Barred Galaxies
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A Sober Look at Bars in Galaxies

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Abstract. I review some of the more notable observational aspects of bars in galaxies. Key issues include the overall occurrence of bars, secular evolution of bars and bulges, the differences in bar properties with Hubble type, the role of bars in star formation and nuclear activity, and the evidence for a bar at the center of the Milky Way. These lead to a "wish list" of future observations.

1. Introduction

This meeting has shown quite clearly that our understanding of the role of bar structures in galaxy dynamics is complex, but in some important aspects now becoming understood. Bars and oval distortions are common enough to make these relevant not just to strongly barred galaxies, but to our understanding of the dynamics of disk galaxies in general. This review highlights some of the more striking themes to emerge from the observational results presented here.

2. Bars in Early and Late Hubble Types

Again and again, several workers have stressed the distinctive behavior of bars in early and late Hubble types. As manifested in light profiles, star formation, gas distribution, and links to external perturbations, bars in each half of the spiral domain seem so different that they could hardly arise from the same phenomena. Some of the differences we have been shown are summarized in Figure 1, with citations of workers who presented the evidence here. The break point between about SBbc and SBc is consistent among the various distinctions. In early-type spirals, the bars are long, have flat light profiles, are associated with well-developed spiral patterns, and drive star formation predominantly at the bar ends. Later-type bars are short, exponential in profile, and exhibit star formation all along the bar. The sample galaxies shown in Figure 2 exemplify the overall morphological changes.

There is some indication from dynamical models that the difference may not be so much in the bars themselves as in their environments - that the different mass distributions and consequent rotation curves may be sufficient to account for these differences. If so, this is a sobering example of similar physical structures showing rather different guises under a change in boundary conditions.

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PROPERTY	EARLY	LATE	SOURCE
Hubble types	Sbc and earlier	Sc and later	Elmegreens
Intensity profile	Flat	Exponential	
Length	$>0.5R_{25}$	$<0.3R_{25}$	
Bar ends	Corotation	inside 4:1	
Interaction link?	Yes	No	
Arms	Grand/multiple	Any kind	
Arm/interarm	Falling	Flat	
Dust lanes	Offset	Centered	
Azim. profile	Non–sinusoidal	Sinusoidal	Ohta
H II regions in bar	Few	Many	Phillips
Rotation curve	Flat	Rising	
H II ring	Yes	No	
Star formation	Bar ends	Gap at ends	
H II LF	$\alpha>2$ (small)	$\alpha<2$ (large)	
FIR enhancement	Yes (complex)	No	Hawarden
CO structure	Twin peaks/core	Bars	Turner/Kenney
Hα enhanced?	Yes	No	Ho

Figure 1. Comparison of bars in early and late Hubble types (broken at SBbc). Sources indicate discussion in these proceedings.

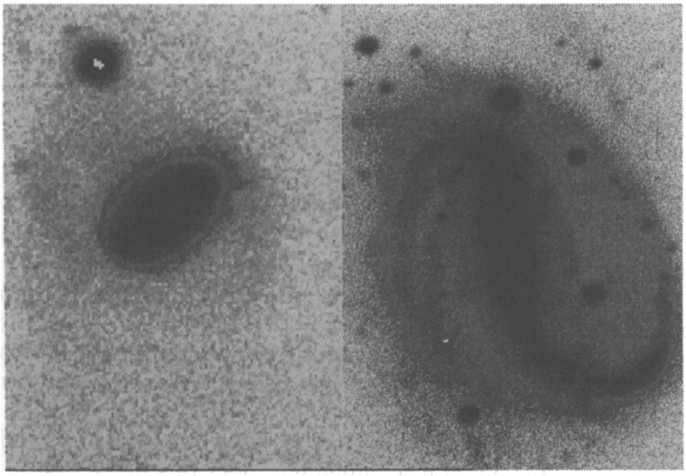

Figure 2. Bars in early and late Hubble types. These are V-band images of Mkn 612 (SBa) and NGC 7479 (SBc), illustrating the differences in star-forming properties - which appear as texture in these images - and intensity distributions of such bars. Both images were obtained with the Lowell Observatory 1.1-m telescope, and are shown with a logarithmic intensity mapping to compress the dynamic range.

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3. Occurrence of Bars

Compilations which recognize transition-type spirals, such as the *Third Reference Catalog* (RC3; de Vaucouleurs et al. 1991) consistently record some evidence of bars in about 2/3 of all spirals, either as SB or SAB families. Additional bars certainly exist, not reflected in the morphological classifications because they are small, nuclear bars, because they are substantially hidden by dust, or because they are predominantly gaseous rather than stellar.

The spectacular finding of a stellar bar in NGC 1068 which is almost invisible at optical wavelengths, through a combination of obscuration by dust and masking by a more widespread population of young stars (Thronson et al. 1989) prompted serious interest in the frequency of such hidden bars, especially in galaxies whose nuclear activity or star formation suggested significant gas inflow. Such hidden bars certainly exist; we saw several new ones at this conference, but perhaps more interesting is the lack of such bars among some of the galaxies which show the strongest nuclear fireworks. If bars or nested bars are generally important in nuclear activity and starburst nuclei, we must seek yet a smaller scale size than has yet been systematically probed (and which can thus transport gas over only a fraction of the radial range needed to fuel the central regions).

Gaseous bars are especially intriguing because they can be rather transient during strong interactions (Barnes & Hernquist 1991), and because they can alter the local potential without an accompanying change in the overall distribution of starlight (since the bulge is often much hotter than the gas). The molecular observations described by Turner and Kenney have shown strong gaseous bars in galaxies with inconspicuous stellar bars, showing that there is the prospect of finding barlike features in the gas for disks of all sorts.

4. Secular Evolution of Bars and Hubble Types

Numerical simulations have long indicated that barred disks can undergo evaporation of the bar, forming a hot axisymmetric structure that we are tempted to identify with a bulge. This is an area where detailed dynamical measurements of bars and bulges are needed - can we tell which bulges formed from the dissolution of bars? If many formed this way, bulges may be comparative latecomers to the cosmic stage, slowly forming over much of a Hubble time. Since the formation of a bulge would change the morphological type in the direction of early classes, the occurrence of SAc and SB0/a galaxies gives some limits to how much of this kind of evolution has taken place.

Given that bars can be transient in at least one direction, and that most spirals now have some kind of discernible bar, does this mean that essentially all spirals are barred at some time? If so, we have actually been talking about all spirals here rather than some subclass of barred spirals. This issue may hinge on whether other mechanisms for bulge formation (heating the central orbits) compete with bar evaporation, and on whether bars can reform in galaxies where an earlier bar has dissolved. To date, doing so seems to require rather special conditions to overcome the high three-dimensional velocity dispersion in the bulge, for example by rapid infall of a large mass of cold gas.

How can we identify formerly barred spirals? Kinematic and chemical clues may remain long after the morphology of the bar has faded. Thus, though Buta et al. (1995) find that NGC 7217 is perhaps the most nearly axisymmetric spiral galaxy in the sky, Zaritsky & Lo (1986) found an oval or barlike structure at the nucleus in the I band, and Zasov at this meeting showed kinematic evidence for barlike motions in a small region about the nucleus. Athanassoula showed that the prominent rings in NGC 7217 fit the locations of the OLR, ILR, and the 4:1 resonance closely, but such rings require a bar for formation. These data taken together suggest that this may be the best-observed case for an ex-barred galaxy. Such a scheme, in fact, gives a non-interaction explanation for the substantial number of stars on retrograde orbits in the inner disk (Merrifield & Kuijken 1994), since some of the stars scattering outward (mostly on chaotic orbits passing near the Lagrange regions, as discussed here by Contopoulos) will end up on retrograde orbits.

A powerful tracer of the morphological past of a spiral galaxy may lie in abundance gradients. Several studies suggest that bars are effective radial mixers, wiping out abundance gradients beyond the extent of the bar proper. As shown by Martin & Roy (1994; see also Zaritsky, Kennicutt, & Huchra 1994) barred galaxies show at most quite mild radial abundance gradients compared to nonbarred galaxies of similar class and luminosity. This recognition may help to make some sense out of the disarming range of claims for the extent and slope of abundance gradients in various kinds of spirals - a gradient may be able to establish itself only after a bar dissolves. If this is so, the slope of the abundance gradient in nonbarred spirals may be a chemical clock set running only when an original bar disappeared.

Data already in the *Hubble Space Telescope* (HST) archive are close to allowing a direct inquiry on bar and bulge evolution. Imaging of many fields at high galactic latitudes (largely as part of the Medium-Deep Survey, REF) yields solid morphological types for spirals as faint as V=23, at typical redshifts $z \approx 0.5$ (Figure 3). Carefully controlled and modelled use of these images, and the redshifts now becoming available, could show whether the incidence of bars is changing with cosmic epoch, independent of any of the dynamical arguments which suggest the possibility.

5. Tracing Resonances

Some of the deepest interest in bars and related phenomena arises from the hope that they give of tracing the locations of resonances in disks, which are in turn strongly diagnostic of the mass distribution and rotation curve. Bars, ring patterns, and the extent of various kinds of spiral structure have been used as resonance indicators, from dynamical studies which suggest that the relationships among various features (position angle, gas and stars in the arms, strength of arms) should change at resonant locations. Much more work needs to be done here - how well do bar ends/rings/spiral extent match the locations of resonances in galaxies where there exist detailed velocity fields? Do the relative locations of dust lanes and spiral ridge lines change on crossing resonant points sometimes or always? In barred systems, this may be one of the (somewhat rare) problems which chaos theory sheds immediate light on - as Contopoulos

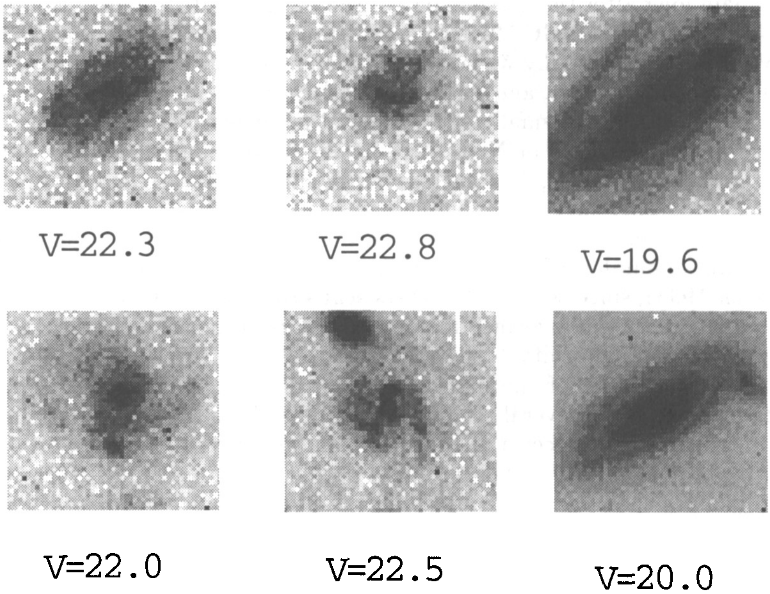

Figure 3. I-band images of a set of faint spiral galaxies (labelled by integrated V magnitude) from a single deep HST WFPC2 exposure (the one used by Driver et al. 1995 for deep morphology and number counts). The image sections are 5 arcseconds square. Each of these can reasonably be classified as to presence and strength of a bar. The typical redshifts probed here are $z = 0.3 - 0.6$, showing that such data are suitable for addressing the history of bars over cosmic time.

noted, much of the evolution of bars should take place via star leakage on chaotic orbits.

The preferential relative orientations of bars and various families of rings shown by Buta is powerful evidence that they trace resonance locations (and that the theory of stellar orbits around bars isn't dramatically incomplete). However, the incidence of rings and bars which do not correlate as well as the majority indicates that there are processes, perhaps historical, which can alter this usual, fairly stable situation.

6. Bars, Gas Inflow, and Star Formation

Connections between bars and star formation seem well established for some kinds of bars, from Hα and far-infrared statistics (as presented by Hawarden and by Ho). The intriguing gas structures shown in the CO maps presented by Turner and by Kenney show that gas-rich bars can be present even when the stellar distribution is at best mildly barred, and that the inner parts of bars

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can produce rings of high gas density around the nucleus, which are closely associated with other tracers of star formation.

However, the basic physical issue - tracing the net flow of gas inward along the bar and the transformation of this gas into stars - has proven difficult to pin down from the data themselves. The orbital speeds of streaming motions along the bar, in both directions, is much greater than the expected net gas flow, and it is not clear that the same phase of the ISM would be observed in both cases. The torque-measurement technique employed by Quillen et al. (1995) marks a considerable advance in this area. They use the K-band starlight distribution and a simple model for the stellar z-distribution to map the potential by a convolution relation with the potential kernel GM/r, and derive the torque and gas flow rate from the angular offset between ridge lines of the potential and gaseous bar.

7. Bars and Active Galactic Nuclei

Since there are strong theoretical grounds to connect bars, or barlike instabilities, to the fueling of gas to the innermost regions of active galaxies, a link between bars and nuclear activity has been discussed repeatedly (as in the "bar-cascade" scheme of Shlosman, Frank, & Begelman 1989). This theme was most notable at this conference by its absence, with only a brief note by Ho as to the absence of any obvious barred/nonbarred distinction among the active nuclei in the Palomar spectroscopic survey. Because this was a survey limited by the apparent magnitude of the host galaxy, luminous and rare AGN are not included. If there is a strong connection between bar distortions and active nuclei, it must be (a) of consequence only for high-luminosity objects, (b) linked to bars on scales too small to show up in the morphological classification, or (c) swallowed up in other effects such as interactions.

8. Bars and Interactions

Interactions have been repeatedly proposed as a way of inducing bars on a variety of spatial scales in galaxies which might not have previously been barred (Noguchi 1988), giving a potential mechanism for driving gas flow to fuel the empirically observed excess of star formation and other fireworks in interacting galaxies. There is some evidence that more galaxies in paired samples of early Hubble type are barred at specified bar strength than in nonpaired samples (Elmegreen, Bellin, & Elmegreen 1990). More complete work is underway, including imaging in near-infrared wavelengths to overcome the obscuring effects of dust and the masking effects of surrounding star formation.

As in most studies of the effects of interactions, the details of sample selection of both the interacting and the comparison samples are crucial. For example, if barred and nonbarred galaxies of similar optical luminosity and morphological stage have different distributions of far-IR luminosity and color, it is easy to produce a bias in favor of barred systems by selecting at particular far-IR wavelengths. The results of such comparisons always need to be very carefully stated, to make clear just what is being held constant in the comparison.

9. The Milky Way Bar

The possibility of a central bar in the Milky Way was discussed as early as 1964 by de Vaucouleurs, based on the noncircular motions shown by gaseous tracers near the galactic center. The kinematics of H I and CO near the galactic center supported this idea (Sinha 1979, Liszt & Burton 1980). The case has become more compelling with the availability of bulge tracers that are not strongly affected by intervening absorption - notably AGB stars (Weinberg 1992), OH/IR stars surveyed by IRAS (reported by Kuijken here) and the COBE measurements of isophotal shapes across the IR spectrum (Weiland et al. 1994), foreshadowed by the 2.4μ balloon-borne mapping performed by Matsumoto et al. (1982) and analyzed in this context by Blitz & Spergel (1991). The asymmetry in the IR bulge isophotes is unmistakable, and well explained as a perspective effect of viewing a bar about 30° from its major axis. The near end of the bar is in the first galactic quadrant.

Kinematic models (Wada et al. 1994) agree that a rotating bar seen almost end-on gives a good fit, this time to the kinematics of bulge stars (as measured by, for example, Blum et al. 1994). However, the windows of low obscuration in which samples are well-selected are located preferentially in one quadrant, so that such features as OH masers may be the best path for tracing the kinematic signature of the bar.

10. The Next Steps

The presentations here have whetted appetites for many further kinds of observations, directly keyed to bars and some carrying more general import for galaxy studies.

The advent of large IR-sensitive arrays makes the time ripe for a new approach to galaxy classification in the near-IR bands, as nearly as possible *ab initio* rather than as a direct mapping from optical classifications. Ron Buta suggests that perhaps 2000 objects spanning the range of observed properties would be needed to form such a classification. This sample size is significant, but not out of the question for current detectors. Are there any takers for the "Buta 2000" challenge? The payoff would include a more complete census of the bar and distortion properties of inner disks, the shape of the stellar potential perturbation in spiral structures, and the obvious advantages in avoiding absorption effects.

Probing the velocity structure in bars and disks is crucial in connecting what we see to a dynamical understanding. The vertical velocity structure is needed if we are to understand the connections among ordinary bulges, "peanut bulges", and bars. Stellar velocity measurements are also needed to cross gaps from gas tracers, which occur in potentially interesting places where the orbital evolution of individual stars may be rapid. The new realization that stellar velocity fields may be locally multivalued has led to recognition of such phenomena as retrograde disk stars (Merrifield & Kuijken 1994, Rubin, Graham, & Kenney 1992). More such observations are undoubtedly on the way and will be important in removing yet one more blinder from our conception of galaxy structure and evolution.

As in studies of galaxy evolution in general, an approach to the history of bar and bulge development can follow dual tracks: direct observations of galaxies at early cosmic times, and detailed observation of local objects in which we can trace ages and kinematics. As demonstrated above, HST images and follow-up redshifts have the potential to show us directly how bars and bulges have evolved, while velocity fields and dynamical models of nearby systems can show us how this has happened in a physically meaningful sense. Detailed study of the stellar populations in bars, including such features as young massive star clusters, can tell us how star formation has proceeded there - smoothly or episodically. The high luminosities of some of the clusters found in nuclear rings by Barth et al. (1995) raise the possibility that globular clusters may still be forming in these environments, and thus that globular-cluster systems can be affected by the history of "barredness" in spirals.

What can we hope to see at the next major bar meeting? One might hope for a coherent sequence of bar and ring development supported by observations at each stage; for a statistical understanding of how vertical (peanut-bulge) structure relates to azimuthal (bar) features; realistic measures of gas inflow and the gas budget for circumnuclear star formation; and a proper synthesis of models and observations to tell whether the dichotomy between bars in early and late Hubble types is more than the natural response of the bar perturbation to different mass distributions.

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