Dynamical Processes in the Central Kpc and Active Galactic Nuclei

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Abstract. We discuss different aspects of nested bar dynamics and its effect on the gas flow and fueling of Active Galactic Nuclei. Specifically we focus on the dynamical decoupling between the primary and secondary bars and the gas flow across the bar-bar interface. We analyze the nuclear gaseous bar formation when gas gravity can be neglected or when it dominates. Finally, we discuss the possible effect of flat core, triaxial, dark halos on the formation of galactic bulges and supermassive black holes (SBHs) and argue in favor of SBH-bulge-halo correlation.

1. Introduction: Emerging Global Connection

Departures from axial symmetry are destined to shorten the timescales of secular and dynamical evolution in disk galaxies. Stellar bars, triaxial halos and tidal interactions play the important roles of driving such evolution on larger spatial scales, but their effect diminishes sharply within the central kpc. Is there any comparable non-axisymmetric morphology within the circumnuclear region which can impose gravitational torques, trigger bursts of star formation, and fuel the nonstellar activity of supermassive black holes (SBHs) — ubiquitous, as recent observations confirm? What are the relevant processes which maintain this morphology, and how much they affect the galactic evolution?

Disk galaxies as a “norm” are barred or ovaly distorted in the near-infrared (NIR). High-resolution ground-based instruments and the availability of the HST has allowed for the first time a meaningful analysis of central morphology and kinematics. Although our knowledge of the inner regions of disk galaxies is clearly incomplete, certain patterns in their dynamical evolution and their relationship to larger and smaller spatial scales have emerged.

At least dynamically, the inner parts of disk galaxies can be defined by the positions of the inner Lindblad resonances (ILRs), typically at about 1 kpc from the center. These resonances play an important role in filtering density waves, propagating between the bar corotation radius (CR) and the center. They are usually delineated by elevated star formation rates and the concentration of molecular gas in nuclear rings, which can serve as reservoirs for fueling the central activity.

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One can distinguish the disk and spheroidal components within the central kpc. Surprisingly, the mass of the central SBH has been claimed to correlate with the bulge properties (e.g., reviews by Kormendy & Gebhardt 2001; Merritt & Ferrarese 2001), despite the common wisdom that black holes are fueled by disk accretion. However, formation of bulges can be tied directly to the properties of triaxially-shaped halos, thus strongly hinting about the ‘global connection’ between smallest and largest spatial scales within the forming and evolving galaxy (Section 3 and El-Zant et al. 2002).

Resolved plane morphology of central kpc in barred galaxies has revealed so-far grand-design (mini) spirals and bars in addition to “traditional” disks and bulges. We refer to large, kpc-scale bars as “primary,” and to the sub-kpc bars as “secondary.” The theoretical rationale behind these definitions is that secondary bars are believed to form as a result of radial gas inflow along the large-scale bars and, therefore, are expected to be confined within their ILRs (Shlosman, Frank & Begelman 1989). Below we review morphologies of the circumnuclear region, analyze dynamical properties of nested bars, their dynamical coupling to larger scales, and the resulting gas flows on scales of $\sim 10$ pc$-10$ kpc, as well as discuss the possible origin of SBH-bulge correlation within the context of triaxial halos.

2. Nuclear Bars in Nested Bars: Gas, Stars and ‘Cocktails’

In the powerful display of nonlinear dynamics, many galaxies exhibit double stellar bars, which can tumble with different or identical pattern speeds. Although examples have been known for nearly three decades, the dynamical importance of nested bars has been first pointed out much later. The largest sample of (112) disk galaxies analyzed so far for this purpose reveals a substantial fraction of nested bars, probably in excess of 20 – 25%. Even more interestingly, about 1/3 of barred galaxies host a second bar (Laine et al. 2002). The gas contents of nuclear bars vary. In some cases, the cold gas can be dynamically important, as evident from the interferometric 2.6 mm CO emission and NIR lines of H$_2$. Depending on the gas fraction contributing to the gravitational potential, one can distinguish stellar-, gas-dominated (i.e., gaseous) and mixed nuclear bars. The nuclear gaseous bars have no large-scale counterparts.

Nuclear bars extend the action of gravitational torques to smaller spatial scales. Their relevance for the AGN depends on the availability of the ‘fuel’ (i.e., gas) which loses angular momentum and falls toward the center. The gas-dominated nuclear bars can be especially important for this process, and therefore we discuss them in some detail below. Probably the most intriguing property of nested bars is their theoretically anticipated stage of a dynamical decoupling, when each bar exhibits a different pattern speed (Shlosman et al. 1989). Several aspects of this problem are analyzed below.

**Gas Flow in Nested Bars.** Here we assume that nested bars tumble with different pattern speeds, $\Omega_s > \Omega_p$, where ‘p’ stands for primary and ‘s’ — for secondary (sub-kpc) bar. Arguments dealing with chaos minimization in such time-dependent system will lead to certain limits, specifically that CR of the secondary bar must lie in the vicinity of the primary bar ILR, constraining $\Omega_s$ (e.g., Pfenniger & Norman 1990). Such dynamical configuration, in principle,
poses a problem for uninterrupting gas inflow towards smaller radii. According to this argument, the gas flow is repelled at the bar CR, inwards or outwards, because of the rim formed by the effective potential there, and hence may not cross the ILR/CR (i.e., bar-bar interface). Shlosman et al. (1989) have argued, in essence, that it is the gas self-gravity that overcomes repulsion by modifying the underlying potential. But even in the limit of negligible gravity in the gas, the flow is capable of crossing the bar-bar interface, although not in a steady manner and only for a restricted range of azimuthal angles (Shlosman & Heller 2002).

The pattern of shock dissipation in nested bars can be inferred from Fig. 1. It allows one to separate the incoming large-scale shocks from those driven by the secondary bar. Note that two systems of spiral shocks occur, each associated with the corresponding bar. The interaction between these shock systems shows detachment when the bars are perpendicular and attachment when they are aligned with each other. The shapes of the shocks depend on the angle between the bars.

Several factors characterize the gas dynamics in the decoupled bars: (i) the time-dependent nature of the potential; (ii) the nonsteady gas injection into the secondary bar which proceeds through the primary shocks penetrating the bar-bar interface. This phenomenon is absent at the CR of the primary bars. Unstable orbits in the interface region preclude the secondary bars from extending to their CR (El-Zant & Shlosman 2002, in preparation); (iii) a fast-tumbling secondary bar which prevents the secondary ILRs from forming. Even in the case of a long-lived decoupled phase secondary bars are not expected to slow down. In fact, the gas inflow across the interface and the resulting central concentration can speed-up the bar (Heller, Noguchi, & Shlosman 1993, unpublished). The low-Mach-number gas flow is well organized and capable of following orbits within the bar with little dissipation. Non-linear orbit analysis reveals that, in the deep interior of the secondary bar, the $x_1$ orbits have a mild ellipticity and no end-loops. This result is robust. No offset large-scale shocks form under these conditions.

Knapen et al. (1995) have analyzed the shock dissipation in a self-consistent potential of ‘live’ stars and gas before the onset of decoupling, when both bars tumble with the same pattern speeds, and when the gas gravity is accounted for. No offset shocks have been found in this configuration either. These results indicate that gas inflows stagnate within the inner parts of fast rotating nuclear bars, forming nuclear disks if gas gravity is neglected — a condition similar to having a low surface density gas.

We conclude that compelling arguments show that no large-scale shocks and consequently no offset dust lanes will form inside secondary nuclear bars either when they are dynamically coupled and spin with the same pattern speeds as the primary bars, or dynamically decoupled, spinning much faster, if gas gravity is neglected. However, the fate of the gas settling inside the nuclear bars cannot be decided without invoking global gravitational effects in the gas which will completely change the nature of the flow.

Dynamical Decoupling of Nested Bars. Decoupling in nested bars is indirectly supported by the observed random orientation of primary and secondary bars. To complicate the matter, both bars can corotate, being completely synchro-
**Left:** Figure 1. Pattern of shock dissipation (left) and density evolution (right) in the central kpc, in the frame of reference of the primary bar (horizontal). Positions of the secondary bar and its length are indicated by a straight line. All rotation is counter-clockwise. Particles in the left column have greater than average dissipation rate. Note the sharply reduced dissipation in the innermost secondary bar and “limb brightening” enveloping it. Also visible are two dissipative systems — the shocks in primary and secondary bars (Shlosman & Heller 2002).  

**Right:** Figure 2. Time evolution of the low-viscosity model: 2D SPH simulation in the background potential of a barred disk galaxy (face on). The gas response to the bar torquing is displayed in the primary-bar (horizontal) frame. The gas rotation is counter-clockwise. Note a fast evolution after \( t \sim 150 \), when the secondary bar decouples and swings clockwise! The bar is “captured” again at \( t \sim 211 \). Time is given in units of dynamical time. This animation sequence and others are available in the online edition of Heller et al. (2001).

nized. This configuration of nearly orthogonal bars may be a precursor to the future decoupled phase. The gas responding to the gravitational torques from the primary bar flows towards the center and encounters the \( x_2 \) orbits, which it populates. The forming secondary bar may be further strengthened by the gas gravity, or the amount of gas accumulating in the ILR resonance region may be
insufficient to cause this runaway. The computational effort has so far gone into analyzing self-gravitating systems (e.g., Friedli 1999; Shlosman 1999).

If the secondary bar forms via gravitational instability (in stellar or gaseous disks), it will spin in the direction of the primary bar with Ω_s > Ω_p (Shlosman et al. 1989; Friedli & Martinet 1993; Heller & Shlosman 1994). The presence of gas appears to be imperative for this to occur. Both bars are dynamically decoupled and the angle between them becomes arbitrary. The secondary bar can also rotate in the opposite sense to the primary bar, resulting from merging — a non-recurrent configuration.

**Decoupling of Non-Self-Gravitating Bars.** The actual degree of viscosity in the ISM is largely unknown. Heller, Shlosman & Englmaier (2001) have investigated the effect of viscosity on the gas settling in the ILR region of a single large-scale stellar bar. The most spectacular evolution occurred in the low-viscosity model, although all the models showed similar initial evolution, during which the gas accumulated in a double ring, corresponding roughly to two ILRs. In all the models the rings interacted hydrodynamically and merged (Fig. 2), forming a single oval-shaped ring corotating with the primary bar and leading it by φ_{dec} — depending on the gas viscosity. The remaining ring becomes increasingly oval and barlike (Fig. 2), its pattern speed changes abruptly, and it swings towards the primary bar, against the direction of rotation. In the inertial frame, this forming gaseous bar spins in the same sense as the main bar, albeit with Ω_s < Ω_p, but in the primary-bar frame it tumbles retrograde (!) for about 60 dynamical times, \( \sim 2-3 \times 10^9 \) yr, until it is captured again by the primary. The shape of the decoupled bar and \( \Omega_s \) depend on bar orientation. The eccentricity, \( \epsilon \), reaches a maximum when bars are aligned. In standard and high-viscosity models, the secondary bar only librates about the primary.

The key to understanding this behavior lies in the distribution of gas particles with Jacobi energy, \( E_J \). After merging the ring is positioned close to the energy where the transition from \( x_2 \) to \( x_1 \) (at the inner ILR) occurs. The exact value of this transition energy is model-dependent, but this is of no importance to the essence of the decoupling. The crucial difference between the models comes from \( i \) the position of the forming gaseous bar on the \( E_J \) axis after ring merging and \( ii \) the value of \( \phi_{\text{dec}} \).

As the gaseous bar forms at \( \phi_{\text{dec}} \) to the primary, gravitational torques act to align the bars. In the low-viscosity model, gaseous bar resides on purely \( x_2 \) orbits and, therefore, responds to the torque by speeding up its precession while being pulled backwards, until it is almost at right angles to the bar potential valley. The decoupling happens abruptly when \( \sim 1/2 \) of the gas finds itself at \( E_1 \) below the inner ILR. The absence of \( x_2 \) orbits at these \( E_1 \) means that the gas loses its stable orientation along the primary-bar minor axis. The gaseous bar has a much smaller \( \epsilon \) in the fourth quadrant. Such an asymmetry with respect to the primary ensures that the torques from the primary bar are smaller in the fourth quadrant. But only for the least viscous model this becomes crucial, and the torques are unable to confine the bar oscillation, which continues for a full swing of \( 2\pi \). The nuclear bar is trapped again, after few rotations.

Correlation between \( \epsilon \) of the gaseous bar and its orientation can be tested observationally. Two additional effects should have observational consequence. First, the gas will cross the inner ILR on a dynamical timescale. Shlosman
Figure 3. Formation and decoupling of a self-gravitating gaseous bar (central kpc) in the reference frame of the large-scale stellar bar (horizontal). All rotation is clockwise. The time increases to the right. The first three frames: formation of elongated ring perpendicular to the stellar bar and at its inner ILR; next three frames: ‘retrograde,’ $\Omega_s < \Omega_p$ non-self-gravitational decoupling (compare with Fig. 2); last six frames: prograde $\Omega_s > \Omega_p$ gravitational modes $m = 2, 4$ develop and take over. This last stage is accompanied by a ‘catastrophic’ growth of the central seed BH (Englmaier & Shlosman 2001, unpublished).

et al. (1989) pointed out that ILRs present a problem for radial gas inflow because the gas can stagnate there. A solution was suggested in the form of a global gravitational instability in the nuclear ring or disk, which will generate gravitational torques in the gas, driving it further in. Recently Sellwood & Moore (1999) resurrected the idea that ILRs would “choke” the gas inflow. Fig. 2 shows that even non-self-gravitating nuclear rings are prone to dynamical instability which drives the gas inward. Accounting for the gas gravity dramatically affects the stability of gas at the inner ILR, as discussed below (see also Fig. 3). This inflow is expected to be accompanied by star formation along the molecular bar, having a quasi-periodic, bursting character.

Decoupling of Self-Gravitating Bars. Gas gravity plays a crucial role in the formation and decoupling of bars, securing $\Omega_s > \Omega_p$. Simulations which tackle this issue have been very limited so far. Friedli & Martinet (1993, and priv. communication) and Combes (1994) experienced difficulties in decoupling pure stellar or gaseous bars. The inner bar in this case is very transient, which may be a result of an insufficient number of particles. For a mixed system the decoupled stage is more prolonged. Simulations explicitly demonstrate the necessity for gas to be present, and confirm that an increased central-mass concentration is important for the dynamical separation of the outer and inner parts. This can
be achieved by moving the gas along the large-scale bar, accumulating it inside the ILR on the $x_2$ orbits, modifying the local potential and forming a double ILR. The gravity of the gas settling onto these orbits is sufficient to “drag” the stars along, but such a configuration still corotates with the primary. Settling onto the $x_2$ orbits depends upon gas sound speed and viscosity. When the gas is too viscous or hot, it will avoid the ILRs completely and remain on the $x_1$ orbits aligned with the bar. Moderately viscous gas will settle onto the innermost $x_2$ orbits. The evolution of nuclear regions in disks, therefore, depends on the (unknown) equation of state of the ISM. The inclusion of star formation in nuclear rings has already demonstrated how the resulting increase in viscosity leads to the mass transfer across the ILRs (Knapen et al. 1995).

Shlosman (2001) have described simulations which have accounted for gravitational effects in the gas. Ring evolution was similar to that without gas gravity, including the swing towards the primary bar. But this was followed by the rapid growth of prograde, $\Omega_s > \Omega_p$, self-gravitating modes with $m = 2$ and 4 with the pattern speed much larger than $\Omega_p$, resulting in an avalanche-type inflow (Fig. 3). A model with the seed SBH revealed that inflowing gas feeds the SBH at peak rates, increasing its mass tenfold. This model shows that, at least theoretically, gaseous bars can dump the fuel at the very vicinity of the SBH.

3. Central Black Holes and Bulge-Halo Connection

Recent observations of galactic centers show clear correlations between the masses of the SBHs, $M_\bullet$, and masses and dispersion velocities of surrounding bulges, $M_B$ and $\sigma_B$, respectively. So far this is the most conclusive evidence that the very centers of galaxies are coupled in their evolution with the main bodies of their hosts. Analysis of the available data has led to the conclusion that the log $M_\bullet - \log \sigma_B$ relation has a slope of 4 (Tremaine et al. 2002). El-Zant et al. (2002) have attempted to provide a physical explanation to this tantalizing phenomenon, based on the interaction between dark halos and baryonic components settling in their midst. In this formulation, the halo properties determine those of the bulge and the SBH.

The basic assumption is that of flat core triaxial halos subject to baryon infall (e.g., El-Zant, Shlosman & Hoffman 2001). The flat cores do not support loop orbits and stable gas motions. It is the baryon influx which perturbs the background harmonic core and leads to the appearance of progressively less oval loops. At the same time, the contracting baryonic component becomes self-gravitating. Interestingly, these two phenomena correlate (Fig. 4), so one expects that the onset of massive star formation coincides with termination of the dynamical infall, forming a bulge-like configuration. Unless the bulge is cuspy, the loop orbits are still absent deep inside, where the infall proceeds until the formation of a central SBH.

This settling of a baryonic matter in the mildly triaxial halos can in principle lead to the simultaneous formation of the SBH-bulge system with a characteristic bulge density, set by the density in the background halo. While the formation of round loop orbits in the vicinity of the SBH will choke the dynamical infall, the bulge will still grow, until a similar process will terminate this. The inner ‘bottleneck’ depends on the bulge-to-halo density ratio, $\rho_B/\rho_H$, while the outer
bottleneck is governed by the bulge-to-halo mass ratio — limiting the SBH-to-bulge mass ratio \( K \) to largely between \( 10^{-4} - 10^{-2} \) (Fig. 5). Such a large spread in \( K \) is indeed observed. The spread in \( M_\bullet - \sigma_B \) relation can be minimized if the halo follows the Faber-Jackson scaling (Faber & Jackson 1976).

The most important prediction from modeling this nonlinear process is that the bulge and SBH parameters are determined by the halo properties. Within this framework, larger and more massive halo cores are expected to produce, on average, larger and more massive bulges. Disks will form outside the halo core, or later, when the baryons destroy the core. If the core is very large, most of the baryonic material is consumed in the first phase and no significant disk forms. This effect is expected to be prominent in larger mass cores, since if these follow the Faber-Jackson relation, more massive halos should have proportionally larger cores. Other predictions include the requirement that the average density of the bulge in the central region should be close to that of the halo core. There is also a minimal bulge mass associated with a given core, although this varies significantly with the critical loop eccentricity assumed. A number of additional consequences for galaxy formation and evolution will be discussed elsewhere.

4. Conclusions

The subjects which have been emphasized in this review are nested bars and the SBH-bulge correlation. The nested bars are interesting for two main reasons, the possibility to find them in the dynamically decoupled stage, and being a prime channel to fuel the AGN. Clearly, the ability of nested bars to trigger the gas
inflow toward the very center depends on the gas fraction within the central kpc. Gaseous bars can dump the fuel at the very vicinity of the SBH. Neglecting the gravitational effects in this gas artificially terminates its subsequent evolution.

The origin of the SBH-bulge correlations can be the manifestation of a global connection between the dark halos and the baryon-dominated luminous parts of galaxies. The flat-core triaxial halos provide the possible physical mechanism which can shape these inner parts, depending on the properties of dark matter component, in particular whether the latter exhibits the Faber-Jackson scaling. The halo shapes will have also a profound effect on the formation and subsequent growth of disk component and its stability to bar formation at higher redshifts.

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