BARS, SPIRAL STRUCTURE, AND SECULAR EVOLUTION IN DISK GALAXIES

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Abstract
Simulations and observations of galactic bars suggest they do not commonly evolve into bulges, although it is possible that the earliest bars formed bulges long ago, when galaxies were smaller, denser, and had more gas. The most highly evolved of today’s bars may become lenses over a Hubble time. Most galaxies in the early Universe are extremely clumpy, with $\sim 10^9 - 10^9 M_\odot$ blue clumps that resemble in color and magnitude the isolated field objects nearby. The presence of blue and irregular bars at high redshift suggests that some bars formed primarily in the gas phase accompanied by giant starbursts, rather than in pure stellar disks like most models. Secular and non-secular processes that cause galaxies to evolve are summarized.

Keywords: Barred galaxies, spiral galaxies, galaxy evolution

Introduction
Secular evolution of galaxies includes too many processes to review thoroughly here. Instead, a selection of processes with contemporary interests will be discussed. They include bar evolution in the present-day Universe and at intermediate to high z, and disk formation at high z, where extremely clumpy structure seems to be common. A brief summary of secular evolution effects over a Hubble time is in Section 1.4. A recent review of secular evolution leading to central mass concentrations and pseudobulges was in Kormendy & Kennicutt (2004).

1. Bar Evolution

Bar Dissolution to Form a Bulge

The disk and halo of a galaxy exert negative torques on a bar and cause the bar to get stronger, longer, and slow down over time (Weinberg 1985; Debattista & Sellwood 1998, 2000; Athanassoula, Lambert, & Dehnen 2005;
Bars also change their shape as more orbital families get populated. They can thicken and develop a peanut-shaped profile perpendicular to the disk as a result of a resonance between the corotating pattern period and the vertical oscillation period (Combes & Sanders 1981). They can become more squared off at the ends, or boxy, as a result of increasing populations of 4:1 orbits. Orbit families are described in Sellwood & Wilkinson (1993) and Athanassoula (2005). Gas accretion to the center and subsequent star formation can lead to a dense nucleus, which either forms an ILR or shifts the existing ILR to a larger radius. Tightly wound starburst spirals or rings may appear near these inner resonances and secondary bars can form inside (e.g., Englmaier & Shlosman 2004).

Perhaps the most startling development of the 1990’s was that the growth of the ILR radius with time depopulates bar-supporting orbits (x1 orbits), which are the elongated orbits parallel to the bar out to nearly the corotation radius. This depopulation can dissolve a bar completely, forming a bulge-like concentration in the center (Hasan & Norman 1990; Friedli & Benz 1993; Hasan, Pfenniger, & Norman 1993). Norman, Sellwood, & Hasan (1996) ran 2D models of bar dissolution with 50,000 star particles, no gas and no active halo. They found that by the time 3-5% of the total disk mass shrank to the galaxy core, the bar was completely dissolved. They also confirmed this result with a 3D model using 200,000 star particles and no active halo.

Shen & Sellwood (2004) also ran 3D star models with no active halo and found in addition that bar weakening occurs in 2 phases, an initially fast stage where the bar-supporting orbits are scattered, and then a slow stage where the whole potential changes. More importantly, they pointed out that the central mass needed to destroy a bar is much larger, by a factor of 10 or more, than the nuclear black hole mass, concluding that bar destruction is in fact unlikely in real galaxies. They showed further that a dispersed central mass, as might result from gas inflow and star formation, required an even higher fraction (e.g., >10% of the disk mass) than a point-like distribution, making the possibility that gas accretion can eventually destroy a bar (i.e., because of its central mass) seem even more remote.

Athanassoula, Lambert, & Dehnen (2005) studied bars with active halos and found that if the halo was massive, the bars survived even with a central mass of 10% of the disk mass. Bars in low-mass active halos were still destroyed, like before. The difference is that an active halo continuously removes angular momentum from the bar, strengthening it by populating x1 orbits. Then the deleterious effect of the central mass is reduced. Halos also promote spiral arm formation by the removal of disk angular momentum (Fuchs 2004).

While bars are strengthened by a loss of angular momentum to a disk or halo, thereby resisting dissolution at the ILR from a central concentration, bars also weaken by the absorption of angular momentum from gas, and thereby
become more prone to dissolution (Bournaud & Combes 2002). Gas within the bar radius shocks at the bar-leading dust lanes. The asymmetric pressures in these shocks cause the gas to lose orbital angular momentum, eventually migrating to the center. The shock is asymmetric only if there is energy dissipation; otherwise the backward impulse the gas feels when entering the shock is compensated by a forward impulse it feels when leaving the shock. From the point of view of the stars, there is a gravitational attraction to the dust lane, which is shifted forward of the orbital apocenter. Because stars in bar orbits spend a longer time at apocenter than at pericenter (on the minor axis), the time-integrated gravitational force from the gas produces a net positive torque on the stars. The resulting angular momentum gain causes the elongated stellar orbits to open up into circular orbits, which have higher angular momentum for the same energy (the same major axis length). Circularization of orbits makes the bar ultimately dissolve. Recent simulations of this effect are in Bournaud, Combes, & Semelin (2005).

Dissolution of a bar by gas torques requires a large amount of gas in the bar region, as essentially all of the angular momentum that was removed from the stars to make the bar in the first place has to be returned from the gas. If the total mass fraction of gas in the bar region is small, then the circularization of bar orbits may be minimal. Block et al. (2002) propose that continued accretion of gas onto the galaxy disk can cause a second or third event of bar dissolution if a new bar forms in the mean time. In this way, bars can dissolve but still have an approximately constant fraction over a large portion of the Hubble time, as observed by Sheth, et al. (2003), Elmegreen, Elmegreen, & Hirst (2004), Jogee et al. (2004), and Zheng, et al. (2005).

Bars Dissolution to Form a Lens

What is the observational evidence for bar dissolution and what happens to old bars? The evidence for bar circularization in more centrally concentrated galaxies (Das et al. 2003) does not actually indicate that bars dissolve. Dissolution may take a very long time and the observed circularization could be only the first step.

There is good evidence for some bar dissolution, however, with the resulting structure a lens (Sandage 1961; Freeman 1975; Kormendy 1977), or perhaps a pseudo-bulge (Kormendy & Kennicutt 2004). A lens is not a spheroid or part of the outer exponential disk. It is a stellar distribution in the inner region with a rather shallow brightness profile and a sharp cutoff at mid-disk radius. Outside the lens, the main disk exponential continues. Kormendy (1979) suggested that lenses are dissolved bars. That is, S0 galaxies with lenses formerly had bars. Of the 121 low-inclination, bright SB0-SBd type galaxies in Kormendy (1979), 54% of early bar types, SB0-SBa, have a lens, 0% of late bar types SBab-SBc
have a lens, and 16% of the sample have both a bar and a lens. The lens looks like it is coming from the bar in these latter cases because the lens size is the same as the bar size. The lenses in early-type non-barred galaxies are also the same size as the inner rings in barred (non-lens) galaxies for the same absolute magnitude galaxy; these rings are another measure of bar size. Lens colors are generally the same as bar colors too. Some bars even “look” like they are dissolving into a lens because the bar spreads out into a circular shape at the ends (e.g., NGC 5101). The axial ratio distribution of lenses weakly suggests they are thick (triaxial).

The presence of lenses in about half of the early type barred galaxies (as mentioned above) but in only a small fraction of early type non-barred galaxies suggests further that bars dissolve very slowly into lenses. The most advanced stages of dissolution are in the early type bars, which are denser and more advanced in total evolution than late-type bars.

There are very few simulations of bar dissolution into a lens. A pure star simulation by Debattista & Sellwood (2000) shows something like a stellar ring forming at the end of the bar. Stars develop complex orbits over time, migrating between inside and outside the bar as the lens builds up.

2. Bar Dissolution into Bulges at Very Early Times

We have found that barred galaxies in the early Universe are slightly smaller than barred galaxies today, by a factor of $\sim 2$ in the exponential scale length (Elmegreen, Elmegreen, & Hirst 2004). Such a measurement avoids problems with cosmological surface brightness dimming. The same small sizes are observed for spiral galaxies in general, based on a sample of 269 spirals in the Hubble Ultra Deep Field (Elmegreen, et al. 2005a). The presence of spirals in these high-z disk galaxies suggests that the disks are relatively massive compared to the halos at that time, unlike the inner disks of today’s galaxies. This suggests, in turn, that galaxies build up from the inside out, as proposed many years ago (e.g., Larson 1976). With such a process, the dynamical time for evolution in a disk, which is proportional to the inverse square root of total density, will be shorter in the early Universe than it is today. That is, the active parts of galaxy disks are gradually evolving toward lower and lower densities and longer evolutionary timescales (a process related to “downsizing” – e.g. Tanaka, et al. 2005).

The implication of increasing dynamical time in an aging Universe is that bar formation and secular dissolution should have been much faster at high redshift, in approximate proportion to the bar size. Also, the higher gas abundance in young galaxies would have led to a more rapid dissolution then too, by the Bournaud & Combes (2002) process. Thus some of the very early stages of bulge formation inside a disk (as opposed to disk accretion around a pre-
existing bulge) could have involved evolution from a bar. There is no direct evidence for this yet, however.

**Observing The Youngest Bars**

![Figure 1](image)

**Figure 1.** Four quantities from the standard \( \Lambda \)CDM cosmology are plotted versus redshift, \( z \): the Universe age and look back time (top left), the physical size of a region subtending 10 pixels of the HST ACS camera (top right), the redshift range, \( \Delta z \), spanning 0.5 Gy (lower left), and the apparent surface brightness of a region having an intrinsic surface brightness equal to the standard Freeman value (lower right).

Observations of the youngest bars are difficult for several reasons. Figure 1 plots various observables as a function of redshift, using the WMAP cosmology (Spergel et al. 2003) and equations in Carroll, Press, & Turner (1992). Beyond \( z \sim 1 \), galaxies are only a few Gy old (top left) and a normal size bar has only rotated around only a few times. Thus the bar will be dynamically young and likely to appear different, perhaps more irregular or round. Also, the bar age is likely to be younger than the gas consumption time, which is typically \( \sim 10 \) orbit times (e.g., Kennicutt 1998), so the bars will still be gas-rich,
like some late-type bars today. This makes them irregular also because of dust obscuration and star formation.

Second (Fig. 1 upper right), between \( z \sim 0.6 \) and 4.6, objects smaller than 2 kpc in physical size, such as a bar thickness, will be smaller than 10 pixels on the HST ACS camera. This makes it difficult to resolve internal structure. Bars were not easily seen in the Hubble Deep Fields North and South (e.g., Abraham et al. 1999) because of the factor of 2 lower angular resolution of the WFPC2 camera. Only the largest bars could be seen in the HDF images (Sheth et al. 2003).

Third (lower left), beyond \( z \sim 3 \) the redshift range corresponding to the duration of bar formation exceeds \( \Delta z = 1 \), which means that the bar formation process gets stretched out over a wide range of \( z \). This is good in the sense that different stages in bar formation may be seen distinctly, but it is bad in the sense that bars beyond \( z \sim 3 \) will be incompletely formed and perhaps unrecognizable.

Fourth (lower right), beyond \( z \sim 4 \) disks with the “standard” rest-B band surface brightness of today’s Freeman-disk, 21.6 mag arcsec\(^{-2}\), are almost too faint to see. The \( 2 - \sigma \) noise limiting surface brightness of the Hubble Ultra Deep Field is \( \sim 26 \) mag arcsec\(^{-2}\) at I band, which is the deepest passband (Elmegreen et al. 2005a). At \( z = 4 \), a Freeman disk will have a central surface brightness of \( \sim 28 \) mag arcsec\(^{-2}\), which requires averaging over areas at least as large as \( \sim 40 \) square pixels to observe at the \( 2 - \sigma \) limit. Thus only large bright regions can be seen. Fortunately the intrinsic surface brightnesses of disks are higher at high redshift because of enhanced star formation, unless the extinction is also high. Whether this star formation is enough to reveal bars at this early epoch is unknown. Surface brightness limitations have already diminished the number of spiral galaxies that can be seen in the UDF (Elmegreen et al. 2005a).

The relatively late formation of disk galaxies compared to spheroids aids somewhat in the study of bar formation because it means that bars in disks form late too, when they can be more easily observed. Nevertheless, there are still considerable problems recognizing and observing young bars. The apparent loss of bars beyond \( z \sim 1 \) could be partly from these selection effects affects.

**The Morphology of Bars out to \( z \sim 1 \)**

Most bars look different at \( z = 1 \) than they do today. High-z bars are typically blue and often clumpy, like giant star-forming regions (Elmegreen, Elmegreen, & Hirst 2004). Sometimes they are off-center. Perhaps this irregularity is not surprising since young disks should still be gas-rich. However, the observation implies something new about bar formation: that it could occur
in gas-rich or pure-gas disks with gas dissipation playing an important role. The bar formation models and simulations existing today are all in pure stellar or dominantly stellar systems, where orbital motions and resonances are important. In a gas rich disk, bar formation is more like a dissipative instability. Recent simulations of bar formation in a pure-gas disk are in Kaufmann et al. (2004).

3. Clumpy Structure in High-z Galaxies

Most galaxies in the Hubble Deep fields and in the Ultra Deep Field are very clumpy. Even elliptical galaxies are clumpy in their cores (Elmegreen, Elmegreen, & Ferguson 2005). A compendium of clumpy structures is shown in Figure 2.

![Figure 2](UDF_Spirals_v2.76e3.jpg
UDF Ellipticals (30/100 had clumps)
UDF Chains

Figure 2. Mosaic of galaxy types from the HST UDF showing extremely clumpy structure. In the lower left, elliptical galaxies are shown with contours to illustrate the overall extents and with unsharp masks at the same scale to highlight the clumps.

The clumps in galaxies in the UDF contain up to $10^9$ M$_\odot$ and are typically bluer than the rest of the disk or elliptical galaxy. Thus they are probably young and still forming stars. They are distinct from spiral galaxy bulges, which are redder and always centrally placed.

An examination of the colors and magnitudes of clumps in 10 highly clumpy galaxies, called “clump clusters,” suggests their ages are several $\times 10^8$ years
This is $\sim 10$ times longer than the dynamical times of the clumps, meaning they are gravitationally bound like star clusters, but it is not so young that they may be interpreted as currently star-bursting. Moreover, the clumps have internal densities that are only a factor of $\sim 3 - 10$ above the local tidal densities in their disks, which means they should disperse relatively soon because of tidal forces. This is probably the process of disk formation; i.e., through the dissolution of giant clumps (see also Elmegreen, et al. 2005b).

The origin of the clumps is unknown at the present time. They could be formed in the disks of spirals and clump cluster galaxies or in the gaseous components of elliptical galaxies as a result of gravitational instabilities (Noguchi 1999; Immeli et al. 2004a,b). They could also come in as dwarf-like galaxies from the surrounding field. Similar but isolated clumps are actually seen in these fields (Elmegreen & Elmegreen 2005; Elmegreen, et al. 2005a).

4. Summary of Evolutionary Effects over a Hubble Time

Evolutionary effects may be divided into two types, non-secular, which result from one-time events, and secular, which result from a progressive slow change. Non-secular events include interactions, major mergers, and gas stripping during motion through a galaxy cluster.

Strong interactions form bars (Noguchi 1988; Gerin, Combes, & Athanassoula 1990; Sundin & Sundelius 1991; Berentzen et al. 2004). Even binary companions promote bar formation and may shift the galaxy to an earlier Hubble type because of torqued inflow (Elmegreen, Elmegreen, & Bellin 1990). Bars are also more common in perturbed galaxies (Varela et al. 2004). Major mergers form ellipticals (Toomre & Toomre 1972; Barnes & Hernquist 1992; Schweizer 1998), and in the process, they form at least the youngest halo globular clusters (Ashman & Zepf 1992), and may produce counter-rotating cores (Kannappan & Fabricant 2001).

Minor mergers are non-secular events although they may occur more or less continuously. They thicken spiral disks (Walker et al. 1996; Schwarzkopf & Dettmar 2000ab; Bertschik & Burkert 2002; Gilmore, Wyse, & Norris 2002) and may also lead to counter-rotating cores. Interactions may form dwarf galaxies in tidal tails (Zwicky 1959; Barnes & Hernquist 1992; Elmegreen, Kaufman, & Thomasson 1993; Duc, Bournaud, & Masset 2004).

Cluster ram pressure strips gas (Gunn & Gott 1972; Warmels 1988; Hoffman et al. 1988; Cayatte 1990; Crowl et al. 2005) and may promote the formation of S0 types (Larson, Tinsley, & Caldwell 1980).

Strong interactions also form ring galaxies (Theys & Spiegel 1976; Lynds & Toomre 1976), polar ring galaxies (e.g., Cox & Sparke 2004), disk warps, tidal tails, and so on (Toomre & Toomre 1972).
Secular interactions include accretion in the form of residual hierarchical build-up from outside the galaxy, continuous accretion of dwarfs (e.g., Lewis et al. 2004), galaxy harassment (e.g., Moore et al. 1996), accretion of gas (e.g., Bournaud et al. 2005), globular cluster accretion from dwarfs (e.g., Bellazzini, Ibata, & Ferraro 2004), halo streams (e.g., Ferguson et al. 2005), and so on.

Secular changes are also driven by internal processes, such as bar and spiral torques, which lead to inner disk accretion and outer disk spreading (see review in Pfenniger 2000). Gas accretion at resonances makes star-forming rings (see review in Buta & Combes 1996). Scattering and vertical resonances thicken disks. Bars dissolve into lenses and (maybe) bulges, as discussed above. And of course, gas converts into stars, while gas viscosity redistributes the disk gas.

Secular changes among galaxies with different average densities cause early Hubble types to age more quickly than late Hubble types. Most evolutionary processes are faster at higher density. As time goes by, the transition between early and late types moves, converting little-evolved galaxies, which still have a lot of gas and star formation, to highly evolved galaxies, which are inactive and fading. As galaxies progress from late to early types, they become more centrally concentrated, have less gas, less star formation, hotter disks, redder populations, and more metals. Galaxy mass and size increase over time by hierarchical buildup at $z > 1$, and they probably still increase over time today for late-type spirals as a result of continued accretion and coalescence. Still, the average mass and size of a galaxy that is actively forming stars tends to decrease with time (“downsizing”). This is because the most massive galaxies tend also to be the densest, and they completed their star formation first. Also with time, galaxies become more and more isolated, which means that flocculent spiral types and perhaps low surface brightness disks appear relatively late.

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