WHY BUCKLING STELLAR BARS WEAKEN IN DISK GALAXIES

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ABSTRACT

Young stellar bars in disk galaxies experience a vertical buckling instability that terminates their growth and thickens them, resulting in a characteristic peanut/boxy shape when viewed edge-on. Using N-body simulations of galactic disks embedded in live halos, we have analyzed the bar structure throughout this instability and found that the outer (approximately) third of the bar dissolves completely while the inner part (within the vertical inner Lindblad resonance) becomes less oval. The bar acquires the frequently observed peanut/boxy-shaped isophotes. We also find that the bar buckling is responsible for a mass injection above the plane, which is subsequently trapped by specific three-dimensional families of periodic orbits of particular shapes explaining the observed isophotes, in line with previous work. Using a three-dimensional orbit analysis and surfaces of sections, we infer that the outer part of the bar is dissolved by a rapidly widening stochastic region around its corotation radius—a process related to the bar growth. This leads to a dramatic decrease in the bar size, decrease in the overall bar strength, and a mild increase in its pattern speed but is not expected to lead to a complete bar dissolution. The buckling instability appears primarily responsible for shortening the secular diffusion timescale to a dynamical one when building the boxy isophotes. The sufficiently long timescale of the described evolution, \( \sim 1 \) Gyr, can affect the observed bar fraction in the local universe and at higher redshifts, both through reduced bar strength and the absence of dust offset lanes in the bar.

Subject headings: galaxies: bulges — galaxies: evolution — galaxies: formation — galaxies: halos — galaxies: kinematics and dynamics — galaxies: spiral

1. INTRODUCTION

Stellar bars are among the extreme signatures of a breakup of axial symmetry in galactic disks. As such, they serve as an impetus for secular and dynamical evolution of galaxies at all redshifts. The bar formation and growth largely depend on the efficiency of angular momentum redistribution, i.e., the ability of the inner (bar unstable) disk to lose the angular momentum and of the outer disks, halos, and interactions to absorb it (Athanassoula 2003). The growth of numerical collisionless bars can be characterized by an increase in the amplitude of the \( m = 2 \) mode and their prolateness, i.e., a decrease of equatorial axial ratio \( b/a \). Bars in this initial stage of evolution appear to be as flat as the disk of their origin, with a shortest-to-longest axis ratio \( c/a \sim 0.1 \). This is supported by numerical modeling of bar instability over nearly three decades (e.g., Sellwood & Wilkinson 1993).

Initial growth of model bars is terminated by the so-called vertical buckling instability, first detected in numerical simulations of Combes & Sanders (1981) and given two alternative explanations: a resonant bending (Combes et al. 1990; Pfenniger & Friedli 1991) and firehose instability (Raha et al. 1991, who invoked the explanation by Toomre 1966; Merritt & Sellwood 1994). This instability leads to the vertical thickening of the bar on a dynamical timescale via a spectacular breakup of vertical symmetry. Interest in this phenomenon has been further amplified by the similarity between frequently observed peanut- and boxy-shaped bulges in edge-on disk galaxies (e.g., Burbidge & Burbidge 1959; Jarvis 1986; Shaw 1987; Bureau & Freeman 1999; Merrifield & Kuijken 1999) and those obtained in numerical models (Patsis et al. 2002b; Aronica et al. 2003; O’Neil & Dubinski 2003).

The addition of an inhomogeneous dissipative component to the disk acts to weaken the buckling and to wash out the boxy inner shape, resulting in a more “classical” bulge with the shape parameter \( n \) larger by a factor of 2 (Berentzen et al. 1998).

Furthermore, numerical simulations capturing this evolution of stellar bars show them to weaken dramatically during the buckling instability. However, the reason for this drop in the bar strength was never explained. Is it caused by the buckling? Can it lead to a complete bar dissolution (e.g., Raha et al. 1991)? Is the bar weakened temporarily or permanently? What fraction of the orbits and which orbits stop to support the bar potential?

In this Letter, we focus on the physical reasons for this behavior and provide quantitative answers to these questions. Our results are based on the self-consistent three-dimensional (3-D) \( N \)-body simulations and a subsequent nonlinear 3-D orbit analysis of the time-dependent numerical models.

The emerging connection between the peanut/boxy bulges in edge-on disks and the buckling instability allows us, in principle, to deduce the face-on properties of galaxies in their most unfavorable orientation. This instability appears to be important in understanding the dynamical and secular evolution of barred galaxies. It bears direct consequences for radial redistribution of their stellar and gaseous components and can affect the distribution of star formation sites—both depend strongly on the bar strength and its pattern speed. Lastly, this is one of the processes that contribute to the growth of the pseudo-bulges (e.g., review by Kormendy & Kennicutt 2004).

The nature of the buckling instability is being slowly understood, and recent progress is based on the analysis of the orbital structure of barred (Pfenniger 1984; Skokos et al. 2002a, 2002b) and unbarred (Patsis et al. 2002a) disks and spheroidal components (Binney & Petrou 1985; May et al. 1985) and is related to the shapes of dominant orbital families. Observationally, the significance of peanut/boxy bulges follows directly from their abundance—almost half of all edge-on disks exhibit them (Lüttinger et al. 2000). The emerging picture is that of two processes: of the firehose instability leading to the buckling in the midplane of the bar and of resonant heating, trapping the particles around stable...
3-D orbits that furnish the bar with the boxy-shaped bulge. The energy deposited initially in the characteristic wavelength of buckling instability subsequently cascades down to smaller wavelengths, increasing the vertical dispersion velocities within the region.

More specifically, Pfenniger & Friedli (1991) have identified 3-D orbital families, which if populated will provide the bar with the specific “butterfly” or peanut shape when viewed edge-on along the minor axis. These families originate at the vertically unstable gap of plane periodic orbits, in other words, at the vertical inner Lindblad resonance (VILR), which is almost always present in the bar, at roughly one-third to two-thirds of its corotation radius. In this picture, the growth of the bar is limited by the formation of unstable plane orbits (Pfenniger 1984). Those

Their projections onto the potential midplane are elongated with the bar, similarly to the main orbit family supporting the bar.

2 RESULTS

We have used version FTM-4.4 of the N-body code (e.g., Heller & Shlosman 1994) with N = 6 × 10^5 collisionless particles, which represent the stellar disk and dark halo components. In a number of runs, the particles have been distributed initially according to the Fall & Efstathiou (1980) analytical model, which
consists of an iteratively relaxed halo and an exponential disk. The dynamical time is $4.7 \times 10^7$ yr, and $r$ and $z$ are the radial and vertical coordinates in the disk. The initial conditions for the model described here are chosen such that the disk/halo mass ratio within 10 kpc is unity. The halo has a flat density core of 2 kpc to avoid excessive stochastic behavior associated with the central cusps (El-Zant & Shlosman 2002). The radial and vertical disk scale lengths are 2.85 and 0.5 kpc, and the Toomre $Q$ parameter is 1.5. Gravitational softening of 160 pc was used. For the orbital analysis, we use the updated algorithm described in Heller & Shlosman (1996). All the discussion involving 3-D orbital structure and resonances in the bar are based on this nonlinear formalism and differ substantially from the epicyclic (linear) approximation. The bar pattern speed, $\Omega_p$, is calculated from the phase angle of the $m = 2$ mode. The energy and angular momentum in the system are conserved to within approximately 1% and 0.05% accuracy, respectively. Our results appear to be reasonably independent of $N$.

The initially axisymmetric model develops a prominent bar in about three rotations (as measured by $m = 2$ amplitude $A_2$; Fig. 1a), which starts to break against the halo and the outer disk, reducing its pattern speed (Fig. 1b). Between about $t \sim 1.6$ and 2.4 Gyr, the bar becomes vertically unstable and buckles, breaking the symmetry with respect to the disk equatorial mid-plane (Fig. 2). After $t \sim 2.4$ Gyr, the bar profile in the $r$-$z$ plane again tends toward symmetry, but the inner bar part has now a larger vertical thickness, $c/u \sim 0.3$, and its isophotes have acquired a boxy appearance, in accordance with previous work on this subject. More careful analysis reveals additional fundamental changes and transformations in the bar. This subtle bar evolution can be followed through changes in its orbital structure.

First, the bar size and strength change in a particular way during the short period of buckling. The size of the bar is defined here in the observational context (following Knapen et al. 2000). Namely, the bar is “detected” by the maximal ellipticity of the face-on fitted bar isophotes (i.e., isodensities) and their constant position angle (P.A.). Its size is taken to be the maximal radius of P.A. = const. We have verified a posteriori that this definition does not contradict the bar size obtained from the extent of the largest stable periodic orbit supporting the bar figure.

The isodensity ellipse fitting to the bar at $t = 1.6$ Gyr resulted in rising ellipticity along the bar, from $-0.45$ at the innermost to about 0.78 at $r \sim 8$–9 kpc and its subsequent drop. For $t = 2.4$ Gyr, the bar ellipticity stayed flat, $-0.5$, up to $r \sim 5$ kpc and dropped sharply for larger $r$. The inner part of young numerical bars hence appears far more nonaxisymmetric than their observational counterparts.

Prior to buckling, the bar grows and extends to nearly its corotation radius, $r_{CR}$, which increases with time owing to the decreasing $\Omega_p$. Between $t \sim 1.9$ and 2.4 Gyr, the bar decreases in its length $r_b$ by about one-third but remains its growth afterward. The ratio $r_b/r_{CR}$ is about 1.05 between $t \sim 1.4$ and 1.9 Gyr, increases to 1.7 at $t \sim 2.4$ Gyr, and drops to 1.4 thereafter. At $t \sim 2.4$ Gyr, the bar size appears to correspond to $r_{VILR} \sim 0.5r_{CR} - 0.6r_{CR}$, or in other words, to the radius of an unstable gap in the main family of $x$-$y$ planar orbits supporting the bar.

Second, as Figure 1a reveals, the weakening of the bar starts in the outer part and propagates inward, and while the amplitude of the inner part drops by a factor of $\sim 3$–4, the outer bar basically dissolves and its $A_2$ amplitude tends to zero, before it rebounds and grows again.

Third, the mass within the central $r \sim 1$ kpc jumps almost by a factor of 2 between $t = 1.6$ and 3.8 Gyr and by about 20% within $r = 3$ kpc, leading to a much more centrally concentrated system. This mass concentration grows rather “impulsively” and can in principle be responsible for periods of a mild spin-up in $\Omega_p$ seen in Figure 1b at $t \sim 2$–2.2 Gyr and after 2.4 Gyr. The buckling instability also injects a (relatively) substantial disk mass above its midplane of $z = \pm 1$ kpc for $r \leq r_{VILR}$, increasing the mass there by a factor of $\sim 6$, at $t \sim 2.4$ Gyr. We have verified that particles that are injected above the plane are those trapped by the bar prior to and during the instability. Their specific angular momentum is lower than for particles remaining in the plane by about 20%. Lastly, the ratio $(\sigma/x)^2$, of vertical-to-radial velocity dispersions in the bar, drops during the bar growth to just below 0.4 and then abruptly rises to about 0.95 at $t \sim 2.4$ Gyr.

3.DISCUSION

The bar overall weakening and dissolution of the outer part during the buckling instability are reflected in kinematical properties and changes of its orbital structure. Those are discussed without invoking a specialized terminology.

The main kinematic change during the instability is that the bar, which is a very fast rotator initially, becomes a slow rotator between $\sim 2.1$ and 3.3 Gyr and again a fast one afterward. The definition “fast/slow” is used here in the sense of the relative extent of the bar with respect to its corotation ($\sim 2$). Because the characteristic offset dust lanes delineating shocks exist only in a narrow range of fast bar parameters (e.g., Athanassoula 1992), we do not expect them to exist or, at least, to have their usual shape, during $\sim 1$ Gyr of the buckling and some time thereafter, when the bar is a slow rotator. In addition, the overall weakening of the bar, which resembles more of an oval distortion during a prolonged period of time, can affect the observed bar fraction, especially at higher redshifts. This and subsequent bar growth are discussed elsewhere (I. Martinez-Valpuesta et al. 2004, in preparation).

We have searched for main families of planar, $z = 0$, and 3-D orbits that support the bar shape before and after the buckling. Within the bar figure, the particles are largely trapped around 3-D orbits that support the bar shape before and after the buckling. In agreement with other studies, we find the 3-D prograde families of orbits originating at the VILR and a retrograde family originating from 1:1 resonance—initially populated only very close to the bar $x$-$y$ symmetry plane. During the buckling of the bar midplane, the main planar orbits acquire the bent shape within $r_{VILR}$. The particles injected above the plane (see § 2) are subsequently trapped on specific 3-D orbits.

Note that $A_2$ maximum is not a good measure of the bar size as higher harmonics, $m = 4$ and 8, have a substantial contribution.
(see § 1), whose x- and z-extensions increase sharply with their energy. Populating them will provide the bar with the peanut shape when viewed along its minor axis. The boxy shape appears somewhat later (Fig. 2, lower panel), which has been also indicated by Raha et al. (1991) for barred and by Patsis et al. (2002a) for nearly axisymmetric disks.

An important observation by Friedli & Pfenniger (1990) that the peanut/boxy shapes appear even when the firehose instability in the bar is artificially suppressed by enforcing the symmetry in the r-z plane provides the crucial insight into the role of this instability. The long evolutionary timescale of the symmetrized bar is the result of the particle diffusion process enhanced by the resonant heating via the VILR—a secular process that ultimately will furnish the bar with its characteristic peanut-shaped bulge, unless some other more efficient heating of the stellar “fluid” will wash this out, e.g., star scattering by inhomogeneous gas (Berentzen et al. 1998).

How does bar buckling change this picture? The important point here appears to be particle injection above the disk plane (§ 2)—those populate the characteristic 3-D family of orbits on a dynamical timescale, not secularly. Thus, the buckling accelerates the process by breaking the symmetry and by taking the evolution from the second-order diffusion process to the first-order dynamical instability.

What exactly is responsible for the sharp drop in the bar’s strength and size? The orbital structure of the bar does not itself provide the answer, as it does not supply us directly with the “population census” of different orbit families. However, some measure of this, especially the fraction of phase space occupied by regular orbits, is given by the surfaces of sections (e.g., Binney & Tremaine 1987). The bar strength is growing steadily prior to instability, and its ellipticity in the outer part is high and peaked at ~0.8. Strong bars are known to generate chaos, starting from near the corotation, and the stochastic region is expected to widen with the bar strength (e.g., Contopoulos 1981). To test this, the representative surfaces of sections corresponding to regions deep inside the bar, at intermediate radii and at the bar ends, are shown in Figure 3. At $t = 1.6$ Gyr, the bar interior is dominated by a trapped regular orbit, prograde for $y > 0$ (left two panels). The outer bar is dominated by stochastic orbits, and the invariant curves have dissolved here (upper right panel). At $t = 2.4$ Gyr; however, while the stochastic region is still visible around the end of the bar, at $x = 5.9$ kpc, its fraction has decreased substantially—in tandem with the decreased bar strength. Note that while the bar corotation propagates outward, the stochastic region expands inward into the bar, dissolving its part outside the peanut shape, which is built at the VILR, and weakening the bar further inside. The phase-space regularity is largely restored after the potential is mostly symmetrized again in the r-z plane. Escaping chaotic orbits from the dissolving region have axial ratios far different from what is needed to support the bar and rapidly precess out of the “valley” of the bar potential—triggering a runaway dynamical process, concurrent with the buckling instability. Figure 4 shows one of the highest energy stable main planar orbits in the bar at $t = 1.6$ Gyr and, for comparison, the similar energy orbit after the buckling—much shorter in its x-extension, less oval, and confined to within $r_{\text{VILR}}$. This demonstrates the dominant trend in the bar evolution during the instability. It also underscores that the outer bar dissolution is concurrent with the buckling and maybe affected by it. The bar cannot dissolve completely as this process is clearly limited to $r \geq r_{\text{VILR}}$.

In summary, a young stellar bar weakens overall, and its outer part beyond the VILR dissolves after the bar reaches its peak strength. We show that this happens as a result of the inward expansion of the stochastic region near corotation. This effect is triggered by the exceptional strength of the growing bar prior to buckling instability. The rapidly developing chaos leads to a self-destruction of the outer bar. There is no indication that the inner part of the bar within the VILR can dissolve. The corollary is that the bar becomes a slow rotator for $\sim$ 1 Gyr, a prolonged period of time, with observational consequences for gasdynamics within the bar and the formation of characteristic dust lanes there. The sharp decrease in the bar strength for a similar period of time can have implications for the observed bar fractions in the local and higher redshift universe, when both spontaneous and tidally induced bars are important.

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