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CORE FORMATION IN GALACTIC NUCLEI DUE TO RECOILING BLACK HOLES

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ABSTRACT

Anisotropic gravitational radiation from a coalescing black hole binary can impart a recoil velocity of up to several hundred kilometers per second to the remnant black hole. We examine the effects of recoiling massive black holes on their host stellar bulges, both for holes that escape their host and for those that return to the galactic center via dynamical friction. We show that removal of a black hole via radiation recoil generally results in a rapidly formed central core in the stellar system, with the effect being largest when the hole stays bound to the bulge and the recoil velocity is comparable to the bulge velocity dispersion. Black hole recoil therefore provides a mechanism for producing cores in some early-type galaxies, but it is expected to be most efficient in faint elliptical galaxies that are known to have steep density profiles. We argue that these results may hint at a significant role for gas in facilitating the coalescence of binary black holes in faint (power-law) early-type galaxies.

Subject headings: galaxies: bulges — galaxies: structure — methods: *N*-body simulations

1. INTRODUCTION

When galaxies with central black holes merge, dynamical friction will drive the holes toward the center of the remnant, creating a black hole binary. If the binary separation a_b becomes small enough that gravitational wave emission is significant, the binary will rapidly coalesce. The primary mechanism for reducing a_b is three-body interactions: stars with orbits passing close to the binary are scattered to high velocities, allowing the binary's orbit to decay (Begelman et al. 1980). The timescale for removing stars from low angular momentum orbits (the "loss cone") via gravitational slingshot is much shorter than the (collisional) timescale for repopulating the loss cone in a spherical galaxy (Makino & Funato 2004). The latter is many gigayears or longer (Milosavljević & Merritt 2003), implying that the decay of the binary would stall before gravitational waves become important.

Recent work has found that a number of processes can increase the hardening rate: Brownian motion of the binary (Quinlan & Hernquist 1997; Chatterjee et al. 2003), triaxiality of the stellar bulge (Yu 2002), interaction with a massive accretion disk (Armitage & Natarajan 2002), and reejection of previously ejected stars (Milosavljević & Merritt 2003) all may help the binary coalesce. Coalescing black hole binaries radiate gravitational waves that carry away energy and both angular and linear momentum. The remnant black hole then receives a recoil velocity $v_{\rm kick}$ in the range of 100–500 km s^{-1} (Favata et al. 2004). The black hole can therefore either leave the host galaxy (if $v_{\rm kick} > v_{\rm esc}$) or oscillate around the center of the galaxy, its orbit decaying because of dynamical friction. Radiation recoil has a number of astrophysical implications, from constraining the growth of high-redshift quasars to the possibility of an intergalactic population of massive black holes (Madau & Quataert 2004; Merritt et al. 2004; Haiman 2004). In this Letter we use numerical experiments to study the reaction of stellar bulges to coalescing black holes at their centers (also see Merritt et al. 2004).

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2. SIMULATIONS

We perform *N*-body simulations to follow the evolution of a stellar bulge containing a central supermassive black hole that has been given a recoil velocity immediately following a binary coalescence. The (purely gravity) simulations are performed using GADGET (Springel et al. 2001), a publicly available *N*-body tree code. We generate initial conditions using the equilibrium distribution function for a spherical stellar system with a central black hole (Tremaine et al. 1994). Since dark matter contributes a small fraction of the mass in the inner tens of parsecs of a typical elliptical galaxy, we ignore its contribution in our simulations. We use the Hernquist (1990) model for the stellar system; this model is attractive because of its simple form and the fact that in projection it closely resembles the de Vaucouleurs $R^{1/4}$ surface brightness law. Furthermore, energy transfer from orbital decay of a black hole binary to surrounding stars is expected to transform dense cusps associated with the growth of a black hole to profiles no steeper than $\rho \propto r^{-1}$ (Milosavljević & Merritt 2001), so an r^{-1} cusp serves as an upper limit for the expected stellar distribution around a coalescing black hole binary.

The density profile of the Hernquist model is given by

$$\rho(r) = \frac{M_*}{2\pi a^3}\frac{a}{r}\frac{1}{(1+r/a)^3},$$

with total mass M_* and scale radius a, related to the half-mass radius by $r_{1/2} = (1+\sqrt{2})a$. The escape velocity from the center of the system and the dynamical time and circular velocity at the scale radius are given by $v_{\rm esc} = (2GM_*/a)^{1/2}$, $t_{\rm dyn} \equiv t_{\rm dyn}(r=a) = (3\pi^2 a^3/GM_*)^{1/2}$, and $v_{\rm circ} \equiv v_{\rm circ}(r=a) = (GM_*/4a)^{1/2}$. We consider only spherically symmetric isotropic models, in which case the phase-space distribution function depends on energy alone and can be calculated from Eddington's formula (Binney & Tremaine 1987):

$$f(E) = \frac{1}{\sqrt{8}\pi^2}\int_0^E \frac{d^2\rho}{d\psi^2}\frac{d\psi}{\sqrt{E-\psi}}.$$

Here ψ is the negative of the gravitational potential,

$$\psi = \frac{GM_*}{r+a} + \frac{GM_{\rm BH}}{r},$$

and E is the binding energy per unit mass ($E \geq 0$). We note that without a central black hole ($M_{\rm BH} = 0$), the only accessible energies are $0 \leq E \leq GM_*/a$, and $f(E)$ is analytic. Adding a black hole allows particles to have $E > GM_*/a$, and $f(E)$ must be computed numerically. We initialize particle positions from the mass profile and then obtain each particle's energy from the calculated distribution function: $P(E|r) \propto f(E)\,[\psi(r) - E]^{1/2}$.

In the presence of a central point mass, $f(E)$ is not a monotonic function of energy [see Tremaine et al. 1994 for plots of $f(E)$ for several values of $M_{\rm BH}/M_*$]. Stability to radial perturbations must therefore be determined numerically. We have tested that our simulations (without black hole recoil) indeed maintain equilibrium for many dynamical times. Such systems are expected to evolve on the two-body relaxation timescale (Spitzer & Hart 1971), forming a $\rho \propto r^{-7/4}$ cusp on small scales (Bahcall & Wolf 1976; Preto et al. 2004), but the relaxation time is on the order of 10^{10} yr or longer in a typical elliptical galaxy, much longer than the timescales relevant to this Letter.

We set the black hole–to–stellar bulge mass ratio to be $M_{\rm BH}/M_* = 1/300$ and simulate cases with $v_{\rm kick}$ both above and below $v_{\rm esc}$ for comparison. We use $N = 10^6$ equal-mass particles to represent the stellar bulge and a force softening of $\epsilon = 0.0176a$ that allows us to resolve down to $\sim 0.2 r_h$, where r_h is the sphere of influence of the black hole given by $M(<r_h) \equiv 2M_{\rm BH}$ (a definition equivalent to the standard $r_h = GM_{\rm BH}/\sigma_*^2$ for a singular isothermal sphere). Typically, r_h is a small fraction of the scale radius of the stellar system, e.g., $r_h = 0.089a$ for $M_{\rm BH}/M_* = 1/300$. Since gravity is the only physics in the simulations, our results can be interpreted at different length and mass scales by rescaling: for $a \to \lambda a$ and $M \to \beta M$, take $v \to (\beta/\lambda)^{1/2} v$ and $t \to (\lambda^3/\beta)^{1/2} t$. For reference, a model with stellar mass $4 \times 10^8\ M_\odot$ and a scale radius of $a = 42.5$ pc has $t_{\rm dyn} = 1.15$ Myr, $v_{\rm circ} = 100$ km s^{-1}, $v_{\rm esc} = 283$ km s^{-1}, and a projected velocity dispersion at one-eighth the effective radius R_E of $\sigma_p\,(R_E/8) \approx 70$ km s^{-1}.

3. STELLAR DENSITY PROFILES

A consequence of gravitational radiation recoil is evolution of the density profile $\rho(r)$ of the stellar system. Figure 1 compares $\rho(r)$ at three epochs soon after the recoil of the black hole. Within $0.1t_{\rm dyn}$ after the black hole leaves the central region of the bulge, $\rho(r)$ flattens substantially. A core of $\sim r_h$ forms and remains for the entire length of the simulation.

Three primary mechanisms could contribute to the rapid flattening of the inner stellar density profile: (1) departure of stars bound to the black hole, (2) energy deposition due to dynamical friction on the black hole, and (3) reequilibration of the stellar system due to the departure of the black hole. We discuss each one in turn.

In process 1, some stars move with the black hole as it recoils from the galactic nucleus. The mass of stars M_b bound to the black hole is a strongly decreasing function of the recoil velocity: for $v_{\rm kick}/v_{\rm circ} = (0, 0.75, 1, 2, 3)$, our simulations yield $M_b/M_{\rm BH} = (0.769, 0.394, 0.249, 0.0157, 0.0012)$. The removal of stars bound to the recoiling black hole is therefore too small to account for the mass deficit of $\sim 2M_{\rm BH}$ seen in the simulations.

Dynamical heating due to energy transferred to stars from the decay of the black hole's orbit (process 2) is relatively slow. The heating timescale is $\sim|E/\dot{E}|$, which is about $5.7t_{\rm dyn}$ (in the $v_{\rm kick} = 2v_{\rm circ}$ run), given that the change in the black hole energy from start to apocenter is $\Delta E/E_{t=0} \approx -0.076$ and that the time required for the black hole to reach apocenter is $\approx 0.43t_{\rm dyn}$. In comparison, Figure 1 shows core development over a much shorter timescale ($<0.1t_{\rm dyn}$), indicating that dynamical friction heating is not the dominant process in the *initial* core formation. Its longer term effect is discussed below.

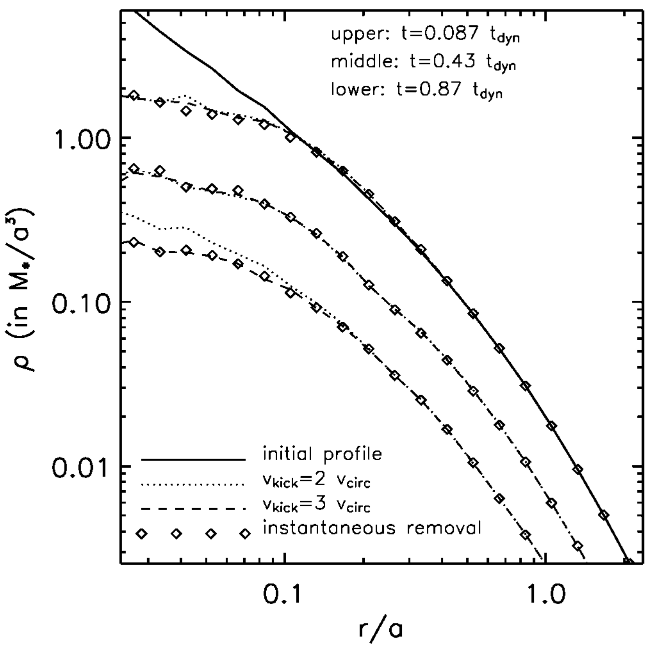

FIG. 1.—Early evolution of the stellar density profile (in units of M_*/a^3) after the black hole (with $M_{\rm BH}/M_* = 1/300$) recoils (at $t = 0$). Three simulations are compared: recoil velocities above (*dashed line*) and below (*dotted line*) the bulge escape velocity $v_{\rm esc} = 2.83v_{\rm circ}$, and a test model in which the hole is removed instantly at $t = 0$ (*diamonds*). All three runs produce a density core inside $\sim r_h$ within $0.087t_{\rm dyn}$ after the recoil; ρ evolves little afterward, so for clarity we offset ρ at $0.43t_{\rm dyn}$ and $0.87t_{\rm dyn}$ by a factor of 3 and 8. For reference, if $M_* = 4 \times 10^8\ M_\odot$ and $a = 42.5$ pc, $t_{\rm dyn} = 1.15$ Myr and $r_h = 0.089a = 3.78$ pc.

To study the effects due to process 3, we first note that the timescale for the stellar system to readjust after the black hole ejection is the crossing time of the core, which is $\approx 0.075t_{\rm dyn}$ for a core of $\approx 0.14a$ shown in Figure 1. This timescale is comparable to the core formation time of $\lesssim 0.087t_{\rm dyn}$; the stellar system therefore has sufficient time to respond to the black hole kick by producing the observed flattening of $\rho(r)$. We test the hypothesis that process 3 dominates the early evolution of the stellar system by performing a simulation in which we remove the black hole instantaneously from an initial equilibrium configuration and then allow the system to evolve to its new equilibrium (also see Merritt et al. 2004). This test eliminates evolution due to gravitational interactions between the black hole and the stars and mimics the effect of $v_{\rm kick} \gg v_{\rm esc}$. Figure 1 compares the stellar $\rho(r)$ for this model with the $v_{\rm kick} = 2v_{\rm circ}$ and $3v_{\rm circ}$ simulations. This figure shows that at early times, all three simulations behave quite similarly; in fact, $\rho(r)$ is virtually indistinguishable at both $0.087t_{\rm dyn}$ and $0.43t_{\rm dyn}$. This supports the hypothesis that dynamical adjustment to the absence of the black hole is responsible for the initial core formation.

The longer term evolution of the stellar density distribution

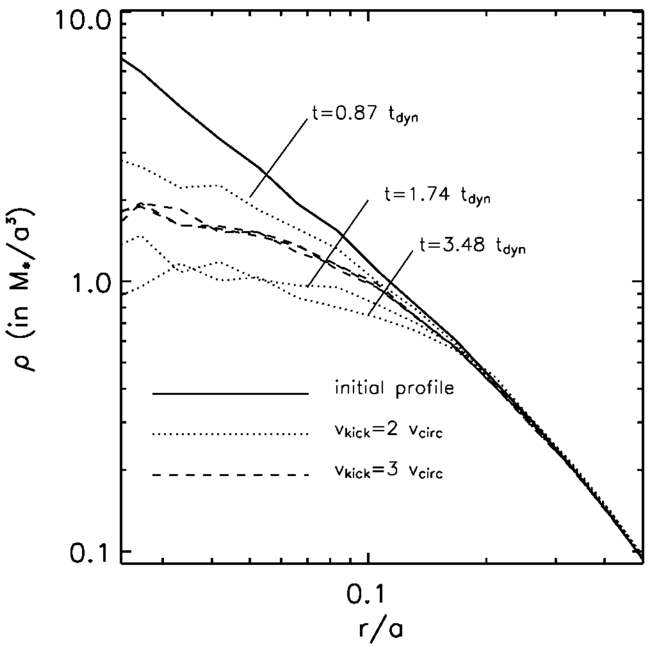

FIG. 2.—Evolution of the stellar density profile at $0.87t_{\rm dyn}$, $1.74t_{\rm dyn}$, and $3.48t_{\rm dyn}$ for the same runs as in Fig. 1. For $v_{\rm kick} = 3v_{\rm circ} > v_{\rm esc}$, the density profile remains constant once the hole leaves the galactic nucleus, while for $v_{\rm kick} = 2v_{\rm circ} < v_{\rm esc}$ there is both early evolution as the stellar bulge dynamically adjusts to the absence of the hole and later evolution due to dynamical friction heating as the black hole returns to the center of the stellar system.

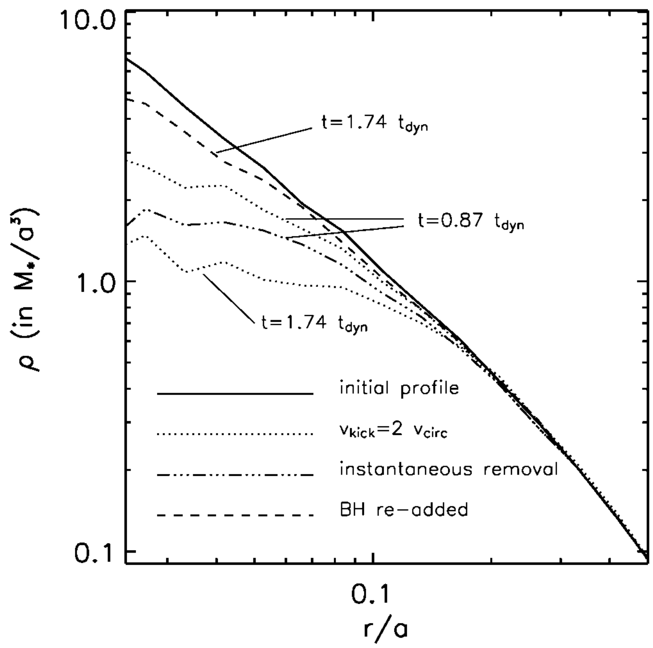

FIG. 3.—Comparison of the $v_{\rm kick} = 2v_{\rm circ} < v_{\rm esc}$ simulation (*dotted curves*) with a calculation in which the hole is instantaneously removed at $t = 0$ and reintroduced at $0.87t_{\rm dyn}$. The results highlight the role of dynamical friction: the static reintroduction of a black hole to the core causes the rebuilding of a central cusp by $t = 1.74t_{\rm dyn}$, while the true simulation shows core formation by dynamical friction heating as the hole returns to the galactic center.

is shown in Figure 2. For the run where the black hole escapes ($v_{\rm kick} = 3v_{\rm circ}$), $\rho(r)$ is essentially unchanged from $0.43t_{\rm dyn}$ up to the end of our simulation at $3.48t_{\rm dyn}$, at which point the black hole is more than 13a from the center of the stellar system. The evolution is qualitatively different, however, if the black hole returns. For $v_{\rm kick} = 2v_{\rm circ}$, the core density at $0.87t_{\rm dyn}$ is higher than that with $v_{\rm kick} > v_{\rm esc}$. This effect is due to the presence of the black hole (and the stars bound to it) on its return path through the center of the system. Subsequently, however, the core becomes less dense relative to the $v_{\rm kick} = 3v_{\rm circ}$ run, at both $1.74t_{\rm dyn}$ and $3.48t_{\rm dyn}$. From $3.48t_{\rm dyn}$ onward, $\rho(r)$ of the $v_{\rm kick} = 2v_{\rm circ}$ run is essentially unchanged and the black hole is nearly stationary at the center of the stellar potential. In both simulations, the velocity dispersion tensor remains isotropic and the bulge remains mostly spherical.

To explore the origin of the additional flattening in the $v_{\rm kick} = 2v_{\rm circ}$ calculation, we perform a control simulation in which we reintroduce the black hole into the "instantaneous removal" simulation at $0.87t_{\rm dyn}$. In this case, dynamical friction is irrelevant (as in the instantaneous removal simulation) but the stellar system readjusts because of the black hole. Figure 3 shows that the equilibrium profile attained after readdition of the black hole is significantly steeper than that found in the $v_{\rm kick} = 2v_{\rm circ}$ simulation at $t = 1.74t_{\rm dyn}$. This comparison test shows that the additional flattening seen in the $v_{\rm kick} = 2v_{\rm circ}$ run is due to the heating of the stellar system by the black hole as dynamical friction returns it to the center of the galaxy. Even though this input of energy is less than 1/1000 of the total energy of the initial stellar system (for $v_{\rm kick} = 2v_{\rm circ}$), it is enough to ensure that the new equilibrium differs substantially from the original at small radii.

The results of this section show that for recoil velocities $v_{\rm kick} \gtrsim v_{\rm circ}$, a steep density cusp is difficult to maintain in a stellar system containing a coalescing black hole binary (simulations with $v_{\rm kick} \lesssim v_{\rm circ}$ show little change in the density profile of the bulge). We now turn to the implications of these results.

4. DISCUSSION AND IMPLICATIONS

In a hierarchical cosmology, mergers of galaxies with central black holes will lead to the formation of black hole binaries. This process occurs on timescales significantly shorter than the Hubble time only in the case of major mergers, where the mass ratio of the two galaxies is within a factor of about 3 (Volonteri et al. 2003). If the timescale for coalescence of the binary black holes is shorter than the typical time between galaxy mergers, it is likely that gravitational radiation recoil will have interesting observational consequences, most notably for early-type galaxies.

Observations of early-type galaxies show that their density profiles fall into two distinct classes (Ferrarese et al. 1994; Lauer et al. 1995). Power-law galaxies, which tend to be faint, have surface brightness profiles that are steep and do not seem to exhibit a significant break at small radii. Core galaxies are generally brighter and have a discernible break in their surface brightness profiles. Faber et al. (1997) discuss several possibilities for the origin of core galaxies. In particular, they and others have argued that the formation of a black hole binary can produce a core in a stellar system, both by the gravitational slingshot of stars during the decay of the binary and by Brownian motion of the binary (Ebisuzaki et al. 1991; Makino & Ebisuzaki 1996; Quinlan & Hernquist 1997; Faber et al. 1997; Milosavljević & Merritt 2001; Ravindranath et al. 2002; Milosavljević et al. 2002). This process of central density reduction due to loss cone depletion should be ubiquitous in galaxies with binary black holes, reducing their central cusps to $\rho \propto r^{-1}$ or shallower.

We have demonstrated in this Letter that in addition to these mechanisms for core formation, gravitational recoil in the predicted velocity range of 100–500 km s^{-1} generically results in the formation of a core in the density profile of a stellar system, which produces a core in the surface brightness analogous to that seen in bright elliptical galaxies. (We note that the late-time *volume* density profiles in Figs. 1–3 also yield *surface* densities that are nearly flat inside ≈ 1–$2r_h$ but do not affect the projected aperture velocity dispersions noticeably.) For recoil velocities $v_{\rm kick} > v_{\rm esc} = 2.83 v_{\rm circ}$ (for the Hernquist model), which are rare for Milky Way–size bulges or larger but plausible for smaller galaxies, we expect the black hole recoil to produce stellar cores that are largely independent of $v_{\rm kick}$ since stellar reequilibration is the dominant process. For $v_{\rm kick} < v_{\rm esc} = 2.83 v_{\rm circ}$, however, recoils of a given $v_{\rm kick}$ have a larger effect on the inner stellar profile in smaller galaxies because $v_{\rm kick}/v_{\rm circ}$ is larger. In addition, black holes that do not escape their host galaxy tend to create larger cores via dynamical friction than black holes that do escape. In the context of these results, it is thus the existence of power-law galaxies that must be explained. Indeed, one might naïvely have predicted that smaller, fainter galaxies would have proportionally larger cores (in units of r_h) because of gravitational recoil, contrary to what is observed.

One resolution of this difficulty is that black holes are rare in low-mass galaxies. The dynamical constraints on black holes in such galaxies are indeed rather poor, although there are suggestive hints of a substantial population of $\sim 10^5$–$10^6\ M_\odot$ black holes in dwarf Seyfert galaxies (e.g., Filippenko & Ho 2003; Barth et al. 2004; Greene & Ho 2004). There are also plausible mechanisms that could rebuild a cusp. A natural explanation for reforming a power-law surface brightness profile is star formation accompanying a dissipative merger of gas-rich galaxies. This scenario requires the black hole binary to coalesce—and the recoiling hole to return to the galactic nucleus—*before* the starburst is completed. If stellar dynamical processes alone are responsible for hardening the binary, the timescale is typically greater than 10^8 yr even in the case of highly triaxial galaxies (Yu 2002). This is comparable to, or somewhat longer than, the expected duration of a merger-triggered starburst (e.g., Mihos & Hernquist 1996). An intriguing possibility is that the presence of substantial amounts of gas can greatly reduce the time for binary black holes to coalesce. If this is the case, as argued by, e.g., Armitage & Natarajan (2002) and Escala et al. (2004), then it is plausible that a black hole binary can coalesce before the end of a starburst and a stellar cusp can be reformed, thus helping explain the existence of power-law early-type galaxies that are built hierarchically. We note that given this scenario, in future work it would be interesting to consider the dynamics of recoiling holes in the presence of a surrounding accretion disk.

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