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Double-barred galaxies

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Abstract. I present a brief review of what is known about double-barred galaxies, where a small ('inner') bar is nested inside a larger ('outer') bar; the review is focused primarily on their demographics and photometric properties. Roughly 20% of S0–Sb galaxies are double-barred; they may be rarer in later Hubble types. Inner bars are typically ~500 pc in radius (~12% the size of outer bars), but sizes range from ~100 pc to >1 kpc. The structure of at least some inner bars appears very similar to that of outer bars (and single large-scale bars). Direct and indirect evidence all support the hypothesis that inner bars rotate independently of outer bars, although actual pattern speeds for inner bars are poorly constrained. Finally, I note that inner bars do not appear to promote nuclear activity.

Key words. galaxies: active – galaxies: elliptical and lenticular, cD – galaxies: kinematics and dynamics – galaxies: spiral – galaxies: photometry – galaxies: structure

1. Introduction

Evidence for double-barred galaxies – galaxies where a smaller, *secondary* bar is nested inside a larger, *primary* bar – dates back to the mid-1970s, when de Vaucouleurs (1975) pointed out three examples (NGC 1291, NGC 1326, and NGC 1543). These and a handful of other candidates identified in the 1980s (e.g., Kormendy 1982) remained isolated observational curiosities for some years.

Theoretical interest was sparked by Shlosman et al. (1989), who suggested that a system of nested bars could be an especially effective way to transfer gas from galactic (kpc) scales down to near-nuclear (sub-100 pc) scales and thereby feed active nuclei. They also sketched a possible formation scenario, in which the gas inflow driven by a large-scale bar gave rise to a central concentration which became dynamically decoupled and unstable, leading in turn to the formation of an independently rotating inner bar.

The early 1990s saw the first attempts to define samples of double bars and to investigate some of their properties, particularly in work by Buta & Crocker (1993) and Friedli & Martinet (1993); this probably marks the point at which double bars became recognized as a distinct category of galaxy. This led in turn to imaging surveys specifically aimed at identifying and characterizing double-barred galaxies, starting with Wozniak et al. (1995) and Friedli et al. (1996), and then with larger samples by Jungwiert et al. (1997), Erwin & Sparke (2002), and Laine et al. (2002). Kinematic studies of double-barred systems are also becoming more common (e.g., Emsellem et al.

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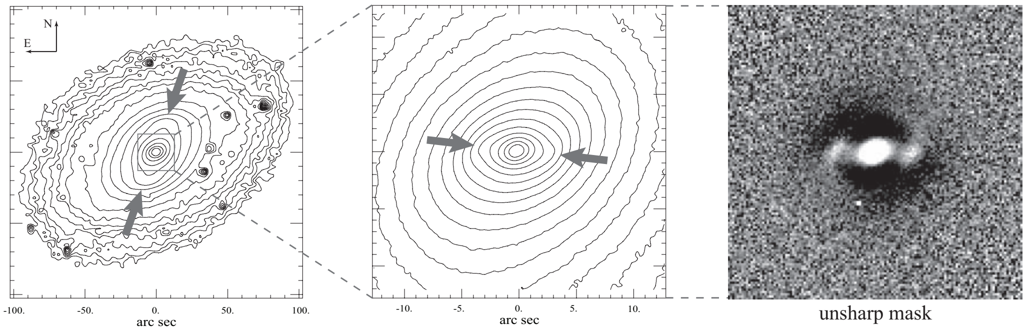

Fig. 1. NGC 2950, an example of a double-barred galaxy. Left and middle panels show *R*-band isophotes, with the outer bar (left panel) and inner bar (middle panel) indicated by arrows. Right panel: unsharp mask of the same image, highlighting the ends of the inner bar. Although the two bars are (almost) perpendicular in this galaxy, inner and outer bars are found at all possible relative orientations (see Fig. 6).

2001; Schinnerer et al. 2001; Moiseev et al. 2004, see Moiseev, this volume).

The same period saw the first detailed attempts to characterize and model double-barred galaxies – and their formation – theoretically (Pfenniger & Norman 1990; Friedli & Martinet 1993; Combes 1994). More recent work has focused on the question of whether and under what circumstances self-consistent orbital structures supporting two bars can exist (e.g., Maciejewski & Sparke 1997, 2000; El-Zant & Shlosman 2003; Maciejewski & Athanassoula 2008), and on hydrodynamical and N-body modeling of double-bar formation (e.g., Rautiainen & Salo 1999; Englmaier & Shlosman 2004; Debattista & Shen 2007). (See Maciejewski, this volume and Shen & Debattista, this volume for more details.)

In this review, I will focus on the current observational status of double-barred galaxies, with a particular emphasis on what know about them as a population, and what we can tell about the *inner* bars, both structurally and dynamically. I will also consider the question, first raised by Shlosman et al. (1989), of whether double-barred galaxies can promote nuclear activity.

2. Demographics

In this section, I consider what we can tell about the general population of double-barred galaxies and the bars within them: how common they are, what type of galaxies they are, how large (or small) the bars are, etc. This is based primarily on two datasets. The first is an expanded version of the Erwin & Sparke (2003) sample, which now encompasses barred and unbarred galaxies of Hubble types S0–Sb with redshifts < 2000 kms^{-1} and major-axis diameters $> 2.0'$. The other source is an updated version of the database published in Erwin (2004), which attempts to keep track of all well-defined double-barred galaxies in the literature. The latter dataset now includes 61 galaxies; it has the disadvantage of being drawn mostly from an extremely heterogeneous set of observations, and so is subject to a variety of poorly known selection effects.

In Fig. 2 I show the double-bar fraction as a function of Hubble types, based on the aforementioned local sample (Erwin & Sparke 2003; Erwin et al., in prep.). The double-bar frequency is roughly constant at ~30% of barred galaxies, or ~20% of all galaxies, from S0 down through Sab. There is *some* evidence that the fraction is smaller for Sb galaxies.

Are double bars basically a phenomenon of early-type disks? Unfortunately, we lack systematic surveys of later Hubble types; such surveys would need to be in the near-IR to avoid dust extinction, and would need to have high spatial resolutions, since bars in late-type spirals are systematically smaller than early-type bars (Erwin 2005). The current version of the Erwin (2004) catalog does have sev-

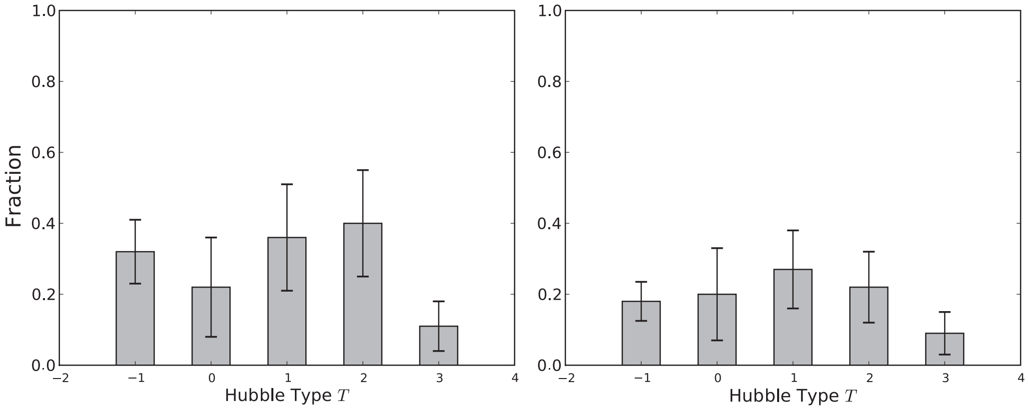

Fig. 2. Fraction of barred galaxies (left panel) and all galaxies (right panel) which are double-barred, as a function of Hubble type.

eral double-barred Sbc galaxies, but only *one* confirmed double bar with a late Hubble type (NGC 6946, Sc). While this suggests a lower frequency of double bars in late Hubble types, the imaging surveys which provided most of the double-bar detections to date have historically been heavily biased towards Hubble types earlier than Sc, in part because many of these surveys have been aimed at Seyfert galaxies (and matched non-active galaxies), which are primarily early types.

Fig. 3 shows the absolute and relative sizes of *inner* bars from the current catalog of double-barred galaxies. In absolute size, inner bars span about an order of magnitude, with semi-major axes ranging from ~100 pc all the way up to 1.2 kpc; the median size is ~500 pc (relative to R_{25}, the range is 0.01–0.10, with a median of 0.04). The sizes of inner bars, while almost always smaller than outer or single bars in early-type disks, thus actually overlap with the low end of single-bar sizes in *late*-type spirals (Sc and later; see Erwin 2005).

Inner bar size *does* correlate with outer bar size, though not very strongly (Spearman r = 0.57). The median size ratio is ≈ 0.12; the true median may be slightly smaller, since resolution limits mean that small inner bars are less likely to be identified. There is a fairly clear upper limit of ~0.25, which is at least roughly consistent with theoretical arguments that inner bars cannot be too large without disrupting the orbits which support the *outer* bars.

The local S0–Sb sample mentioned above contains 55 single-barred and 21 double-barred galaxies. Are there systematic differences between the two types, which might help use understand why some galaxies have two bars and other have just one? The answer, for the most part, is no: single- and double-barred galaxies appear to be very similar in their global properties (e.g., absolute magnitude, rotation velocity, central velocity dispersion). The only genuinely significant difference appears to be in the sizes of the large-scale bars: the outer bars of double-barred systems are *longer* (typically ~4 kpc in radius) than the bars of single-barred galaxies (typically ~2.5 kpc).

3. The structure of inner bars

Are inner bars simply miniature versions of large-scale bars, or are they a different type of beast altogether? Theoretical arguments and models suggest that inner bars should rotate relatively slowly, with corotation well outside the end of the bar. Thus, they should differ dynamically from typical large-scale bars in early-type disks (where most double bars are found); these large-scale bars tend to be 'fast' in the relative sense, with corotation at or just beyond the end of the bar. So we might wonder if this hypothesized difference in relative

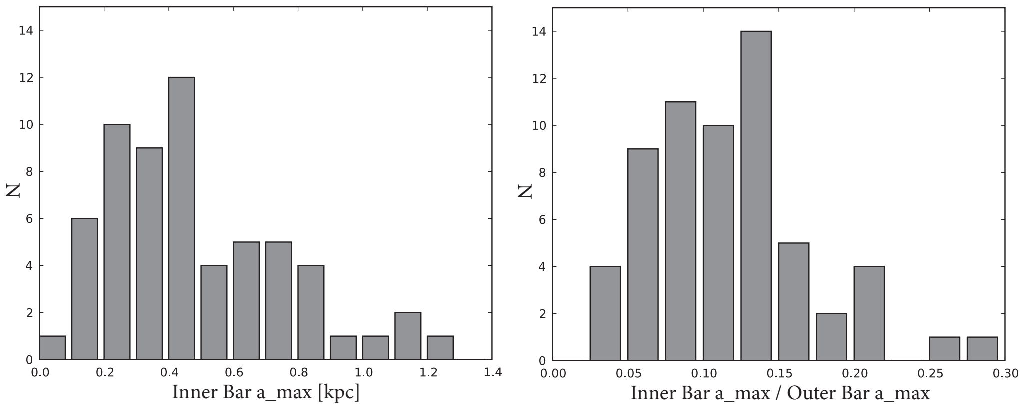

Fig. 3. Absolute semi-major axis sizes of inner bars (left panel) and relative semi-major axis sizes (right panel, inner bar size as a fraction of outer bar size). All sizes are deprojected.

speeds is reflected in a difference in structure. In addition, as more realistic models of inner bars emerge (e.g., from N-body simulations), there is some hope that we can test these models by comparing their stellar structure with that of real inner bars.

What is curious, then, about the gross photometric structure of inner bars is that it is often rather similar to that of large-scale bars. A crude comparison can be had via the use of unsharp masks (e.g., Erwin & Sparke 2003; Erwin 2004), which suggests that inner bars have distinct 'ends' (i.e., regions where the surface brightness steepens abruptly), and that some inner bars may have rather high axis ratios.

This can be seem more directly by comparing surface-brightness profiles along the bar major axis. Fig. 4 does this for NGC 2950, where the profile of the inner bar appears to be a scaled-down replica of the outer bar: a relatively shallow profile (extending out of the bulge-dominated region) which breaks at a certain radius and then falls off more steeply, gradually blending into the disk outside. These are classical examples of what Elmegreen & Elmegreen (1985) first identified (for large-scale bars!) as 'flat' bar profiles, which are common in early-type disks but rare in late types, where the bar profile is usually a steep exponential.

3.1. Dissections

Just as Padova (the site of this workshop) was where Galileo undertook much of his pioneering research — which helped break the dogma of Classical (Aristotelian and Ptolemaic) physics — it was also the place where the anatomist Andreas Vesalius helped break the dogma of Classical medicine, by performing a ground-breaking series of dissections, culminating in *De humani corporis fabrica* (Vesalius 1543). Taking this as inspiration, then, I present selections from an ongoing project aimed at 'dissecting' several double-barred galaxies.

The main approach is modeled on that of Ohta et al. (1990), who extracted large-scale bars from several early-type spirals by modeling and subtracting the disk and bulge, with the residue being the bar proper. An elaboration of this process applied to NGC 1543 and NGC 2859 (Erwin, in prep.) produces two isolated inner bars (Fig. 5). That of NGC 1543 is quite narrow (axis ratio ≈4:1), and strikingly similar to at least some large-scale bars (e.g., several of those in Ohta et al. 1990); evidence for a very faint stellar nuclear ring can be seen. In NGC 2859, the bar is less elongated and is embedded in a region of twisted isophotes outside, possible forming a lens. As the profiles make clear, both bars are indeed 'flat' in the sense of Elmegreen & Elmegreen (1985). Although one should not generalize too

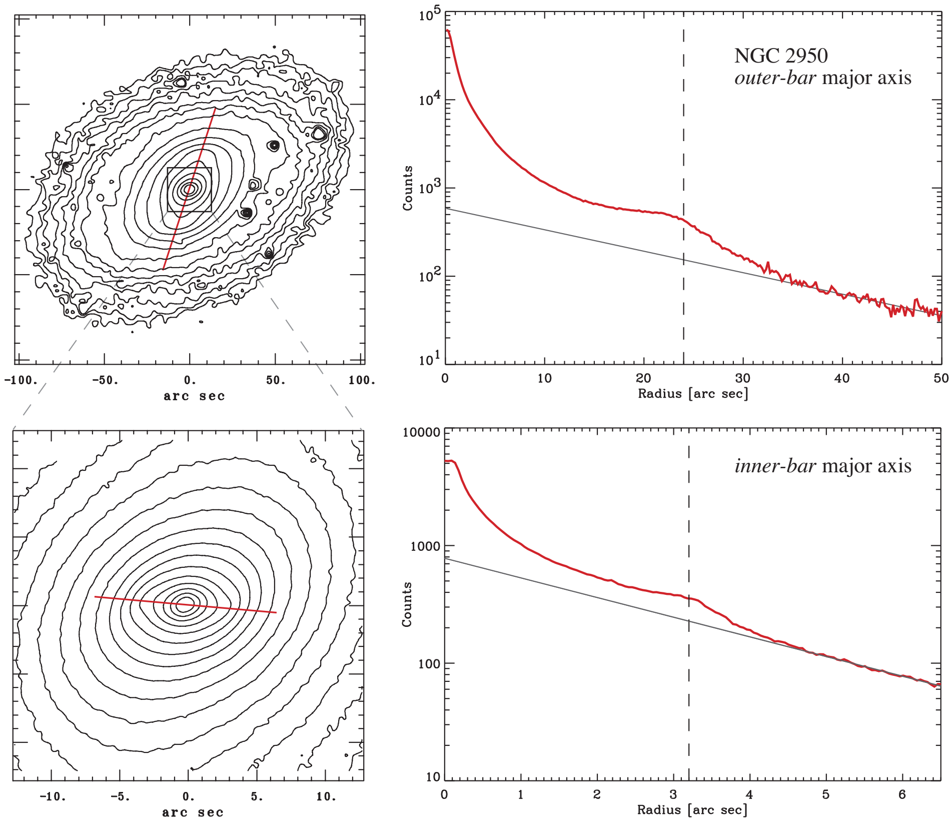

Fig. 4. Profiles along major axes of outer and inner bars of NGC 2950. Because the bars are (almost) perpendicular, it is easier to trace their profiles independently. Both bars have remarkably similar profiles — excellent examples of so-called 'flat' profiles first identified for large-scale bars by Elmegreen & Elmegreen (1985). Vertical dashed lines mark the radius of maximum isophotal ellipticity for each bar.

freely from a sample of two, it is curious that at least some inner bars do resemble scaled-down outer (or single) bars quite closely, given that the theoretical expectation is that they should differ dynamically.

As a bonus, we can use the extracted bars as direct estimates of how massive these inner bars are — i.e., what fraction of the total stellar light (and thus stellar mass) they make up. This turns out to be ∼4% in the case of NGC 1543 and ∼10% for NGC 2859; put another way, the inner bar is ∼7% of the outer bar's mass in NGC 1543, but it is ∼25% of the outer bar's mass in NGC 2859. These latter values can potentially test models of double-barred galaxies, since theoretical arguments suggest that an inner bar must be massive enough to to produce orbits which can support it, but cannot be *too* massive or it will disrupt the orbits making up the *outer* bar (e.g., Maciejewski & Sparke 2000; El-Zant & Shlosman 2003; Maciejewski & Athanassoula 2008).

4. Pattern speeds

The earliest theoretical arguments (Shlosman et al. 1989; Pfenniger & Norman 1990) and models (e.g., Friedli & Martinet 1993) suggested that inner bars would be decoupled from — and in fact faster-rotating than — outer bars. Both orbital models (see Maciejewski, this volume) and N-body simulations (see Shen

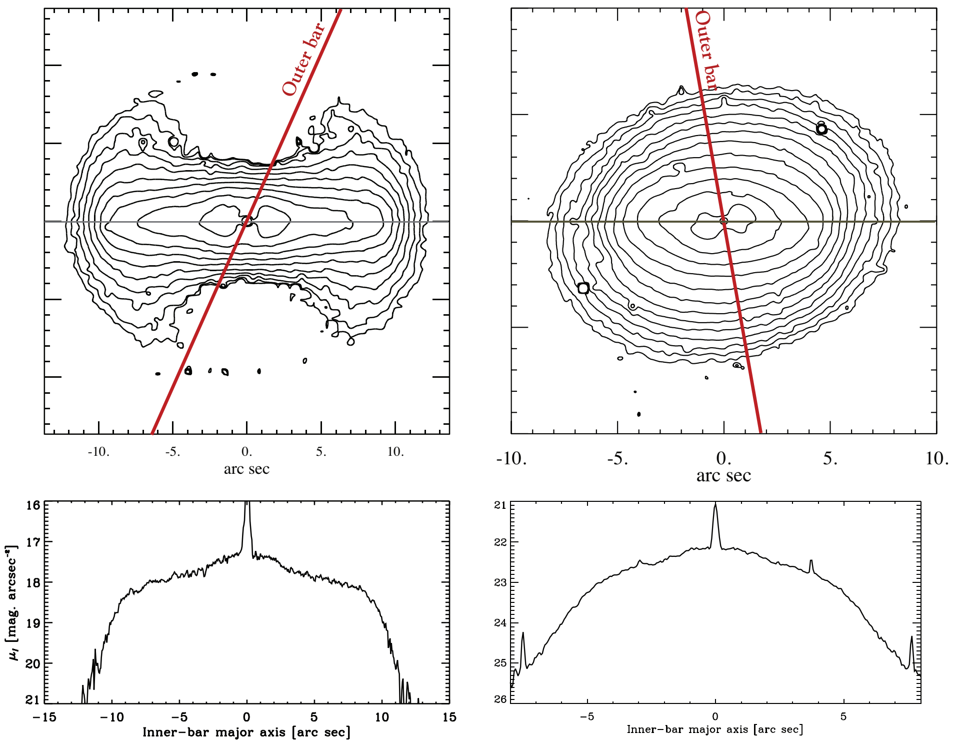

Fig. 5. Isolated inner bars of NGC 1543 (left panels, WFPC2 F814W) and NGC 2859 (right panels, ACS/WFC F814W). All other galaxy components except stellar nuclei have been subtracted. Upper panels show logarithmically scaled isophotes; red lines indicate outer-bar position angle for each galaxy. Lower panels show cuts along the major axis of each inner bar; both profiles are 'flat' in the sense of Elmegreen & Elmegreen (1985).

& Debattista, this volume) support this from a theoretical point of view.

From an observational point of view, there is good *indirect* evidence for decoupled inner bars. The first observational studies of double bars as a class (Buta & Crocker 1993; Friedli & Martinet 1993) pointed out that inner and outer bars seemed to be randomly oriented with respect to each other — in particular, inner bars were not found preferentially either perpendicular or parallel to outer bars, which the simplest models of corotating double bars would require. There have been some more sophisticated models of corotating inner bars (Shaw et al. 1993; Heller & Shlosman 1996), but even these predict preferred orientations (the inner bar must lead the outer bar).

Fig. 6 shows an updated plot of relative position angles between inner and outer bars. As was seen earlier with smaller numbers, inner bars do not preferentially lead or trail outer bars, and the relative angles between them appear to be randomly distributed. This is consistent with the general argument that inner bars rotate independently. Although some recent models (Maciejewski & Sparke 2000; Debattista & Shen 2007) suggest that the relative patten speeds of inner bars should vary, so that inner bars spend more time perpendicular to outer bars, this cannot be a very strong effect, as inner bars are not preferentially seen in near-perpendicular orientations.

There is limited evidence for decoupled pattern speeds from hydrodynamical modeling

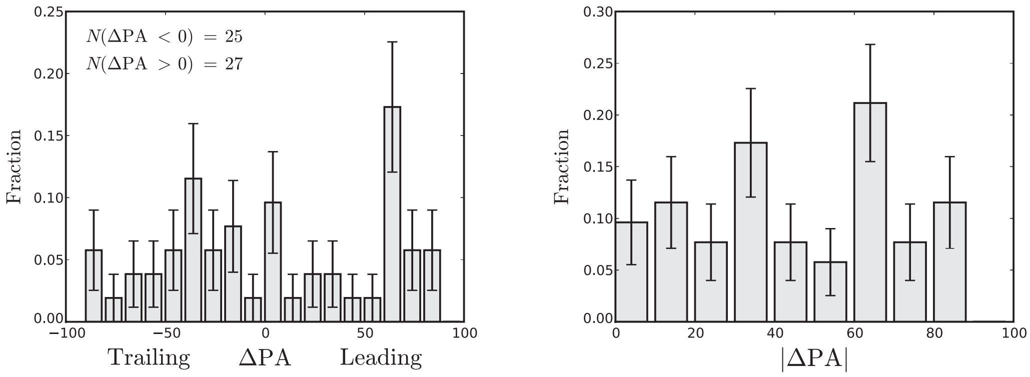

Fig. 6. Deprojected relative positions angles between the bars of double-barred galaxies. Left panel: position angles in a leading/trailing sense (positive = inner bar leads outer bar), for 52 galaxies where sense of rotation can be determined. Right panel: absolute position angle between inner and outer bars, for 61 galaxies.

of individual galaxies, where one attempts to match the gas flow in potentials with one or more rotating bars to the observed gas kinematics of a particular galaxy. For example, Ann (2001) found a good match for gas morphology when the inner bar of NGC 4314 was rotating faster than the outer bar; however, no kinematic comparison was made. More promising are the cases of NGC 1068 and NGC 4736, though complete, self-consistent modeling for both galaxies is lacking (see the summary in Erwin 2004).

To date, there has been only one published attempt to *directly* measure pattern speeds in a double-barred galaxy, by Corsini et al. (2003). They applied the Tremaine-Weinberg (TW) method to NGC 2950 (Fig. 1), and were able to show that the two bars did *not* have the same pattern speed. While a pattern speed for the outer bar was measured, determining a specific speed for the inner bar proved more difficult. The peculiar TW results for the latter have prompted arguments that the inner bar might actually be *counter*-rotating (Maciejewski 2006; see also Shen & Debattista 2009). While this is an intriguing possibility, the existing models for forming counter-rotating inner bars (Friedli 1996; Davies & Hunter 1997) require the majority of stars in the inner galaxy to counter-rotate, to the point of producing clear reversals in the stellar rotation curve — something not seen in NGC 2950 (compare Figs. 6 and 7 of Friedli 1996 with Fig. 4 of Corsini et al. 2003). One possible test of the counter-rotating inner-bar hypothesis would be to compare hydrodynamical simulations of prograde and retrograde inner-bar systems with observed gas flows — or even with observed dust lanes — since the resulting gas flows and shocks would presumably be rather different.

5. Double bars and active galactic nuclei?

Because the original theoretical motivation for nested-bar systems was to provide a mechanism for fuelling active galactic nuclei (AGN, Shlosman et al. 1989), the question of whether double bars actually enhance nuclear activity has been a relatively popular one.

Most recent observational studies actually suggest that inner bars play at best only a minor role in promoting nuclear activity. Martini & Pogge (1999) and Martini et al. (2001) noted that nuclear bars were not common in a small sample of local Seyfert galaxies; Erwin & Sparke (2002) compared single- and double-barred galaxies and found no significant difference in nuclear activity.

The study of Laine et al. (2002), which used larger samples of Seyfert and non-Seyfert galaxies, seems at first glance to indicate a correlation between double bars and AGN: the fraction of galaxies in their Seyfert sample with two bars is 21%, versus only 13% for the non-Seyfert galaxies. However, this is primarily a function of the higher overall bar fraction in their Seyfert galaxies. If we restrict ourselves to *barred* galaxies, then the fraction of (barred) Seyferts with inner bars is not significantly higher than that for the control galaxies (29% vs. 25%).

A comparison of bar frequencies for different bar sizes in the Laine et al. study yields a curious result: galaxies hosting very small bars (radii < 1 kpc), whether inner or not, are roughly as common in the Seyfert and non-Seyfert samples (Kolmogorov-Smirnov P = 0.67). But galaxies with very large bars (radii > 3 kpc) are far more likely to be Seyferts (48% of Sy galaxies, 21% of control galaxies; KS P = 0.0051). So *if* bars fuel nuclei, it may only be *large* bars that matter.

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