DYNAMICS OF KICKED AND ACCELERATED MASSIVE BLACK HOLES IN GALAXIES

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Received 2007 December 19; accepted 2008 February 12

ABSTRACT
A study is made of the behavior of massive black holes in disk galaxies that have received an impulsive kick from a merger or a sustained acceleration from an asymmetric jet. The motion of the gas, stars, dark matter, and massive black hole are calculated using the GADGET-2 simulation code. The massive black hole escapes the galaxy for kick velocities above about 600 km s\(^{-1}\) or accelerations above about 4 \(\times 10^{-8}\) cm s\(^{-2}\) over timescales of the order of 10\(^8\) yr. For smaller velocity kicks or smaller accelerations, the black hole oscillates about the center of mass with a frequency that decreases as the kick velocity or acceleration increases. The black hole displacements may give rise to observable non-axisymmetric morphological features. Section 4 discusses the results for the cases of one-sided jet motion of the gas, stars, dark matter, and massive black hole. Section 5 gives the conclusions of this work.

Subject headings: galaxies: kinematics and dynamics — galaxies: nuclei — galaxies: structure

1 INTRODUCTION
Recent breakthroughs in numerical general relativistic hydrodynamics have led to predictions of large recoil velocities of merged binary black holes (BHs) as the binary radiates away linear momentum as gravitational waves during the final stages of merger (González et al. 2007; Campanelli et al. 2007). The velocity or “kick” of the merged black hole in the nucleus of a galaxy can be as large as 4000 km s\(^{-1}\), which would be more than enough to eject the BH from the galaxy. However, it is more likely that typical kick velocities are much smaller (<200 km s\(^{-1}\)) because of gas accretion by the merging BHs and a large ratio of the masses of the two initial BHs (Bogdanović et al. 2007).

In another situation, the asymmetric or one-sided jet from the disk around a massive BH can give a steady acceleration of the black hole over the Salpeter timescale \(\sim 10^8\) yr (Shklovsky 1982; Tsygan 2007), and this may push the BH out of the galaxy. Wang et al. (1992) pointed out that some combinations of dipole and quadrupole symmetry magnetic field components threading the accretion disk of the BH can produce a much stronger magnetically driven jet on one side of the disk than on the other. It is of interest that a bright quasar has been discovered that is not inside a massive galaxy (Magain et al. 2005), and so it may have been ejected from a galaxy.

Field galaxies themselves may be morphologically or dynamically nonaxisymmetric, even in the absence of tidal companions (Baldwin et al. 1980). Up to 30% of field galaxies are nonaxisymmetric (Komreich et al. 1998; Zaritsky & Rix 1997). If central supermassive BHs receive impulses from mergers or asymmetric jets, causing motion in the host galaxy, some of that motion may be transmitted to the galaxy via dynamical friction. We may expect that in such galaxies, morphological or dynamical effects may be seen in the stellar or gas distribution as a result of this transfer of momentum.

The objective of this work is to determine the BH displacement as a function of time for different initial kick velocities and directions, different accelerations due to a one-sided jet, and different BH masses. A second objective is to study the influence the BH displacement has on the morphology and the kinematics of the host galaxy and determine whether nonaxisymmetricities are attributable to motions of the BH. We have chosen to concentrate on the morphology of disk galaxies rather than ellipticals, because the dynamics of disk galaxies, being supported by bulk rotation rather than random motions, are more likely to exhibit signs of disturbance if the motion of the BH interferes with that rotation.

Section 2 of the paper describes the initial conditions and the numerical methods used. Section 3 discusses the results, first for the case of velocity kicks of a 10\(^8\) \(M_\odot\) BH and then for a 10\(^9\) \(M_\odot\) BH. Section 4 discusses the results for the cases of one-sided jets, first for the 10\(^8\) \(M_\odot\) BH and then for the 10\(^9\) \(M_\odot\) BH. Section 5 gives the conclusions of this work.

2 NUMERICAL METHODS AND INITIAL CONDITIONS
The computations for this experiment were performed using the N-body, smoothed particle hydrodynamics (SPH) GADGET-2 code of Springel (2005). We have added the ability to assign a particular particle an arbitrary acceleration, in addition to the calculated gravitational acceleration, in order to simulate forces due to an asymmetric jet. This particle is given significant mass and placed initially at the center of the galaxy. Each computation was performed on a cluster of 32 2.0 GHz processors and typically required 3–4 days.

The considered galaxy consists of a dark halo, a stellar disk and bulge, and a gas disk. The gas particles are treated gravitationally and hydrodynamically, while the other particles interact gravitationally. The halo, disk, and bulge particles differ in mass and spatial distribution, but are otherwise treated identically in the
computation. The central stellar bulge is modeled as a Plummer (1915) sphere, which has a density distribution of a relaxed $n = 5$ polytrope given by

$$\rho(r) = \frac{3}{4\pi R_b^2} \frac{M_b}{(1 + (r/R_b))^2} \left[1 + (r/R_b)^2\right]^{5/2},$$ (1)

with bulge scale radius $R_b = 1$ kpc and mass $M_b = 10^{10} M_\odot$.

This bulge is placed at the center of a softened isothermal dark matter halo of density profile

$$\rho(r) = \frac{\rho_0}{1 + (r/r_c)^2}$$ (2)

and total mass $5.6 \times 10^{11} M_\odot$, with a cutoff radius 50 kpc and core radius $r_c = 2$ kpc. A stellar and gas disk of scale radius $r_0 = 3.5$ kpc and cutoff radius $R = 50$ kpc of exponential surface density

$$\Sigma(r) = \frac{M_d}{2\pi r_0^2} \left[1 - e^{-r/r_c}(1 + R/r_0)\right] e^{-r/r_c} \left(\frac{10}{C_0}\right)^{5/2}$$ (3)

surounds the bulge with total mass $M_d = 2.8 \times 10^{10} M_\odot$, at a gas mass fraction of 25%. In the vertical direction, the disk particles are given velocity dispersions and uniformly random initial positions corresponding to a disk of 1 kpc thickness.

The total dynamical mass of the galaxy model is therefore $M_{\text{tot}} = 5.98 \times 10^{11} M_\odot$. This model was chosen to conform to parameters observed in giant disk galaxies, such as those described by Rownd et al. (1994) and Dickey et al. (1990) in particular, a circular velocity of 220 km s$^{-1}$ with a 10 km s$^{-1}$ velocity dispersion in the disk. The total number of simulation particles used in the model was $2 \times 10^8$ for most model runs.

In one sequence of runs, we gave the central black hole an initial impulsive velocity kick to simulate the recoil from the merging of two black holes. In one sequence, the kick was in the plane of the galaxy, and in the other, it was normal to the galaxy plane. The black hole was given no further acceleration. In another sequence of two black holes. In one sequence, the kick was in the plane of the galaxy, and in the other, it was normal to the galaxy plane. The relation between initial velocity and initial position of the kick to be efficiently transferred to the galaxy via dynamical friction.

3. VELOCITY KICKS

3.1. Black Hole Mass $10^8 M_\odot$

In this series of model runs, the BH was placed near the center of mass of the galaxy and given an initial velocity in the plane of the disk. The series of initial velocities started at zero and progressed in increments of 50 km s$^{-1}$ up to a velocity of 650 km s$^{-1}$, at which the central BH escaped the galaxy. It is interesting to note that this critical kick velocity is significantly larger than the escape velocity of the center of the galaxy, which was measured to be 450 km s$^{-1}$. We attribute this excess to dynamical friction.

The general behavior of the BH after receiving the kick was to oscillate about the model center of mass approximately sinusoidally (Fig. 1). The amplitude and frequency of the motion remain roughly constant over a period of 0.5 Gyr, but depend on the kick magnitude, as shown in Figure 2. Error bars represent the 1 $\sigma$ standard deviation of these values as calculated for each cycle. For kick velocities below 400 km s$^{-1}$, the relation between ampi- tude and initial velocity $V_0$ is linear, with $A(V_0)(\text{kpc})^{-1} = (9.3 \pm 0.53) \times 10^{-3} V_0(\text{km s}^{-1})^{-1} + (0.088 \pm 0.082)$. For initial velocities above 400 km s$^{-1}$, the BH amplitude is beyond the visible disk and becomes exponentially large until it escapes at 650 km s$^{-1}$. The frequency of the oscillation is also linear, with $f(V_0)(\text{Gyr})^{-1} = (17.64 \pm 0.57) - (0.0317 \pm 0.0015) V_0(\text{km s}^{-1})^{-1}$.

Smaller kicks resulted in the BH remaining in the more massive parts of the galaxy within 10 kpc for their entire cycles, allowing momentum from the kick to be efficiently transferred to the galaxy via dynamical friction. In these cases, damping of the oscillation was on timescales of 0.7 Gyr. The galaxy center of
mass thus gained velocity in the direction of the kick, resulting in the offsets depicted in the low kick amplitude curves in Figure 2. Larger kicks, while imparting greater momentum to the BH, caused it to spend a great deal of time in the thin regions of the galaxy. Qualitative results were similar to the plane of the galaxy. This is the behavior we observed throughout this set of runs.

A series of runs was also conducted with the velocity kick normal to the plane of the galaxy. Qualitative results were similar to the case in which the kick is in the plane of the galaxy, with the BH oscillating roughly sinusoidally through the center of mass. The amplitude–initial kick relation remains linear for a slightly smaller range of kicks, however (Fig. 5). For velocity kicks less than 350 km s$^{-1}$, the amplitude–initial kick relation is $A(V_0)(\text{kpc})^{-1} = (8.06 \pm 0.51) \times 10^{-3} V_0 (\text{km s}^{-1})^{-1} + (0.126 \pm 0.067)$, making the linear part of the amplitude–initial kick relation independent of direction to within 2 $\sigma$. Again, escape from the galaxy occurs for an initial kick 650 km s$^{-1}$.

As in the coplanar case, little disturbance of the morphology and kinematics of the stellar or gas disk is observed; only a displacement of the BH from the center of the galaxy disk is observed. However, when viewed nearly face-on, some streaming motions are observed in the gas kinematics, as illustrated in Figure 6.
3.2. Black Hole Mass $10^9 M_\odot$

When receiving an impulsive initial velocity kick, a large $10^9 M_\odot$ black hole exhibits behavior quantitatively similar to the $10^8 M_\odot$ black hole, as shown in Figure 7. In this case, however, it is clear that the damping time of the oscillation is significantly shorter. In the $10^9 M_\odot$ case, the damping scale time was on the order of 1.5 Gyr; however, for the $10^9 M_\odot$ case, damping times are of the order of 0.8 Gyr.

During the period of significant motion of the black hole, significant dynamical disturbance can be detected in the H\textsubscript{i} velocity maps. After a damping scale time, however, the dynamics recover to a normal rotation curve. The morphology outside the disk scale radius remains generally undisturbed, although minor observable asymmetries occasionally appear in the central gas distribution. Despite the normal disk and gas morphology, however, as in the previous case, the central black hole could be found offset from the center of the disk by several kpc.

Typical induced kinematic asymmetries are presented in Figure 8. In these plots, gas particle velocities were convolved and combined in a simulated Gaussian telescope beam and lines of constant radial velocity drawn. If the galaxy were a symmetric rotator, then constant radial velocity lines should be straight and parallel as they pass through the dynamical center. However, as can be seen in the figure, these kinematics have been disturbed by the motion of the BH, which has resulted in a dynamical friction interaction with the galaxy. The central regions of the galaxy within the disk scale radius of 3.5 kpc react quickly to the transferred momentum of the BH and tend to move with it in its direction of motion. Beyond that radius, particles are shielded from the gravity of the central BH and react sluggishly. As a result, the dynamical center of the central galaxy is displaced from the overall dynamical center in the direction of the initial impulse given to the BH. In the transition region between the two regimes, streaming motions are evident, with magnitudes on the order of 30 km s\textsuperscript{-1}.

![Fig. 4.—Morphology and kinematics of the galaxy model at $t = 0.12$ Gyr after the central BH of mass $10^8 M_\odot$ has been given a velocity kick of 300 km s\textsuperscript{-1} in the plane of the galaxy. Top: Stellar disk illustrated in gray scale. The logarithmic contour lines indicate the density of H\textsubscript{i} gas, after convolution with a simulated Gaussian beam (bottom left). Bottom: Convolved radial velocity of the gas indicated by the contour lines, labeled in km s\textsuperscript{-1}. The inclination to the line of sight is 20°. In both diagrams, the BH is indicated by the black dot slightly to the right of center. Major tick marks delineate 25 kpc distances.](image)

![Fig. 5.—Amplitudes (top) and frequencies (bottom) of the BH motion resulting from velocity kicks perpendicular to the plane of the galaxy for a BH of mass $10^8 M_\odot$.](image)
Finally, because of the BH’s resulting orbit around the new dynamical center of the distribution, at most times its actual location was offset from the dynamical center, as in the second frame of Figure 8.

4. BH ACCELERATION DUE TO A ONE-SIDED JET

In order to simulate the influence of a one-sided jet, we did a series of runs in which the massive BH was placed in the center of the galaxy with zero initial velocity relative to the galaxy, but with an applied constant acceleration for a time of the order of the Salpeter time. The available accretion power from a BH is \( L_a = \epsilon M_a c^2 \), where \( M_a \) is the mass accretion rate and the efficiency is assumed to be \( \epsilon = 0.1 \). Usually, the accretion rate is measured in units of the rate, which would give the Eddington luminosity for the BH, that is, \( \dot{M}_{\text{Edd}} = \frac{L_{\text{Edd}}}{c} \approx 2.2(M_{\text{BH}}/10^8 M_\odot) M_\odot \text{ yr}^{-1} \), where \( L_{\text{Edd}} \approx 1.26 \times 10^{46}(M_{\text{BH}}/10^8 M_\odot) \text{ ergs s}^{-1} \) and \( M_{\text{BH}} \) is the BH mass. Thus, the accretion luminosity can be written as \( L_a = \dot{m} L_{\text{Edd}} \), where \( \dot{m} = M_a/M_{\text{Edd}} \). The exponentiation time of the BH mass growth, the Salpeter (1964) time, is \( T_S \approx 4.5 \times 10^7 \text{ yr}^{-1} \).

It is widely thought that the jets of active galaxies are due to the presence of a strong, ordered magnetic field (~\( 10^3-10^4 \text{ G} \)) threading the BH accretion disk. For the commonly considered case of a field with dipole symmetry, the magnetically driven jets are of equal strength on the two sides of the disk (Lovelace 1976). However, as Wang et al. (1992) pointed out, an ordered field in the disk consisting of dipole and quadrupole components can give magnetically driven jets of unequal strength on the two sides of the disk. In fact, one side of the disk may have a dominant jet. The timescale for the jet to be on one side \( \tau \) in this model is of the order of the time for plasma and magnetic field to move through the disk. This time may be shorter than \( T_S \). Nevertheless, in our simulations we emphasize the influence of a one-sided jet by maintaining its force on the BH for a time of the order of \( T_S \) after which the force is zero. We assume that the BH carries along with it bound gas and stars sufficient to supply \( M_a \) during this time.

For the case of a one-sided jet, we can write the jet luminosity as \( L_{\text{jet}} = f_{\text{jet}} L_a \), where \( f_{\text{jet}} \leq 1 \) is the fraction of the accretion luminosity going into the jet. Alternatively, for asymmetrical, oppositely directed jets we take \( L_{\text{jet}} \) to be the difference in the luminosities of the two jets. Assuming that the jet outflow is highly relativistic, the force on the BH-disk system is therefore

\[
F_{\text{BH}} = -L_{\text{jet}}/c \approx 4.2 \times 10^{35} f_{\text{jet}} \dot{m} \left( \frac{M_{\text{BH}}}{10^8 M_\odot} \right) \text{ dynes},
\]

and the BH acceleration is

\[
a_{\text{BH}} = \frac{|F_{\text{BH}}|}{M_{\text{BH}}} \approx 2.1 \times 10^{-6} f_{\text{jet}} \dot{m} \text{ cm s}^{-2},
\]

(Wang et al. 1992). The momentum imparted to the BH during a time \( T \) is \( \dot{L} = \int_0^T dt M_{\text{BH}} a_{\text{BH}} = T M_{\text{BH}} a_{\text{BH}} \), for a constant one-sided jet. For a jet that changes sides randomly on a timescale \( \tau \ll T \), the
imparted momentum is much smaller, \( I \sim (\tau T)^{1/2} M_{\text{BH}} a_{\text{BH}} \). The small values of the BH displacements estimated by Wang et al. (1992) resulted from an invalid assumption about the rigidity of the central potential of the galaxy.

As a reference value for our simulations, we take \( a_{\text{BH}} = 2 \times 10^{-3} \) cm s\(^{-1}\), which corresponds to \( f_{\text{ref}} \Delta m = 0.01 \). For this value of \( a_{\text{BH}} \), note that \( \int_0^\tau dt a_{\text{BH}} = T a_{\text{BH}} \approx 1260( T/2 \times 10^8 \) yr \) km s\(^{-1}\). We confirmed the relevance of this value by observing that the hole remains bound to the galaxy for applied accelerations up to \( a_{\text{BH}} = 4.5 \times 10^{-8} \) cm s\(^{-2}\) and escapes the galaxy for larger \( a_{\text{BH}} \). A 100 times larger value of \( a_{\text{BH}} \) was considered by Tsygan (2007) to apply over a timescale \( T_S \), and this will strongly eject the BH from the galaxy.

When an external acceleration was applied in the plane of the galactic disk, the typical behavior was for the \( 10^8 M_\odot \) black hole to find an equilibrium position off-center with respect to the morphological and dynamical center of the galaxy and to oscillate about that position as long as the acceleration was applied. Figure 9 illustrates the BH displacement as a function of time for two typical examples of this experiment, in which the \( 10^8 M_\odot \) black hole was given an applied acceleration of \( 2.0 \times 10^{-8} \) cm s\(^{-1}\) and \( 4.0 \times 10^{-8} \) cm s\(^{-1}\) in the plane of the galaxy. The center of mass of the galaxy is also depicted for the first experiment. This accelerates as well, as dynamical friction transfers momentum between the BH and the galaxy. In the second run, the BH escapes the galaxy entirely within 0.1 Gyr. In each run for which the BH remained bound, we confirmed that the acceleration of the center of mass was equal to \( a_{\text{BH}} (M_{\text{BH}}/M_{\text{tot}}) \), where \( a_{\text{BH}} \) was the acceleration imparted to the BH, and also that when \( a_{\text{BH}} \) was turned off after 200 Myr, the final velocity of the center of mass agreed with the total impulse \( I = \int_0^\tau dt M_{\text{BH}} a_{\text{BH}} \) given, within errors that were taken to be the observed fluctuation in the center of mass velocity and acceleration of a galaxy with no kick (approximately 10%).
For BHs of mass $10^8 M_\odot$, slight to moderate asymmetries were induced in the dynamics of the host galaxy during the “on” phase, although nothing detectable was induced in the morphology, as illustrated in Figure 10. When viewed with the galaxy inclined to the line of sight, with the axis inclination aligned with the applied acceleration, deformations of the contours of constant radial velocity of order 40 km s$^{-1}$ are clearly observed in the kinematics of the galaxy gas. Note that no grand-design spiral arms have formed in the stellar or gaseous components, ruling out density waves as a possible explanation for these. These streaming motions are also present when the line of sight is at other orientations to the observer, but are less prominent. These disk asymmetries disappeared when the acceleration was turned off, but the BH continued...

**Fig. 10.**—Galaxy model gas density contours (top) and velocity map (bottom), convolved with a simulated Gaussian telescope beam, for the $10^8 M_\odot$ BH with an applied acceleration of $2.0 \times 10^{-8}$ cm s$^{-2}$ at time $t = 0.2$ Gyr. The inclination to the line of sight is 30° about the axis of acceleration. Major tick marks delineate 25 kpc distances.

**Fig. 11.**—BH displacement as a function of time along the direction of the applied acceleration perpendicular to the plane of the galaxy for a $10^8 M_\odot$ black hole. The simulated jet acceleration is $2.0 \times 10^{-8}$ cm s$^{-1}$. The dotted line shows the center of mass of the galaxy.

**Fig. 12.**—Displacement vs. time along the direction of applied acceleration for the black hole of mass $10^9 M_\odot$ with simulated jet acceleration of $2.0 \times 10^{-8}$ cm s$^{-2}$. Acceleration in the plane of the galaxy is represented by the solid line, perpendicular to the plane by the dotted line. Bottom: Acceleration shut off at 0.2 Gyr.
to oscillate about the center of mass with an amplitude that depended slightly on the initial acceleration, but was typically of order $1 \times 10^{-2}$ kpc.

In the case in which the BH is given an acceleration perpendicular to the galaxy plane, a similar behavior is observed, as illustrated in Figure 11. The BH oscillates around an equilibrium point, slowly dragging the galaxy along with it via dynamical friction. In this case, however, the amplitude of the motion is smaller and the frequency higher. The acceleration required for escape in this case is $3 \times 10^{-3}$ cm s$^{-2}$, as compared with 4.5 for the case in the plane of the galaxy. This case produces no detectably significant asymmetries in the morphology or kinematics of the galaxy disk.

### 4.2. Black Hole Mass $10^{9} M_{\odot}$

When given an acceleration in the plane of the galactic disk, the large $10^{9} M_{\odot}$ black hole exhibited behavior similar to that of the smaller hole. In this case, as illustrated in Figure 12, the larger impulse “drags” the galaxy a proportionally greater distance. When the acceleration is turned off after 0.2 Gyr, the velocity imparted to the galaxy is 200 m s$^{-1}$.

As the black hole was accelerated, it became displaced from the morphological and dynamical center of the galaxy, as illustrated in Figure 13. These induced asymmetries in the galaxy disk are more pronounced in this case than in the $10^{8} M_{\odot}$ case, in particular tending to drag the central regions of the galaxy with the movement of the black hole via dynamical friction. In particular,
while the BH in the first frame of Figure 13 appears displaced from the morphological center of the galaxy, the second frame of the figure illustrates how the dynamical center of the galaxy has been displaced toward the direction of acceleration of the black hole. The result is a characteristic tongue-shaped extension of the velocity contours on the side of the galaxy opposite the acceleration and flattened contours on the side of the galaxy in the direction of the acceleration. In test runs with a much larger, possibly unphysical $10^{10} M_\odot$ BH, these features became associated with a central core region of the disk that moved along with the black hole, being more strongly coupled to it than to the galaxy, and causing strong morphological asymmetries in the disk as the bulge was dragged off-center. We did not observe such strong asymmetric features in the morphology of the $10^9 M_\odot$ galaxy, but do observe the “tongue” features that indicate that the BH is beginning to dominate the dynamics of the inner 2–5 kpc of the disk.

A similar behavior is observed when the acceleration is perpendicular to the plane of the galaxy. Again, streaming motions and dynamical asymmetries are observed for the first 0.5 Gyr of acceleration, as shown in Figure 14. Following that period, only slight streaming motions remain as part of the stabilized disk kinematics.

5. DISCUSSION

We have analyzed the motions of massive black holes in the centers of galaxies that have received an impulsive kick (because of the merging of two BHs) or received a sustained acceleration due to a one-sided jet. We have studied the BH displacement from the galaxy center and the influence this has on the galaxy morphology and kinematics. An impulsive kick exceeding 600 km s$^{-1}$ will eject the BH from the galaxy. Accelerations of the order of $4 \times 10^{-8}$ cm s$^{-2}$ or larger for times of the order of $2 \times 10^8$ yr eject the BH from the galaxy. This acceleration is smaller than the Eddington limit on the one-sided jet luminosity (Tsygan 2007) by a factor of about 50.

For smaller velocity kicks or smaller sustained accelerations, the BH is observed to oscillate through the galaxy center for times of order 1 Gyr. The frequency of these oscillations decreases as the BH velocity kick increases or as the BH acceleration increases. In such galaxies, we can expect to observe central BHs that are offset from the centers of their host galaxy disks or have large radial velocity differences from their hosts. Larger mass BHs undergoing these oscillations induce streaming motions in their galaxies due to dynamical friction. This process may be a source of disk morphological and dynamical asymmetry in galaxies such as NGC 1637 or NGC 991, which exhibit nonaxisymmetries, but are located in isolated fields far from potential sources of tidal interactions (Kornreich et al. 1998).

The asymmetries in the galaxy disk induced by the BH motion are of course more pronounced for more massive black holes. The BH tends to drag the central regions of the galaxy with it because of dynamical friction. The dynamical center of the galaxy is seen in some cases to be displaced toward the direction of the BH acceleration with a characteristic tongue-shaped extension of the velocity contours on the side of the galaxy opposite the acceleration.

As a check on the results, additional model runs with fewer ($10^5$) or more ($10^7$) particles yielded substantially similar behavior for the BH. Asymmetries induced in the galaxy disk remained qualitatively similar for each run, although the details of the locations and intensities of the induced asymmetries varied somewhat.

These results are in general agreement with Gualandris & Merritt (2008), who found damping times of oscillating supermassive BHs to be of order 1 Gyr in simulations of elliptical galaxies. This is expected, as escape times from the disk are very short, of order 0.1 Gyr, and after that the gravitational potential is essentially that of the spheroidal halo.

We thank Martha Haynes and Larry Kidder for discussions. This work has made use of the computational facilities of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.

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