OFF-NUCLEAR AGNs AS A SIGNATURE OF RECOILING MASSIVE BLACK HOLES

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Received 2008 September 3; accepted 2008 September 23; published 2008 October 8

ABSTRACT

During the final phases of inspiral, a massive black hole (MBH) binary experiences a recoil due to the asymmetric emission of gravitational waves. We use recent results from numerical relativity simulations together with models of the assembly and growth of MBHs in hierarchical cosmologies, to study the dynamics, statistics, and observability of recoiling MBHs. We find that, at redshift \( z < 3 \), kicked nonrotating holes are typically found between 1 and 30 kpc from their galaxy centers, while rapidly rotating ones are typically between 10 and a few hundred kpc. A recoiling hole that carries an accretion disk may shine as an “off-nuclear AGN” while it moves away from the center of its host galaxy. We predict that, depending on the hole spin distribution and the duration of their active phase, a population of off-nuclear AGNs may already be detectable at low and intermediate redshifts in present deep Hubble Space Telescope observations. The James Webb Space Telescope may discover tens of wandering AGNs per square degree, most of them moving within their host halos on unbound trajectories.

Subject headings: black hole physics — cosmology: theory — galaxies: nuclei — quasars: general

Online material: color figures

1. INTRODUCTION

The massive black holes (MBHs) observed today at the centers of nearby galaxies (see, e.g., Richstone et al. 1998) are expected to have grown through a series of gas accretion episodes, when they shine as active galactic nuclei (AGNs), and of binary coalescences following the merger of their host galaxies (e.g., Begelman et al. 1980; Volonteri et al. 2003a). Coalescing MBH pairs will give origin to the loudest gravitational wave events in the universe, and are one of the primary targets for the planned Laser Interferometer Space Antenna (LISA; e.g., Sesana et al. 2004). In general, gravitational waves also remove net linear momentum from the binary and impart a kick to the center of mass of the system. The outcome of this “gravitational rocket” has been the subject of many recent numerical relativity studies. Nonspinning holes recoil with velocities below 200 \( \text{km s}^{-1} \) that only depend on the binary mass ratio, whereas much larger kicks are predicted for rapidly rotating holes (Camppanelli et al. 2007; González et al. 2007; Herrmann et al. 2007).

If it is not ejected from the host altogether (e.g., Madau et al. 2004; Merritt et al. 2004; Haiman 2004; Volonteri & Rees 2006; Schnittman & Buonanno 2007), the recoiling MBH will travel some maximum distance and then return to the center subject to dynamical friction (Madau & Quataert 2004). Historically, MBH ejections have been explained to explain the nature of radio jets (Saslaw et al. 1974; Valtonen & Heinämäki 2000) and trails and filaments in spiral and interacting galaxies (e.g., Arp 1976; Arp et al. 2001). Haque-Copilah et al. (1997) present a comprehensive compendium of early ideas on MBH ejections that have been recently revitalized.

Galaxy mergers are frequent at early times, so a significant number of coalescing MBH binaries are expected to form then. Galaxy mergers are also a leading mechanism for supplying gas to their nuclear black holes, and a recoiling hole can retain the inner parts of its accretion disk, providing fuel for a continuing luminous phase along its trajectory. Two possible observational manifestations of gravitational-radiation ejection have then been suggested: (1) off-nuclear AGN activity (Madau & Quataert 2004; Loeb 2007); and (2) broad emission lines that are substantially shifted in velocity relative to the narrowline gas left behind (Bonning et al. 2007). In this Letter we use models of the assembly and growth of MBHs in hierarchical cosmologies to study the dynamics and statistics of recoiling holes, and explore the conditions dictating their observability as off-nuclear AGNs in deep optical and X-ray imaging studies.

2. BASIC MODEL

We follow the assembly history of dark matter halos and associated MBHs via cosmological Monte Carlo realizations of the merger hierarchy from early times to the present in a CDM cosmology, using a model that captures many features of the MBH/AGN population (e.g., luminosity function of quasars and its evolution, black hole mass density today, stellar core formation due to MBH binary mergers). The main assumptions of the models have been discussed elsewhere (e.g., Volonteri et al. 2003a, 2003b; Volonteri 2007 and references therein). MBHs get incorporated through halo mergers into larger and larger structures, sink to the center owing to dynamical friction against the dark matter background, and form bound binaries. The MBHs in galaxies undergoing a major merger (i.e., having a mass ratio \( \geq 1:10 \)) have masses corresponding to the Mass-Arelation of their hosts, i.e., at coalescence the MBH binary mass ratio scales with the central velocity dispersions of the progenitor halos. After the formation of the binary, the black hole pair shrinks and coalesces on a timescale that is shorter than the merger time of the progenitor halos, as a result of stellar and gas-dynamical processes (e.g., Berczik et al. 2006; Mayer et al. 2007).

The recoil velocity \( V_{\text{kick}} \) depends on the binary mass ratio \( q = M_2/M_1 \), on the dimensionless spin vectors of the pair \( a_i \), and on their postage stamp.
and $a_j$ ($0 < a < 1$), and on the orbital parameters. All current numerical data on kicks can be fitted by (Baker et al. 2008)

$$V_{\text{kick}} = v_{\text{e}} e + v_{\perp} (\cos \xi e + \sin \xi e) + v_{\parallel} e, \quad (1)$$

$$v_{\parallel} = A \eta (1 - 4 \eta (1 + B \eta)), \quad (2)$$

$$v_{\perp} = H \eta (1 + q)^{-1} (a_{\perp}^2 - q a_{\parallel}^2), \quad (3)$$

$$v_{\parallel} = K \eta (1 + q)^{-1} \cos (\Theta - \Theta_0)(a_{\parallel}^2 - q a_{\parallel}^2), \quad (4)$$

where $\eta \equiv q/(1 + q^2)$ is the symmetric mass ratio, the indices $\parallel$ and $\perp$ refer to projections parallel and perpendicular to the orbital angular momentum, respectively, $e_{\parallel}$ and $e_{\perp}$ are orthogonal unit vectors in the orbital plane, $\Theta$ is the angle between $(a_{\parallel}^2 - q a_{\parallel}^2)$ and the separation vector at coalescence, and $\Theta_0$ is some constant for a given mass ratio. Here, $A = 1.35 \times 10^4$ km s$^{-1}$, $B = -1.48$, $H = 7540 \pm 160$ km s$^{-1}$, $\xi = 215^\circ \pm 5^\circ$, and $K = (2.4 \pm 0.4) \times 10^5$ km s$^{-1}$ (Baker et al. 2008). We will assume in the following that the orbital parameters and the spin orientations are isotropically distributed. The configuration producing the maximum recoil kick (equal-mass rapidly rotating holes with antialigned spins oriented parallel to the orbital plane, with the pair recoiling along the z-axis), $V_{\text{kick}} = K \eta = 3750$ km s$^{-1}$, is then quite rare (cf. Bogdanović et al. 2007). Little is known about the masses of MBH binaries and their spins. The distribution of all binary mass ratios expected in hierarchical models is found to be relatively flat (Volonteri et al. 2005). In this work we focus on binaries that could give origin to detectable off-center AGNs: we therefore select pairs coalescing at $z < 3$ with total masses $M_1 + M_2 > 10^5 M_\odot$. The distribution of mass ratios for this subsample is shown in Figure 1. For comparison, we have also derived a distribution of mass ratios by Monte Carlo sampling the $z = 0$ MBH mass function (adopting the Schecter fit in Merloni & Heinz 2008), where we have assumed $M_1, M_2 \in \{10^4 M_\odot, 10^5 M_\odot\}$, and we have imposed the condition $M_1 + M_2 > 10^5 M_\odot$. In the sampling of the $z = 0$ mass function most binaries are composed of two rather small holes of similar mass, skewing the mass ratio toward unity ($q = 0.17 \pm 0.23$, implying $V_{\text{kick}} \sim 250$ km s$^{-1}$ for $a = 0.9$). The binary mass threshold we impose in the cosmological sampling also causes a loss of coalescing pairs with $q \approx 1$, because of the limited major merger activity of the corresponding host galaxies (of order of 0.1 Gyr$^{-1}$; White et al. 2007).

Large spins are a natural consequence of prolonged disk accretion episodes (e.g., Bardeen 1970; Volonteri et al. 2005), but can be avoided if AGNs are fed by a series of small-scale, randomly oriented accretion events (King & Pringle 2007). To bracket the uncertainties, we consider here two extreme scenarios: prior to coalescence, both holes are assumed to be either nonrotating or are rapidly spinning with $a = 0.9$. The resulting distributions of kick velocities for these two cases are plotted in Figure 1. Close to 7% of all coalescing nonrotating holes are ejected from the nucleus with kick velocities between 100 and 200 km s$^{-1}$; in the spinning case, 12% get kicks above 100 km s$^{-1}$ and 2% above 500 km s$^{-1}$.

3. DYNAMICS OF RECOILING HOLES

In our default model the host galaxy is described by two spherical mass components: (1) the dark matter follows a Navarro et al. (1997) profile with median concentration $c_{\text{med}} = 9(1 + z)^{-1} (M_{\text{tot}}/8 \times 10^{12} h M_\odot)^{-0.14}$ and scatter around the median of $\Delta \log c = 0.14$ (Bullock et al. 2001); (2) the central stellar profile is modeled instead as an isothermal sphere with one-dimensional velocity dispersion $\sigma$ and density

$$\rho_\star(r) = \frac{\sigma^2}{2\pi G(r^2 + R_{\text{halo}}^2)}, \quad (5)$$

The velocity dispersion is related to the halo circular velocity $V_\star$ at the virial radius by $V_\star = \sqrt{2} \sigma$, (cf. Ferrarese 2002). We truncate $\rho_\star$ at the “bulge” radius $R_B = 6$ kpc ($\sigma/200$ km s$^{-1}$)$^2$; this ensures that the stellar bulge mass within $R_B$ is equal to 1000 $M_\odot$ (Haring & Rix 2004), using $M_B = (10^4 M_\odot) (a/200$ km s$^{-1})^4$ (Tremaine et al. 2002). The stellar profile is also truncated inside a core radius $R_{\text{hi}}$, as stars within the gravitational sphere of influence of the hole, $R_{\text{hi}} = GM_{\text{hi}}/\sigma^2$, are bound to it and do not contribute to dynamical friction. The escape speed from such a two-component potential can be approximated as $v_{\text{esc}} \approx 29(\sigma^2 f(c)^{-1}(1 + c)^{-1} + \ln (R_v/R_{\text{hi}}))^{1/2}$, where $f(c) = \ln (1 + c) - c/(1 + c)$. Following a kick, the radial orbit of a MBH in a spherical potential is governed by

$$\frac{d^2 r}{d t^2} = -\frac{GM(r)}{r^3} - \frac{4\pi G^2 \ln \Delta \rho M_{\text{halo}} f(x) v}{v^2}, \quad (6)$$

where $f(x) \equiv \text{erf}(x - (2 x/\sqrt{\pi}) e^{-x^2})$, $x \equiv vt/\sqrt{2} \sigma$, and the velocity dispersion $\sigma$ is derived from the Jeans’ equation for the composite profile, assuming isotropy (e.g., Binney & Tremaine 1987). Here $M(r)$ describes the total mass of the host galaxy within $r$, $\rho(r)$ is the total density profile, and the second term represents dynamical friction against the stellar and dark matter background (e.g., Binney & Tremaine 1987). Stars and gas bound to the hole are displaced with it: here we assume, in first approximation (see below), that the total ejected mass is $M_{\text{ej}} = 2M_{\text{hi}}$. The Coulomb logarithm, $\ln \Delta$, in equation (6) is taken equal to 2.5 (Gualandris & Merritt 2008).
A MBH ejected with $V_{\text{kick}} < v_{\text{esc}}$ will oscillate about the nucleus losing orbital energy via dynamical friction (Madau & Quataert 2004; Blecha & Loeb 2008). Note, however, that the assumption that the central stellar density profile is unmodified by the heating effect of dynamical friction tends to artificially shorten the MBH decay timescale (Boylan-Kolchin et al. 2004). Moreover, while in a spherical potential the hole will remain on a purely radial orbit, in a realistic triaxial galaxy the hole acquires angular momentum and does not return through the dense center. This is known to reduce the effect of friction and to increase the decay time by a factor of a few relative to the spherical case (Vicari et al. 2007). To approximate the delaying effect of a triaxial geometry and of a decreasing core density, we have also run a case in which MBHs move in a bulgeless pure NFW potential. The two left panels in Figure 2 show two examples of orbital decays for $V_{\text{kick}} = 0.6 v_{\text{esc}}$, $0.8 v_{\text{esc}}$ in a NFW+bulge (“short decay”) and NFW only (“long decay”) model. The right panel depicts the ensuing distributions of MBH displacements for all $z < 3$ kicked binaries in our cosmological realizations, with and without spin. In all but the NFW+bulge $a = 0$ case, a significant fraction of recoiling holes are found between 10 and 100 kpc from their galaxy centers (at redshift 2, a displacement of 10 kpc corresponds to an angular size of 1.2°). Note that, in our realizations, only 0.1%–0.3% of all MBHs at a given cosmic epoch are actually off-center.

4. OFF-NUCLEAR AGNs

A recoiling hole that carries an accretion disk may be detected as it moves away from the center of its host. To assess the detectability of a subpopulation of off-nuclear AGNs in deep imaging surveys, we assume that all recoiling holes accrete at a fraction $f_{\text{e}}$ of the Eddington rate $M_{\text{Edd}} = 4\pi GM_{\text{BH}} m_{\text{j}} / c \sigma_{T}$, with radiative efficiency $\epsilon$. The rest-frame optical part of their spectrum is modeled as a multicolor Shakura & Sunyaev (1973) disk with maximum temperature $kT_{\text{max}} \sim 1$ keV ($M_{\text{disk}}/M_{\text{BH}})^{1/4}$, following a power-law with $L_{\nu} \propto \nu^{-\alpha}$ at $h\nu < kT_{\text{max}}$. The X-ray spectral energy distribution is described by a power law with photon index $\Gamma = 1.9$ and an exponential cutoff at 500 keV (Marconi et al. 2004). The duration of the luminous phase depends on the amount of disk material out to the radius $R_{\text{out}} \approx GM_{\text{BH}}/V_{\text{kick}}^2$ that is carried by the hole. In the case of an $\alpha$-disk, this is given by (Loeb 2007)

$$M_{\text{disk}} \approx (1.9 \times 10^6 M_{\odot}) \alpha_{-1}^{-0.8} (\epsilon_{-1} f_{\text{e}})^{-0.6} M_{\odot}^{-2/3} V_{\text{kick}}^{-2.8},$$

(7)

where $\epsilon_{-1} = \epsilon/0.1$, $M_{\odot} = M_{\text{BH}}/10^7 M_{\odot}$, $V_{\text{kick}} = V_{\text{kick}}/10^3$ km $s^{-1}$, and $\alpha_{-1} = \alpha/0.1$ is the viscosity parameter. The condition $M_{\text{disk}} \leq M_{\text{BH}}$ requires

$$V_{\text{kick}} \geq 550 \text{ km s}^{-1} \alpha_{-1}^{-0.28} (\epsilon_{-1} f_{\text{e}})^{-0.21} M_{\odot}^{0.43}.$$  

(8)

When the above equation is not satisfied, we impose $M_{\text{disk}} = M_{\text{BH}}$ corresponding to an AGN lifetime of $t_{\text{max}} = c \sigma_{T} / (4\pi G M_{\text{BH}} f_{\text{e}}) \approx 4.5 \times 10^7$ yr ($\epsilon_{-1} f_{\text{e}}$). A hole/disk system with $(M_{\odot}, \alpha, \epsilon_{-1} f_{\text{e}}, M_{\text{BH}}) = (1, 0.1, 0.1, 1, M_{\odot})$ recoiling with $V_{\text{kick}} = 500$ km s$^{-1}$ could still be shining as far as 30 kpc away from the center of its host and appear as an off-center quasar.

Figure 3 shows the expected number of detectable off-center AGNs in deep and large surveys such as the Chandra Deep Field North and HST-COSMOS, and the predicted counts for future observations with the JWST. We set the minimum resolvable separation between a recoiling MBH and its galaxy centroid to twice the telescope resolution (i.e., 0.2° for HST and JWST, 1° for Chandra). We do not correct our counts for obscuration or Compton-thick sources. In the HST-COSMOS fields (2 deg$^2$) we expect ~30 sources for the best case of large
kicks (spinning holes), long decay timescales (no bulge), and long active phase ($f_a = 0.1$, $\alpha = 0.01$), but less than 1 in the unfavorable cases. In the small CDF-N field we expect at most 1 off-nuclear AGN in the most optimistic case, while in the $0.77 \degree$ X-ray Chandra-COSMOS we can expect up to a few sources. Follow-up X-ray observations will be essential for the identification of the source as a genuine off-center AGN. The JWST yields the highest counts, about 40 sources per square degree in the best scenario.

5. SUMMARY

Motivated by recent numerical simulations of black hole binary coalescence and ensuing gravitational-wave kicks, and by the large rate of MBH binary formation expected during the assembly of massive galaxies, we have assessed the detectability of recoiling holes that retain the inner parts of their accretion disk along their trajectory and shine as off-nuclear AGNs. While the search for kinematically offset QSOs in the Sloan Digital Sky Survey (SDSS) indicates that large kicks rarely occur during a long-lasting active phase (with an upper limit on the incidence of wandering AGNs with line-of-sight velocities above $800 \text{ km s}^{-1}$ of $0.2\%$; Bonning et al. 2007), a strong candidate for a rapidly recoiling MBH has been recently found in the SDSS database by Komossa et al. (2008) showing an emission-line spectrum offset by 2650 km s$^{-1}$ (but see Bogdanović et al. 2008) and Dotti et al. (2008) for a different interpretation). Here, we have traced the formation history of MBH binaries in galaxies through cosmological Monte Carlo realizations of the halo merger tree, assigned a kick velocity to every MBH binary coalescence expected in our simulation, followed the orbital evolution of the ejected hole in the potential of the host, and determined the duration of an off-nuclear AGN phase on scales that can be resolved by current and future optical, IR, and X-ray satellites. The basic conclusion of this Letter is that, depending on the hole spin distribution and the duration of their active phase, a population of off-nuclear AGNs may already be detectable at low and intermediate redshifts in present deep HST observations. The JWST should discover tens of wandering AGNs per square degree, moving within their host halos on unbound trajectories.

Support for this work was provided by NASA grants NNG04GK85G and NNX08AV68G (P. M.) and NNX07AH22G and SAO-G07-8138 C (M. V.).