Creation of Peanut-Shaped Bulges via the Slow Mode of Bar Growth

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Abstract. Recent theoretical work has implicated fast bar formation modes and subsequent evolution as the creation mechanism for the observed peanut-shaped bulges in some edge-on disk galaxies. We demonstrate an N-body simulation of a disk undergoing a contrasting slow mode of bar growth, unsubjected to a buckling instability, which nonetheless grows the 4:1 orbit family responsible for a peanut-shaped bulge. We also present a simulation with fast mode bar growth, which exhibits thickening similar to other work. A novel orbit classification method that finds dynamically distinct families is presented, allowing for a detailed analysis of angular momentum transfer channels within the disk.

1. Introduction

When viewed edge-on, 45% of disk galaxies show a boxy or peanut-shaped bulge (Bureau et al. 2006). Kinematic observations have revealed cylindrical rotation in some (Williams et al. 2011), which is interpreted as evidence for secular evolution: the cylindrical rotation in these bulges is a kinematic memory of the disk that the stars were elevated out of over many dynamical times. Boxy and peanut bulges, therefore, stand apart from spheroidal bulges, thought to be formed by merging processes, and hence do not result in cylindrical rotation.

Informative simulations of disk and halo systems have suggested boxy and peanut-shaped bulges to be edge-on bars. Bars in these simulations are overwhelmingly produced by simulating an initially highly unstable disk—the fast mode of bar formation (e.g. Athanassoula & Misiriotis (2002), Debattista et al. (2006), Saha et al. (2010)). In this mode of formation, bars typically buckle via the firehose instability to form thickened structures. The slow mode of bar formation (Polyachenko & Polyachenko (1996)) has been underreported, perhaps simply owing to the uncertain nature of N-body initial conditions that would lead to this mode. In the slow mode, angular momentum transfer exploits the dark halo as an accepting angular momentum reservoir for stability against buckling instabilities.

Identifying and isolating the channels for angular momentum transfer is therefore of the utmost importance for understanding the mechanisms behind the observed morphology. The analysis of properly executed simulations can shed light on the situation. In the next section, we detail two such simulations. In the third section we discuss the analysis and dynamical implications. We conclude with a statement of the utility of this study for informing future work.
2. Simulations

Previous work has focused on two general classes of initial conditions: halo- or disk-dominated systems with cored halos. For our simulations, we select a different approach. The first simulation features a cuspy central profile, \( \rho_h \propto r^{-1} \), while the second simulation features a cored central profile, \( \rho_h \propto \text{constant} \) \( (R_{\text{core}} = 0.01) \). The rotation curves are shown in Figure 1. In appearance, these simulations probe the same halo- and disk-dominated parameter space; in practice, these simulations probe different dynamical modes. The cuspy profile features a rich spectrum of orbital frequencies as \( r \to 0 \), while the cored profile allows orbits to pile up at select frequencies. This difference proves crucial for the bar formation mechanism and subsequent evolution.

Weinberg (1999) presented an algorithm to solve the Poisson equation through an expansion in empirical orthogonal functions. Implemented as EXP, a massively parallelized N-body code, such a basis may be tailored to the length scales and asymmetries of interest, reducing the overall degrees of freedom and subsequently the diffusive relaxation. Our simulations follow a disk \( (N_{\text{disk}} = 10^6, a = 0.01, h = 0.001, M_{\text{disk}} = 0.02M_{\text{halo}}) \) embedded in a live dark matter halo \( (N_{\text{halo}} = 10^7, c = 15) \) from \( T = 0.0 \to 2.0 \) (all units are listed in virial units for scaling purposes; for a Milky Way size galaxy, \( r = 1.0 \to 300 \text{kpc}, M = 1.3 \times 10^{12}M_\odot, v = 1.0 \to 135 \text{ km s}^{-1}, T = 1.0 \to 2.2 \text{ Gyr} \).

For a more detailed discussion of initial conditions, including the distribution function realization, see Holley-Bockelmann et al. (2005).

![Figure 1. Initial circular velocity curves for the two simulations. Contributions from the disk and halo are shown as dashed and dotted lines, respectively. The solid line shows the total. Left: cuspy halo. Right: cored halo. The disk is the same in both simulations.](image)

3. Analysis

To analyze orbits, we have adopted the use of a \( k \)means algorithm (Lloyd 1982) orbit classifier. Briefly, our \( k \)means algorithm iteratively determines \( k \) spatial centers of the set of \((x, y)\) apsides (local maxima in \( r \)) positions for a given orbit in the bar frame. In the bar frame, apsides of trapped orbits will remain (within some tolerance) stationary in spatial position. For example, in a 2:1 orbit the classifier will find the position of \( k = 2 \) centroids for the apsides, which will be located along the major axis of the bar. The orbital decomposition for the cuspy-halo system is shown in Figure 2. We find three primary orbit families: (1) 2:1 orbits that make up the bar quadrupole potential, (2) 2:1\( \perp \) orbits that are perpendicular to the bar, and (3) 4:1 orbits that align with the
bar and comprise the bulk of the vertically thickened structure. We classify the other orbits to be in the 'field'—these orbits are overwhelmingly outside the influence of the bar and reside on mostly circular orbits.

Both simulations result in the same three primary orbit families. However, the fractional occupation of each family differs. In the cusp simulation, the three family decomposition returns fractional occupations of \([2:1, \ 2:1_\perp, \ 4:1, \ \text{field}] = [0.226, 0.023, 0.311, 0.440]\), while the core simulation returns \([0.316, 0.056, 0.238, 0.390]\). To first order, this gives a measure of the bar mass at late times by identifying orbits that are trapped in the potential of the bar. In addition, separating the disk into distinct orbit families allows for the analysis of angular momentum channels. In Figure 3 we plot the fractional angular momentum (left, black axis) change for each orbit family during the simulations. The 2:1 orbits that make up the bulk of the bar (as well as the 2:1_\perp orbits) quickly shed the majority of their angular momentum in both simulations. Overlaid on the plot in gray is the total power in the \(m = 2\) component of the potential expansion (right, gray axis), which is a measure of bar strength. This gives some understanding of when the bar formation epoch has ended (\(T \approx 0.70\) and \(T \approx 0.35\) for the cusp and core, respectively). At this time, the angular momentum transfer becomes roughly linear in 2:1 orbits. 4:1 orbits show a roughly linear decrease in angular momentum over the course of the simulation. We understand this as the catalyzation of the disk into trapped elevated populations by the bar.

An illuminating difference is observed in the field populations of the simulations. In the cusp simulation, the field stars have nearly constant angular momentum, as the trapped orbits transfer angular momentum to the halo through resonant coupling channels. In the cored simulation, the field stars gain the angular momentum that the trapped orbits lost during the bar formation phase, as the cored halo is unable to accept angular momentum at fractions of a bar radius (as expected owing to the lower resonance den-
sity and phase-space gradient in a core). In total, the halo accepts 10% (5%) of the disk angular momentum in the cusp (core) simulation.

Figure 3. Black (left axis): angular momentum relative to initial angular momentum for the (2:1 + 2:1_{⊥}), 4:1, and field orbits (dashed, dotted, and solid, respectively). Gray (right axis): $m = 2$ power relative to $m = 0$ for the potential realization. Upper panel: cuspy halo. Lower panel: cored halo. The cored halo buckles at $T = 0.2 \rightarrow 0.3$, indicated by asymmetric terms in the potential expansion.

4. Conclusion

The main findings of this ongoing work are twofold: (1) we characterize the contrast between two modes of secular bar growth in N-body simulations, one of which, the slow mode, deserves more dedicated study and (2) present a method to accurately split the simulations into dynamically distinct orbit populations that can be applied generally. We have begun to isolate angular momentum transfer channels to illustrate the variations in dynamical mechanisms between two bar formation modes, both of which can result in a boxy or peanut-shaped bulge.

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