SECULAR EVOLUTION OF BARRED GALAXIES WITH MASSIVE CENTRAL BLACK HOLES

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ABSTRACT

The influence of central black holes on the dynamical evolution of bars in disk galaxies is examined. In particular, we use numerical simulation to estimate the minimum mass black hole (BH) needed to destroy a bar. Initially, bars form in the disks via dynamical instability. Thereafter, once a bar is fully developed, a BH is adiabatically added at the center of the disk. To mitigate the global effects of gravitational softening, Poisson’s equation for the disk is solved by expanding the density and potential of the galaxy in a set of basis functions.

Our results indicate that a bar can be completely destroyed in a time much smaller than a Hubble time if the central mass exceeds about 0.5% of the disk mass. Since the implied minimum BH mass for bar destruction is of order $10^{8.5} M_\odot$ for a typical disk galaxy, this process should not be a rare phenomenon. The bar amplitude decreases gradually with time after the BH is added, and the rate at which the bar is destroyed increases with increasing BH mass. This suggests that bar destruction arises from scattering of stars that support the bar as they pass close to the center.

Subject headings: celestial mechanics, stellar dynamics — galaxies: structure — methods: numerical
1. INTRODUCTION

Recent observations indicate that massive central black holes exist in disk galaxies as well as in ellipticals. For example, NGC 4945 (type Sc), the Milky Way (type Sbnc), NGC 1068 (type Sb), M31 (type Sb), NGC 4258 (type Sbc), and NGC 4594 (type Sa) are thought to harbor central black holes with masses $\sim 10^6 M_\odot$, $2 \times 10^6 M_\odot$, $10^7 M_\odot$, $3 \times 10^7 M_\odot$, $4 \times 10^7 M_\odot$, and $5 \times 10^8 M_\odot$, respectively (see, e.g., Kormendy & Richstone 1995; van der Marel 1998; and references therein). When combined with data on nearby ellipticals (e.g., Magorrian et al. 1998) it is plausible that most, if not all, large galaxies contain central black holes whose masses range from $\sim 10^6 M_\odot$ to $\sim 10^{9.5} M_\odot$.

Such a large mass concentration at the center of a galaxy could affect the structure of the entire system. Of great interest is the influence of a central black hole (BH) on the structure of a bar, in view of the fact that roughly half of all disk galaxies are barred. Some studies (e.g., Hasan & Norman 1990; Hasan, Pfenniger, & Norman 1993; Norman, Sellwood, & Hasan 1996) have shown that central mass concentrations can destroy a bar within a relatively short period of time. In particular, Norman et al. (1996) have concluded that a central massive object with about 5% the total mass of a disk plus bulge can result in the dissolution of a bar within a Hubble time. Remarkable as their result is, the implied mass for bar destruction becomes about $10^{9.5} M_\odot$ when scaled to a typical disk galaxy with a mass $\sim 10^{10.5} - 10^{11} M_\odot$. If this mass concentration is associated with a central black hole, the required BH mass is greater than that inferred in nearby spirals and is comparable to the largest BH masses derived observationally in ellipticals. This suggests that bar destruction by central black holes might be a rare phenomenon, although this process could alternatively be driven by, e.g., sufficiently dense concentrations of gas.

In this paper, we employ N-body simulations to examine the influence of a central black hole on a bar to determine how massive a BH is required to destroy a bar. To avoid the complications arising from softening of gravitational forces, we employ a self-consistent field (SCF) method, as termed by Hernquist & Ostriker (1992), which solves Poisson’s equation by expanding the density and potential in a set of basis functions. Our results demonstrate, in fact, that in at least some cases the minimum black hole mass for bar destruction may be at least a factor of ten smaller than that suggested by the work of Norman et al. (1996). Of course, this is not necessarily in conflict with the conclusions of Norman et al., since they modeled the consequences of the build-up of gas concentrations in the inner regions of a barred disk, while we are specifically interested in the influence of a central black hole.
2. MODELS AND METHOD

In the calculations described here, we study the evolution of razor-thin exponential disks without bulges and halos, whose surface density distributions are given by

\[ \mu(R) = \mu_0 \exp\left(-\frac{R}{h}\right), \]  

(2-1)

where \( h \) is the exponential scale-length and \( R \) is the distance from the center of the disk. The disks are truncated at \( R = 15h \). The full phase-space is realized by employing the approach of Hernquist (1993), who approximated the velocity distribution using moments of the collisionless Boltzmann equation. We choose parameters such that the typical Toomre (1964) \( Q \) parameter is of order unity, and the models are globally unstable to the formation of bars.

For simplicity, the black holes are handled as external fields and their potentials are approximated using a Plummer model given by

\[ \phi_{BH}(R) = -\frac{GM_\bullet(t)}{\sqrt{R^2 + \epsilon^2}}, \]  

(2-2)

where \( G \), \( M_\bullet(t) \), and \( \epsilon \) are the gravitational constant, BH mass, and scale-length of the potential, respectively. The BH is added at \( t = t_{BH} \) long after the bar instability has occurred, and grows slowly from 0 to \( M_{BH} \) as follows:

\[ M_\bullet(t) = \begin{cases} 
M_{BH} \left\{ 3 \left[ (t - t_{BH})/t_{grow} \right]^2 - 2 \left[ (t - t_{BH})/t_{grow} \right]^3 \right\} & \text{for } t_{BH} \leq t \leq t_{BH} + t_{grow}, \\
M_{BH} & \text{for } t > t_{BH} + t_{grow},
\end{cases} \]

(2-3)

where \( t_{grow} \) is the time for the BH to grow to its full amplitude \( M_{BH} \). Thus, the BH is made to grow adiabatically by taking \( t_{grow} \) to be sufficiently long. Here, we consider cases in which \( \epsilon = 0.01h \), and \( M_{BH} = 0.01M \), \( 0.005M \), and \( 0.001M \), where \( M \) is the total mass of the disk.

In most of the experiments described below, we took \( t_{grow} = 10 \). Identical calculations but with \( t_{grow} = 5 \) and 20 for \( M_{BH} = 0.01M \) yielded no practical differences in the subsequent evolution from the choice \( t_{grow} = 10 \). These values for \( t_{grow} \) can be compared with the typical rotation periods of the bars in the simulations, \( T_b \). To estimate \( T_b \), the phase angle \( \phi_b(t) \) of the bar pattern is obtained from the phase of the expansion coefficients \( A_{22}(t) \) divided by 2 (see below). Thus, the bar rotation period can be calculated from the time derivative of \( \phi_b(t) \). We obtain \( \Omega_b = 0.392 \) between \( t = 60 \) and \( t = 100 \) when there was no BH. This means that the bar rotation period is \( T_b = 2\pi/\Omega_b = 16.0 \). While our adopted values for \( t_{grow} \) are not large compared to \( T_b \), the black hole growth is adiabatic in the sense that the BH is added on a timescale long compared with the dynamical times of stars near the center of the disk.

Once the disks have been realized with particles, we evolve them forward in time using an SCF method with Aoki & Iye’s (1978) basis set, which is appropriate for systems that are flat and have no vertical extent. In a dimensionless system of units, the basis functions are

\[ \mu_{nm}(R) = \frac{2n + 1}{2\pi} \left( \frac{1 - \xi}{2} \right)^{3/2} P_{nm}(\xi) \exp(im\theta), \]

(2-4)
\[
\Phi_{nm}(R) = -\left(\frac{1-\xi}{2}\right)^{1/2} P_{nm}(\xi) \exp(i m \theta),
\]

where \( R = (R, \theta) \) is the position vector, \( P_{nm} \) is the Legendre function, and \( n \) and \( m \) \((n \geq m)\) are the radial and azimuthal “quantum numbers”, respectively. In particular, positive values of \( m \) correspond to the number of arms in spiral patterns. In equations (2-4) and (2-5), the radial transformation

\[
\xi = \frac{R^2 - 1}{R^2 + 1}
\]

is used. With these basis functions \((\mu_{nm}, \Phi_{nm})\), each pair of which satisfies Poisson’s equation, the density and potential of the system can be expanded as

\[
\mu(R) = \sum_{nm} A_{nm}(t) \mu_{nm}(R),
\]

\[
\Phi(R) = \sum_{nm} A_{nm}(t) \Phi_{nm}(R).
\]

The amplitude of the \((n, m)\)-mode is calculated from the absolute value of the expansion coefficients, \(|A_{nm}(t)|\). If a spatially constant shape like a bar pattern emerges in a model disk, \( A_{nm}(t) \) will be proportional to \( \exp(-i \omega t) \), where \( \omega \) is the complex eigenfrequency, and \( \text{Im}(\omega) \) will be almost zero in a nonlinear regime. Thus, the pattern speed for the \((n, m)\)-mode is obtained from \( \text{Re}(\omega)/m \). In practice, we pay attention to only the fastest growing mode with \((n, m) = (2, 2)\).

The maximum number of radial expansion coefficients, \( n_{\text{max}} \), is taken to be 16, and the number of azimuthal expansion coefficients, \( m_{\text{max}} \), is set to be 2 with only even values being used; that is, \( m = 0 \) and 2. Although we carried out a simulation with \( n_{\text{max}} = 32 \), we found no difference between the results with \( n_{\text{max}} = 16 \) and those with \( n_{\text{max}} = 32 \). We employ \( N = 100,000 \) particles of equal mass. The equations of motion are integrated in Cartesian coordinates using a time-centered leapfrog algorithm. We employ a system of units such that \( G = M = h = 1 \). If these units are scaled to physical values appropriate for the Milky Way, the unit of time is \( 1.31 \times 10^7 \) yr.

We first run a simulation until the bar has developed completely in the disk, and then we continue the evolution, after growing a BH according to equation (2-3). Prior to adding a BH, we use a timestep \( \Delta t = 0.1 \) up to time \( t = 100 \) when the bar is no longer evolving. After \( t = 100 \), when we add a BH, we employ a timestep \( \Delta t = 0.005 \). This choice of timestep was determined by performing simulations with different values of \( \Delta t \) and requiring that the results of the integrations no longer depended on \( \Delta t \). For the choice \( \Delta t = 0.005 \), the total energy of the system after the full growth of the BH was, in all cases, conserved to better than four significant figures.

One might be concerned that our results will be affected by various numerical approximations. For example, our decision to use razor-thin disks could enhance the influence of the black hole on the disk by requiring the orbits of stars to remain in a single plane. We intend to examine this issue in future studies, but for now we note that Norman et al. (1996) modeled disks both with and without vertical extent, and did not find a significant difference in the magnitudes of the central mass concentrations required for destroying a bar. On the other hand, by softening the black hole
potential and by forcing it to remain stationary at the origin, we may be underestimating the response of the bar. In reality, a black hole near the center of a galaxy would generate a potential that is essentially that of a point mass, and would “wander” about the origin as it achieves equipartition with the background stars, possibly enhancing the rate at which a bar would be destroyed (see, e.g., Quinlan & Hernquist 1997).

3. RESULTS

To quantify the consequences of a black hole for a bar, we record the amplitude of the azimuthal term in the density of the disk as determined by the SCF expansion. In Figure 1, we show the time evolution of the bar amplitude for three values of the BH mass: $M_{\text{BH}} = 0.01, 0.005,$ and $0.001$. These choices bracket the range in $M_{\text{BH}}$ over which the black hole begins to have a significant effect on the bar in our models. In all cases, black hole growth commenced at $t = 100$, after the bar was fully developed, and was completed by $t = 110$. The evolution beyond $t = 110$ thus reflects the influence of the black hole on the bar.

We can see from Figure 1 that the bar amplitude decreases with time for $M_{\text{BH}} = 0.01$ and $0.005$ while it remains nearly constant to the end of the simulation for $M_{\text{BH}} = 0.001$. As a further comparison, we also evolved a disk up to $t = 300$ without growing a black hole in it, and the outcome of this calculation is indicated by the uppermost curve at late times in Figure 1. While not identical to the case with a BH of mass $M_{\text{BH}} = 0.001$, the results of these two experiments are sufficiently close that we cannot yet claim that a BH of this low mass has a noticeable influence on the bar.

Figure 1 demonstrates that the rate at which the bar is destroyed is higher with increasing BH mass: the time required for bar dissolution becomes shorter for increasingly more massive black holes. In addition, in cases where the influence of the black hole is significant, the bar dissolves gradually with time. In the experiments with black holes of masses $M_{\text{BH}} = 0.01$ and $0.005$, the amplitude of the bar decays nearly exponentially with time $\sim \exp(-t/\tau)$, once the BH is fully developed. From the decline of $\ln|A_{22}|$ with time, we estimate decay times $\tau \sim 115$ and $\tau \sim 295$ for the simulations with BH masses $M_{\text{BH}} = 0.01$ and $M_{\text{BH}} = 0.005$, respectively. When scaled to values appropriate for the Milky Way, these correspond to timescales $\sim 1.5 \times 10^9$ and $\sim 3.8 \times 10^9$ years, respectively. Since these time intervals are small (but not negligible) compared with the estimated ages of disk galaxies, we tentatively conclude that black holes even with masses as small as 0.5% that of the disk can destroy a bar which formed at around the same time as the disk.

These arguments are supported by examining the structural properties of the bars in each of our simulations following the growth of the black hole. We determine the axis ratios of the bars by calculating the moment of inertia tensor for particles included in a specified radius, and use this information to derive the axis ratio at that radius. In Figure 2, we show the axis ratio of the bars thus computed for the four experiments in Figure 1. As is apparent from Figure 2, the axis ratio
Fig. 1.— Time evolution of the bar amplitudes of the fastest growing mode, $|A_{22}|$, for $M_{\text{BH}} = 0.01$, 0.005, and 0.001.
Fig. 2.— Change in axis ratios from $t = 100$ to the end of the simulations for $M_{BH} = 0.01$, 0.005, and 0.001.
has become $\gtrsim 0.96$ for $M_{BH} = 0.01M$ at $t = 300$ and $\gtrsim 0.92$ for $M_{BH} = 0.005M$ at $t = 400$ from $\sim 0.72$ at $t = 100$ within the bar regions. On the other hand, the axis ratio has changed little from $t = 100$ to $t = 300$ for $M_{BH} = 0.001M$. Thus, the bar can be destroyed within a short time scale as compared to a Hubble time if the BH mass exceeds about 0.5% of the disk mass.

4. DISCUSSION AND CONCLUSIONS

We have shown that a massive central BH can dissolve a bar within a short time scale if the BH is as massive as about 0.5% of the disk mass. This means that the minimum BH mass necessary for bar dissolution would be of order $10^{8.5}M_\odot$ for a typical disk galaxy. This minimum BH mass is an order of magnitude smaller than that implied from the results of Norman et al. (1996), if we associate the central mass concentrations in their models with black holes. Since our minimum BH mass is not extremely large compared with the BH masses suggested by observations, bar dissolution should not be a rare event but could occur at some unexceptional rate in real barred galaxies.

It is not yet clear why we obtain a minimum mass for bar destruction that is so smaller than that which is suggested by the Norman et al. results. Our simulations differ from theirs in several respects, and we do not know which difference is most responsible for our lower value of this BH mass. We suspect that a likely culprit is the difference in the galaxy models employed in the two studies. Norman et al. employ multi-component models in which the disk is represented by a Kuzmin-Toomre mass profile (Kuzmin 1956; Toomre 1963) and 25% of the mass resides in concentric bulge and “core” components that are modeled as Plummer spheres. To mimic the effects of gas inflow, the scale-length of the Plummer sphere representing the central mass concentration is reduced slowly with time. In cases of interest, the core component contains up to 10% of the system mass.

In our simulations, the disks have exponential profiles, and we allow the black hole mass to grow slowly with time, but we do not alter the scale-length of the black hole potential. While it is conceivable that the important difference is the manner in which the density of the central mass concentration is varied (Norman et al. fix the mass while we fix the scale-length) a more likely possibility is our use of a disk profile that is significantly more concentrated than that in the Norman et al. simulations. For example, it is possible that a relatively larger fraction of the stars supporting the bars in our simulations pass sufficiently near that central mass that they could be strongly perturbed by it. Indeed, Norman et al. argue that the critical mass will likely depend sensitively on the properties of the galaxy and the bar. However, there are other technical differences between the two sets of calculations and we have not explored parameter space in sufficient detail to show that the structure of the galaxy is primarily responsible for our smaller critical BH mass.

For cold systems in which rotation is dominant, the introduction of a softening length can
alter the dynamics of a disk. Earn & Sellwood (1995) have demonstrated that for an isochrone disk, the growth rate of the fastest growing two-armed mode obtained with their smallest softening length is still 20% smaller than that derived from linear analysis. On the other hand, if an SCF method is used, the growth rate is in excellent agreement with that predicted by linear theory. As a result, the estimated BH mass may differ from that which is actually needed to destroy a bar, when a numerical code requiring force softening is used.

Another interesting difference between our results and those of Norman et al. (1996) is the rate at which bars are destroyed in response to the central mass concentrations. In our models, as indicated by Figure 1, the amplitude of the bar declines smoothly and slowly with time. Norman et al. find that the bars in their simulations are destroyed relatively abruptly when the central mass exceeds some critical value, and they argue that this results from chaotic behavior caused by the modification to the potential by the central mass. It is unclear if this difference is driven by the different mass models employed for the galaxies in the two studies, or if it is numerical in origin. However, this difference may be related to the physical process by which the bar is destroyed.

Several authors have argued that a central black hole can scatter stars on orbits supporting a bar, and that a bar would be gradually eroded by this process (e.g., Norman 1984; Norman, May, & van Albada 1985; Gerhard & Binney 1985). In principle, this interpretation can account for the evolution seen in our models. If this is indeed the case, even a relatively small BH mass could affect the structure of a bar, if a sufficient number of orbits pass within the black hole’s “sphere of influence.” In our simulations, a BH with $M_{BH} = 0.001$ was unable to destroy a bar. It is possible that this outcome was unduly influenced by poor resolution near the center of our disks and our suppression of black hole “wandering”. Clearly, simulations with a larger number of particles and a greater degree of physical realism will be required to work out the true nature of the mechanism of bar dissolution.

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