using stellar ages and metallicities from our simulations. This mass range corresponds to galaxies with magnitudes fainter than $-15$ in the...
Figure 1. Top panel: distribution of BH radial distances to their halo centers for 40 BHs in four simulated galaxies.

Figure 2. Mass distribution of BH-hosting satellites before they are stripped by the primary. The solid line indicates the total mass of the satellites, while the dashed line is the stellar mass only. Our simulations are incomplete for halos below a total mass of $3 \times 10^8 M_\odot$, however due to the UV background field (Haardt & Madau 1996) most halos with mass below $10^8 M_\odot$ have very few stars.

$V$ band, which includes several Local Group dwarfs, including the Large and Small Magellanic Clouds. Examining these local dwarfs for IMBHs may help constrain the locations and masses of SMBH seeds. A confirmed detection of an IMBH would provide an upper limit to the initial mass of SMBH seeds and possibly allow us to differentiate between the various proposed formation mechanisms of such seeds.

3.2. Connection with Off-Nuclear ULXs?

While wandering BHs may be present in the Milky Way halo, observing such objects would require either a fortuitous gravitational lensing detection, or a triggered accretion event, resulting in X-ray emission. We investigate situations where a wandering BH could undergo substantial accretion in a galactic halo, which could explain the existence of objects such as HLX-1.

While the majority of ULXs are attributed to star formation regions (Swartz et al. 2004), a smaller number of off-planar ULXs are not cospatial with star formation, and we focus on the possible origins of these objects here. We first examine whether a wandering BH passing through a dense portion of the host galaxy disk could reproduce the properties of off-nuclear ULXs. We trace the orbits of each BH and examine the frequency with which they cross the disk region, which we define as three disk scale lengths ($r_s$). The last few Gyr of orbital history for the BHs in our simulated galaxy h239 are shown in Figure 3. Several of the BHs pass through the $3r_s$ limit, which we denote as a disk passage. The average BH disk passage rate for all of the simulations combined is $10.6 \text{ Gyr}^{-1}$; however, this rate increases with time ($13.3 \text{ Gyr}^{-1}$ for the last few billion years of galaxy evolution) due to the increased population of wandering BHs in the halo (since more mergers have occurred).

The likelihood of observing such a disk passage depends on the column density of gas in the disk, the number of passages made, and the velocity of the BHs. We use results from H i measurements of the surface densities of local disk galaxies (Leroy et al. 2008) to estimate an average disk column density of $10^4 M_\odot \text{pc}^{-2}$. The ability of the passing BH to attract a sufficient amount of gas to be observed as a ULX depends most strongly on its velocity, which ranges between 154 and 662 km s$^{-1}$, and on average is $470 \text{ km s}^{-1}$ for BHs at pericenter. To estimate a BH’s luminosity, we developed a simple scenario where the passing BH is able to collect the gas within a radius of influence determined by its mass and pericenter velocity: $M_{\text{coll}} = \Sigma_{\text{disk}} \pi (GM_{\text{BH}}/v_{\text{BH}})^2$. We perform a Monte Carlo simulation taking into account the observed ranges of BH velocities and estimate that the amount of mass collected by a BH during its disk passage ranges from $10^{-3}$ to $10^{-4} M_\odot$. (A color version of this figure is available in the online journal.)

Figure 3. Each curve represents the radial distance vs. time of a BH to the halo center for the simulated galaxy h239. The red dashed horizontal line denotes a distance of three scale lengths ($r_s = 2.8 \text{ kpc}$) from the center; each instance of an orbit crossing this line is defined as a disk passage. The black dashed horizontal line shows the gravitational softening, while the dotted line represents the virial radius. The yellow line indicates the central BH, while the green line denotes an in-spiraling BH which has not yet reached the halo center. The other curves represent BHs which reside predominantly in the halo.
Assuming an accretion luminosity $L \sim \eta M c^2$ with $\eta = 0.1$ and the canonical luminosity of $L_{\text{ULX}} = 10^{39} \text{ erg s}^{-1}$, the BH will accrete and radiate in a high state for a mean duration of 2000 years, though a slower BH may radiate for up to $10^5$ years. However, if the ULX transitions from a high state to a low state at any point, the accretion rate would drastically decrease and the observed emission could continue for much longer.

This simple scenario, however, is not sufficient to reproduce the properties of HLX-1, which is at least 1 kpc away from the plane of its host galaxy. A BH passing through the disk may exhibit X-ray emission of molecular clouds. SMBH gravitational recoil events passing through or near the disk can produce luminosities of ULXs if they pass through or near the disk, which in our scenario may be observable as ULXs.

However, our wandering BH scenario would be feasible if HLX-1 is not an isolated BH, but is traveling with a bound clump of gas and stars. The magnitude and colors of the detected optical counterpart of HLX-1 are consistent with a globular cluster (Soria et al. 2010). This cluster may in fact be the stellar remnants of a stripped dwarf galaxy core that is still bound to the BH. HLX-1 could be similar to the object G1 in M31, a globular cluster that may actually be the nucleus of a stripped dwarf galaxy (Meylan et al. 2001) and harbors the most promising Local Group candidate for an IMBH (Ulvestad et al. 2007). If we presume that the wandering BHs in our simulations retain a nuclear star cluster and gas reservoir from their parent halos, then the instance of a wandering BH passing near the center of the primary could cause instabilities in its accretion disk, triggering an accretion event of sufficient magnitude to power a ULX with a high luminosity as seen in HLX-1. Our simulations do not have sufficient resolution to follow the tidally stripped cores of galaxies in detail, though other simulations have shown that a tidally stripped dwarf galaxy can retain its core after a close passage with the primary (Mayer & Wadsley 2004). Thus, in the likely instance that a wandering BH retains the core of its host galaxy, its passage near the galaxy disk can explain the origin and properties of HLX-1.

Previous studies have estimated luminosities for massive BHs wandering through the ISM, but prior to this Letter none have explored the issue in a cosmological context. Krolik (2004) showed that IMBHs with masses ranging from $10^2$ to $10^4 M_\odot$ can produce luminosities of ULXs if they pass through or near molecular clouds. SMBH gravitational recoil events passing through the disk may exhibit X-ray emission of $L > 10^{39} \text{ erg s}^{-1}$ (Fujita 2009). Mapelli et al. (2008) performed an $N$-body+SPH simulation of IMBHs in a galaxy merger, and found that a few halo IMBHs reside in orbits that pass through the disk, which in our scenario may be observable as ULXs.

### 4. SUMMARY

We provide compelling dynamical scenario for the presence of “wandering” massive BHs in the halos of galaxies. A natural consequence of the hierarchical build up of galaxies in a $\Lambda$CDM scenario, the tidal stripping of galaxies containing seed BHs can populate the halo of a massive disk galaxy with wandering BHs. These objects often retain their original seed mass, are found throughout the galaxy halo, and may pass through the galactic disk at an average rate of $10.6 \text{ Gyr}^{-1}$. We predict that Local Group dwarf galaxies such as the Magellanic Clouds are likely to host IMBHs. Detections of these wandering BHs may give an upper limit to the initial mass of BH seeds and may allow us to differentiate between the various proposed formation mechanisms of such seeds. Our scenario provides a physically motivated explanation for off-nuclear ULXs as IMBHs which have been stripped from their host galaxies, if they retain a gas reservoir/accretion disk that, when dynamically destabilized, might be funneled toward the BH and form an accretion disk.
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