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Internal secular evolution in disk galaxies: the growth of pseudobulges

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Abstract. Observational and theoretical evidence that internal, slow ("secular") evolution reshapes galaxy disks is reviewed in Kormendy & Kennicutt (2004). This update has three aims. First, I emphasize that this evolution is very general – it is as fundamental to the evolution of galaxy disks as (e. g.) core collapse is to globular clusters, as the production of hot Jupiters is to the evolution of protoplanetary disks, and as evolution to red giants containing proto-white-dwarfs is to stellar evolution. One consequence for disk galaxies is the buildup of dense central components that get mistaken for classical (i. e., merger-built) bulges but that were grown out of disk stars and gas. We call these pseudobulges. Second, I review new results on pseudobulge star formation and structure and on the distinction between boxy and disky pseudobulges. Finally, I highlight how these results make a galaxy formation problem more acute. How can hierarchical clustering produce so many pure disk galaxies with no evidence for merger-built bulges?

Keywords. galaxies: bulges, galaxies: evolution, galaxies: formation, galaxies: photometry, galaxies: kinematics and dynamics, galaxies: nuclei, galaxies: structure

1. The fundamental way that disks evolve is by spreading.

Galactic evolution is in transition from the early Universe dominated by hierarchical clustering to a future dominated by internal secular evolution. There are many ways that stars and gas can interact with collective phenomena such as bars, oval disks, spiral structure, and triaxial dark halos. Different processes deserve – and are getting – detailed study. In this paper, I want to emphasize common features that make the ensemble of internal evolution processes fundamental. This point is important enough that it should appear in these Proceedings, so I quote a discussion from Kormendy & Fisher (2005).

"A general principle of the evolution of self-gravitating systems is that it is energetically favorable to spread – to shrink the inner parts by expanding the outer parts. How to see this depends on whether the system is dominated by rotation or by random motions.

1.1. *If Dynamical Support Is By Random Motions*

Then the argument (Lynden-Bell & Wood 1968; Binney & Tremaine 1987) is based on the fundamental point that the specific heat of a self-gravitating system is negative. Consider an equilibrium system of N particles of mass m, radius r, and three-dimensional velocity dispersion v. The virial theorem says that $2\,\mathrm{KE} + \mathrm{PE} = 0$, where the kinetic energy $\mathrm{KE} = Nmv^2/2$ and the potential energy $\mathrm{PE} = -G(Nm)^2/r$ define v and r. The total energy of a bound system, $E \equiv \mathrm{KE} + \mathrm{PE} = -\mathrm{KE}$, is negative. But temperature T corresponds to internal velocity as $mv^2/2 = 3kT/2$. So the specific heat $C \equiv dE/dT \propto d(-Nmv^2/2)/d(v^2)$ is also negative. In the above, G is the gravitational constant and k is Boltzmann's constant.

The system is supported by heat, so evolution is by heat transport. If the center of the system gets hotter than the periphery, then heat tends to flow outward. The inner parts shrink and get still hotter. This promotes further heat flow. The outer parts receive heat; they expand and cool. Whether the system evolves on an interesting timescale depends on whether there is an effective heat-transport mechanism. For example, many globular clusters evolve quickly by two-body relaxation and undergo core collapse. Giant elliptical galaxies – which otherwise would evolve similarly – cannot do so because their relaxation times are much longer than the age of the Universe.

1.2. *If Dynamical Support Is By Rotation*

Tremaine (1989) provides a transparent summary of an argument due to Lynden-Bell & Kalnajs (1972) and to Lynden-Bell & Pringle (1974). A disk is supported by rotation, so evolution is by angular momentum transport. The 'goal' is to minimize the total energy at fixed total angular momentum. A rotationally supported ring at radius r in a fixed potential $\Phi(r)$ has specific energy $E(r)$ and specific angular momentum $L(r)$ given by

$$E(r) = \frac{r}{2}\frac{d\Phi}{dr} + \Phi \quad \text{and} \quad L(r) = \left(r^3\,\frac{d\Phi}{dr}\right)^{1/2} .$$

Then $dE/dL = \Omega(r)$, where $\Omega = (r^{-1}d\Phi/dr)^{1/2}$ is the angular speed of rotation. Disks spread when a unit mass at radius r_2 moves outward by gaining angular momentum dL from a unit mass at radius $r_1 < r_2$. This is energetically favorable: the change in energy,

$$dE = dE_1 + dE_2 = \left[-\left(\frac{dE}{dL}\right)_1 + \left(\frac{dE}{dL}\right)_2\right] dL = \left[-\Omega(r_1) + \Omega(r_2)\right] dL\,,$$

is negative because $\Omega(r)$ usually decreases outward. 'Thus disk spreading leads to a lower energy state. In general, disk spreading, outward angular momentum flow, and energy dissipation accompany one another in astrophysical disks' (Tremaine 1989).

1.3. *Self-Gravitating Systems Evolve By Spreading*

The consequences are very general. All of the following are caused by the above physics.

Globular and open clusters are supported by random motions, so they spread in three dimensions by outward energy transport. The mechanism is two-body relaxation, and the consequences are core collapse and the evaporation of the outer parts.

Stars are spherical systems supported by pressure. They spread in three dimensions by outward energy transport. The mechanisms are radiation or convection mediated by opacity. Punctuated by phases of stability when nuclear reactions replace the energy that is lost, stellar evolution consists of a series of core contractions and envelope expansions. One result is red (super)giants containing cores that will become white dwarfs, neutron stars, or stellar mass black holes.

Protostars are spherical systems coupled to circumstellar disks by magnetic fields that wind up because of differential rotation. This drives jets that look one-dimensional but that really are three-dimensional; they carry away angular momentum and allow the inner circumstellar disk to shrink and accrete onto the star (Shu *et al.* 1994, 1995).

Protoplanetary disks are supported by rotation; they spread in two dimensions by outward angular momentum transport. Dynamical friction produces, for example, hot Jupiters and colder Neptunes.

Galactic disks are supported by rotation. They want to spread in two dimensions by outward angular momentum transport. Efficient driving mechanisms are provided by bars and globally oval disks. Like all of the above, the evolution is secular – it is slow compared to the collapse time of the disk. Secular evolution is the subject of this paper.

2. Secular evolution and the growth of pseudobulges

That interactions with collective phenomena such as bars and spiral structure result in secular evolution was emphasized as long ago as Kormendy (1979a, b; 1982a, b). One of the earliest examples of a specific process was the suggestion by Duus & Freeman (1975), now confirmed by many papers (e. g., Simkin, Su, & Schwarz 1980), that gas in a barred galaxy settles into a ring surrounding the end of the bar (Figure 1). The formation of bars is likely to be partly secular (Sellwood 2000). Another early result was the demonstration (Combes & Sanders 1981) that n-body bars heat up in the axial direction; when seen edge-on, they resemble – and, we believe, explain – box-shaped bulges (§ 4). By 1982, the secular evolution of barred galaxies was a thriving industry (see Kormendy 1982a for a review). Sellwood & Wilkinson (1993), Kormendy (1993), and Buta & Combes (1996) provide interim reviews. In the past decade, progress has accelerated rapidly. Recent reviews include Kormendy & Cornell (2004); Kormendy & Fisher (2005); Athanassoula (2007a, b), and most thoroughly, Kormendy & Kennicutt (2004, hereafter KK04).

Figure 1 illustrates the results of gas evolution in a barred galaxy. Disk gas is rearranged into an "outer ring" at ~ 2.2 bar radii, an "inner ring" that encircles the end of the bar, and a dense central concentration of gas. As the gas density increases, star formation is likely, and indeed, the features produced in gas closely resemble the stellar outer rings, inner rings, and pseudobulges seen in the figure. Much observational evidence supports these interpretations, as discussed in the above reviews.

Pseudobulges are the consequence discussed in this paper. In the simulations, gas falls to the center and builds high densities, often in rings. Since star formation rate density $\Sigma_{\rm SFR}$ increases faster than linearly with gas density $\Sigma_{\rm gas}$, $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.4}$ (Kennicutt 1998a, b), high star formation rates are expected. They are observed. KK04 review observations of nuclear starbursts, often in spectacular rings and often associated with bars and oval disks. The star formation rates in starbursting nuclear rings imply, with modest replenishment of the observed nuclear gas, that they would build the stellar densities that we observe in pseudobulges in 1–3 billion years. That is, the formation picture suggested by the simulations is clearly consistent, via observed gas densities, star formation rates, and plausible timescales, with the disky pseudobulges discussed in the next section.

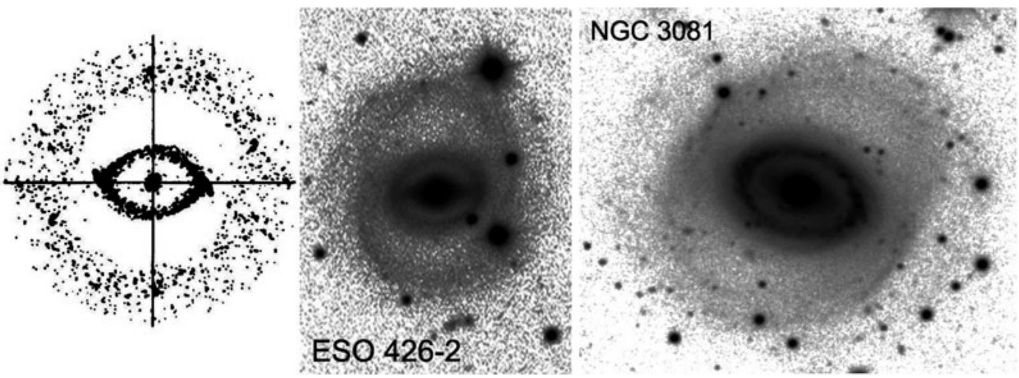

Figure 1. Secular evolution products: (left) Gas particles at the end of a sticky-particle simulation of evolution in a rotating bar potential (horizontal but not shown; Simkin, Su, & Schwarz 1980). After 7 bar rotations, gas has collected into an outer ring, an inner ring around the end of the bar, and a dense central concentration. Such features are seen in SB galaxies; e. g., ESO 426-2 (Buta & Crocker 1991) and NGC 3081 (Buta, Corwin, & Odewahn 2007). Detailed hydrodynamic simulations confirm and enrich this picture (see especially Athanassoula 1992). This figure is adapted from Kormendy & Kennicutt (2004).

3. Update on pseudobulge properties and star formation

The properties that allow us to classify pseudobulges are listed in KK04. I have space here for only a brief update of pseudobulge properties and star formation rates.

Fisher (2006) used *Spitzer Space Telescope* images to derive, for 50 galaxies, 3.6 μm–8 μm color profiles that are a measure of star formation rates (Wu *et al.* 2005). He found that morphologically identified classical bulges have lower star formation rates than their disks. Pseudobulges have star formation rates similar to those of their associated disks. If most pseudobulges show ongoing star formation, then it must be secular (KK04).

Drory & Fisher (2007a, b) show that bulge type correlates with the division of galaxies into a red sequence and a blue cloud in Sloan Survey color-magnitude diagrams (Strateva *et al.* 2001). Red sequence galaxies contain mainly classical bulges. Blue cloud galaxies contain pseudobulges. The division into red and blue is not due to different mixtures of red bulges and blue disks; rather, classical bulge galaxies globally formed most of their stars early, and pseudobulge galaxies (excepting S0s) continue to form stars throughout.

Peletier (2007) reviews SAURON observations that show, in superb, two-dimensional detail, evidence for pseudobulges with disky dynamics and young stellar populations.

Fisher & Drory (2007) measure surface brightness distributions in 84, S0 − Sc galaxies in which they morphologically classify the bulges as classical or pseudo. They decompose major-axis profiles into Sérsic (1968) $\log I \propto r^{1/n}$ profiles + exponential disks. They find:

(*a*) Almost all pseudobulges have $n \leqslant 2$ and almost all classical bulges have $n \geqslant 2$. This extends results of (e. g.) Courteau, de Jong, & Broeils (1996); Carollo *et al.* (2002); MacArthur, Courteau, & Holtzman (2003), and KK04. We do not understand how to predict n in either type of bulge, but the above correlation is good enough so we can use n as an (imperfect, to be sure) classification criterion.

(*b*) Bulge-to-total luminosity ratios B/T are smaller for pseudobulges than for classical bulges over the whole Hubble sequence and also at a given Hubble type. Almost no pseudobulges have $B/T > 1/3$, as expected if they are built out of disk material.

(*c*) Pseudobulges are flatter than classical bulges; in fact, the flattest classical bulge in their sample is less flattened than the average pseudobulge. But the roundest classical and pseudo bulges have similar intrinsic flattenings. Not all pseudobulges are flat.

4. Where are the bulges in galaxies with box-shaped, edge-on bars?

Figure 2 (left) shows a normal, early-type barred galaxy. It is easy to distinguish the bar from the bulge (which happens to be a pseudobulge: KK04). Ignoring, for present purposes, the distinction between lens and outer ring, there are three main components, the disk, the bar, and the pseudobulge. The next two panels show NGC 4565, a familiar galaxy with a boxy pseudobulge. The middle image is an infrared (3.6 μm) version of the view that we normally see in print. Two components are visible, the disk and the boxy bulge. As long as we thought that a boxy shape was a minor structural detail of bulges, our mental picture of this galaxy was entirely canonical: it is an Sb galaxy with a big disk and a small bulge. But now we know that boxy bulges are edge-on bars. So the central image shows two components, a disk and a bar. Where is the bulge in this Sb galaxy? The same question applies to all edge-on galaxies with boxy bulges.

The right-hand image and plot provide the answer (Kormendy & Barentine 2007). NGC 4565 contains a high-surface-brightness but tiny pseudobulge that is clearly distinct from the boxy bar. The key to seeing this component is to observe far enough into the infrared to reduce the dust absorption that is a problem in the optical. A 3.6 μm *Spitzer Space Telescope* archive image and an HST NICMOS image are unaffected by dust near the center. The latter provides high enough spatial resolution so that we can measure the Sérsic index of the central component. Is it a classical bulge or is it a pseudobulge? It's

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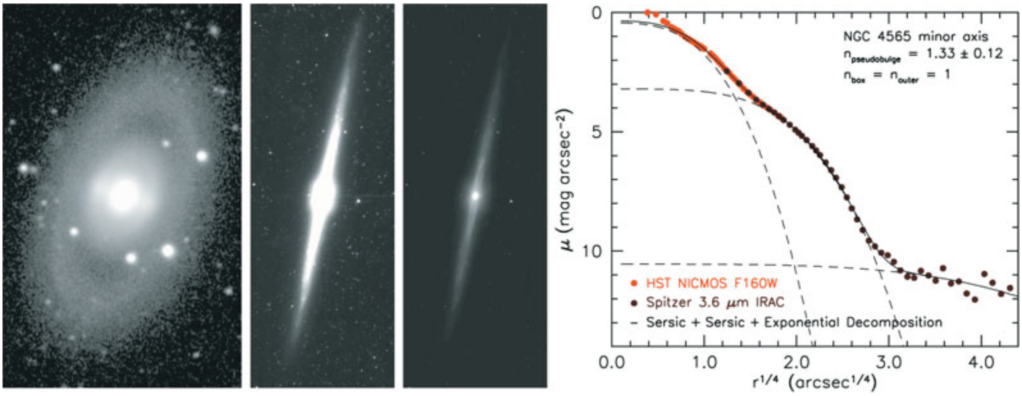

Figure 2. The left panel shows a visible-light image of the SB0 galaxy NGC 3945. It contains a pseudobulge, a bar that fills a lens component along the minor axis, and an outer ring. The central panels show a *Spitzer Space Telescope* 3.6 μm IRAC image of NGC 4565 at different brightnesses and contrasts to emphasize the box-shaped bulge (left) and the central pseudobulge (right). The rightmost panel shows the minor-axis brightness profile derived from the *Spitzer* image and from a *Hubble Space Telescope* (HST) NICMOS F160W image. Also shown is a three-component decomposition into a central Sérsic function for the pseudobulge, a Sérsic function for the boxy bulge, and an outer exponential. From Kormendy & Barentine (2007).

axial ratio is consistent with a classical bulge – it is not particularly flat. But it's Sérsic index is $n = 1.33 \pm 0.12$. This means that it is a pseudobulge (§ 3). Kormendy & Barentine (2007) find similar results for NGC 5746, another edge-on galaxy with a boxy bulge.

This is remarkable: Except for the faint thick disk and halo, *the thickest component in NGC 4565 is the edge-on bar, which is part of the disk. The next thickest component is the thin disk. The component with the smallest scale height is the pseudobulge.* It has the shape of a classical bulge, but its scale height is only $1\farcs2 \sim 90$ pc. In contrast, the scale height of the boxy bar + thin disk is $10'' \sim 790$ pc. Four implications deserve emphasis:

(a) Seeing a pseudobulge distinct from the boxy bar increases confidence in our picture of secular evolution. It is easier to believe that we understand boxy bars in edge-on galaxies if we also find (pseudo)bulges like those associated with bars in face-on galaxies.

(b) B/T ratios in edge-on galaxies with "boxy bulges" are smaller than we thought.

(c) Published B/T values in edge-on and face-on barred galaxies are inconsistent. In edge-on galaxies, we count box-shaped structures as bulge light. When we see such a galaxy face-on, we identify this light as a bar and measure a smaller B/T ratio.

(d) A problem with cold dark matter galaxy formation gets more acute. Simien & de Vaucouleurs (1986) find that $B/T = 0.4$ in NGC 4565. But B refers to the boxy bar. Figure 2 shows that the pseudobulge is much less luminous than the boxy structure. And it has the properties of pseudobulges that were grown out of disks. Yet the disk rotates at 255 ± 10 km s^{-1} interior to the outer warp (Rupen 1991). In a hierarchically clustering Universe, how can a galaxy grow so massive with no evidence for a major merger?

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