Barred Galaxies
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Barred Galaxies: Scientific Overview

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Abstract. In this scientific overview, I discuss some of the important features of barred galaxies, and attempt to identify some of the outstanding problems.

1. Introduction

Barred galaxies were once regarded as a curiosity, but this is no longer so: it is becoming clear that the bar phenomenon is pervasive, complex, and very important for most areas of galactic structure and evolution. This is an exciting time for our subject. Ideas are changing rapidly, with new insights from dynamical theory and rapidly expanding observational opportunities; endless questions remain. So this is an excellent time for the first major conference to be held on the subject of barred galaxies

In this overview of barred galaxies, I plan to go lightly over many items, and will mostly avoid names and references. The program for this meeting is very comprehensive, and we will hear much more on all of these items from the people who did the work. Towards the end, I will discuss a few topics in a little more detail. There is much that we do not understand in our subject, but nearly all of the experts are here, and we can look forward to an exciting and illuminating week.

For detailed references and discussion, please see the comprehensive reviews by Bosma (1992), Combes (1994), Martinet (1995), and Sellwood & Wilkinson (1993).

2. General Properties of Barred Galaxies

The bar phenomenon is common among the disk galaxies: about one-third show a strong bar structure (SB) and another one-third have a weaker inner bar (SAB). The gravitational potential in these systems, as in other disk galaxies, is dominated by the stars and the dark corona; the gas is a minor contributor. The bars typically contribute between 10 and 30 percent of the total blue luminosity. The resulting bar potential is asymmetric enough to induce non-circular streaming in the gas and the stars. The bars rotate, with a pattern speed that is believed to be close to the angular circular speed in the disk near the bar ends. The pattern speed of the bar is difficult to measure directly, so indirect estimates based on the location of resonances and the formation of shocks in the interstellar gas are often invoked.

The spiral arms in barred spirals appear in most cases to be associated with the bar, but it is not yet clear that the bar drives the spiral structure. There are examples of barred spirals in which the pattern speed of the bar and the pattern speed of the spiral pattern may be different. The kinematics of the gas in barred spirals shows the usual large-scale rotation associated with disk galaxies, but with characteristic deviations from pure circular motion associated with the bar. The gas flows indicate elliptical streamlines in the bar, and there are some examples of galaxies in which the gas and stars are counter-rotating. As in other disk systems, the shapes of the rotation curves require the gravitational contribution of a massive dark corona.

The dust lanes lying along the bars of barred galaxies are a characteristic feature. Typically, they are offset from the major axis of the bar, and are sometimes curved. They are believed to be associated with the gas flow within the bar, as suggested by velocity discontinuities across the dust lanes and the concentration to the dust lanes of the CO and nonthermal radio continuum emission in a few examples.

2.1. The Rings

Barred spirals frequently show ring structures. These rings belong to three ring families, and are very useful dynamical diagnostics. Much of what we know about rings in barred galaxies comes from the work of Buta and associates: see for example Buta & Crocker (1993).

The *outer* rings lie far beyond the ends of the bar, with mean diameters of about 22 kpc. They have a mean axial ratio of about 0.82 and are believed to lie close to the outer Lindblad resonance (OLR). Their orientation may be parallel or perpendicular to the bar, corresponding to the orientation of the ring-like periodic orbits outside and inside the OLR.

The *inner* rings typically lie close to the bar ends, with mean diameters of about 9 kpc. They again have a mean axial ratio of about 0.81 and are mostly oriented parallel to the bar, although some examples of inner ring misalignment are known. They are believed to be associated with the 4:1 ultraharmonic resonance near corotation.

The innermost regions of some barred spirals show *nuclear* rings, with typical diameters of about 1.1 kpc and a range of orientations and shapes. An inner Lindblad resonance (ILR) is believed to be necessary for nuclear ring formation; if two ILRs are present, the ring accumulates near the inner ILR.

The rings are among the better understood features of barred galaxies. They are believed to form through radial gas flows associated with the gravitational torques in these asymmetric systems. The inner and outer rings tend to be bluer than the underlying disk and appear to be driven by the bar, with the same pattern speed as the bar. Some outer rings are gas-rich, and for these it is possible to measure noncircular motions confirming their noncircular shapes. The high surface density of gas associated with nuclear rings may be an important element in understanding the incidence of starbursts and the fuelling of nuclear activity in barred galaxies.

Some normal (SA) spirals show rings, while some barred galaxies do not. This is not yet fully understood.

2.2. The Bars

The shape of bars is typically rectangular. For bar isophotes represented by $(|x|/a)^c + (|y|/a)^c = 1$, the value of c is in the range 2.5 to 5.5. Some bars appear thicker than their disks, while others are probably not. For example, the bar/bulge of our Galaxy has an exponential scale height of about 300 pc, similar to that of the old disk.

The rotation of bars makes their analytical dynamics difficult, except for weak bars and bars with simple artificial potentials. The orbital properties of stars in rotating bars are important for understanding their equilibrium and their gas dynamics. Numerical studies of stellar orbits in bars show many families of periodic orbits. The two major families in the galactic plane, both prograde, are usually denoted x_1 and x_2. The x_1 orbits are elongated in the same sense as the bar and are the most important for defining the structure of the bar itself. The elongation of the x_2 orbits is perpendicular to the major axis of the bar and the existence of this orbit family depends on the presence of an ILR. The effect of the x_2 orbits is evident in the observed gas flows and the nuclear bars.

The orientation of the planar periodic orbit families changes across boundaries defined by the various resonances: e.g. between ILR and co-rotation (CR), the orbits lie parallel to the bar, and switch orientation across the ILR, CR, and OLR boundaries (recall the comments above about the orientation of the outer rings inside and outside the OLR).

Two- and three-dimensional bar models (N-body and Schwarzschild) show that the bar is supported primarily by quasi-periodic orbits around the x_1 family or its 3D extensions. It is these orbits that generate the observed stellar streaming in the bar. Three-dimensional orbits are important because their properties can lead to the formation of peanut-shaped bars. These properties include:

- vertical resonances coupling the planar and vertical (z) motions. Stars in the zone between ILR ($\Omega_p = \Omega - \kappa/2$) and vertical ILR ($\Omega_p = \Omega - \nu_z/2$) can oscillate along orbits extending far from the plane.
- the buckling (fire hose) instabilities suffered by a thin bar.

The association of peanut-shaped bulges (in edge-on galaxies) with bars is now fairly convincing, although it is certainly possible to construct stellar dynamical axisymmetric peanut-shaped stellar systems. Kuijken & Merrifield (1995) have invented an effective way to test whether an edge-on peanut bulge is indeed a bar: the line-of-sight velocity distribution from an edge-on bar is double-peaked because of the contribution from different periodic orbit families. This effect has already been observed in emission and absorption lines from two edge-on peanut bulge systems.

Stellar dynamical bars must be made primarily from 3D non-chaotic (quasi-periodic, regular) orbits in order to recover the shape of the bar itself. Bar models in which the distribution function depends only on the Jacobi integral would be rounder than the bar itself. A central mass concentration of only a few percent is sufficient to break the integrals associated with the quasi-periodic orbits that define the bar, and so make the stellar orbits irregular, and thereby transform the bar into a more nearly axisymmetric bulge. This suggests a picture of forming small bulges from the disk itself. The bar forms from instability of the disk (see below); this bar is then destroyed by a central mass which accumulates from gas in the region of the bar through the torque of the bar itself. This has broad significance for galactic evolution, because it means that small bulges may form later than the disk (i.e., the bulge structure could be relatively young, although the bulge stars would be old). There is also the interesting possibility that the bar may reform in the presence of fresh cold material in the disk, so the process of bar formation and destruction may occur several times in the life of a disk galaxy.

2.3. Bar Formation

Rotationally supported disks are prone to vigorous bar instabilities. The bars arising from these instabilities in N-body simulations are long-lived and have pattern speeds Ω_p such that the bar ends near co-rotation. Tidal triggering of bar formation in interactions is also a serious related possibility, as shown by the apparent overabundance of barred galaxies in binary systems and small groups, and the incidence of Magellanic barred systems with companions.

It is not obvious why some disk galaxies do not have bars. It is possible to control bar formation by:

- making the disk kinematically hot enough (inner disks are observed to be as hot as bulges).
- a dark corona with significant contribution to the potential gradient in the inner regions.
- destroying bars by building up a central mass *via* radial gas transport.

All of these may be relevant in different galaxies and at different stages of galaxy evolution (e.g., the dark corona for lower luminosity disk galaxies in which the potential gradient is dominated throughout by the dark matter).

2.4. Nuclear Bars

Some barred galaxies show a nuclear bar in addition to their primary bar. These nuclear bars, which have typical bar lengths of about 1 kpc, show a wide range of orientations and are probably related to the ILR. From theoretical arguments, corotation for the nuclear bar lies near the ILR of the primary bar. Gas dissipation and the x_2 orbit family are probably important in the development of nuclear bars, to shift the orbital phases relative to the primary bar. For misaligned stellar primary and nuclear bars, one would in general expect different pattern speeds.

In the evolution of double-barred systems, the secondary bar dissolves, leaving a triaxial bulge-like central body. This suggests that some triaxial bulges may be the relics of destroyed secondary bars.

2.5. Lenses

In many barred galaxies, the bar appears immersed in a more axisymmetric lens component. This lens has a similar radial extent to the bar itself, which suggests an association of lens and bar. Lenses have a fairly flat radial luminosity distribution, and are seen more often in the earlier-type galaxies. They are believed to be disk-like and are kinematically relatively hot. The origin of lenses is not understood. They may be dynamically associated with the inner ring or with stochastic stellar orbits in the bar region.

Lenses are seen also in some normal (SA) galaxies; it is possible that in these systems the lenses are the remnants of bar destruction, through the transformation of the regular bar-supporting orbits to irregular orbits filling their (Jacobi) equipotentials.

2.6. Bar-Disk-Corona Coupling

The issue here is the evolution of the pattern speed Ω_p for the bar through angular momentum transfer between the different components of the galaxy. This subject has a long history. More recently, Little and Carlberg (1991) studied a disk in a 2D live corona. They found that angular momentum is transferred from the disk to the corona, with the bar forming in the disk and slowing down by a factor of 2 in a Hubble time. In their simulation, the CR moves outwards from about 1.1 to more than 1.3 bar semi-lengths. Friedli & Benz (1993) modelled 3D disks with gas, and showed how gas accretion to the center changes the rotation curve and can lead to an *increase* in Ω_p.

3. Abundance Gradients and Gas Flows

3.1. Abundance Gradients

The presence of a bar appears to affect the chemical abundance gradient in the disk of its parent galaxy. This is usually interpreted as the result of gas mixing through the bar-driven gas flows. Recently Martin & Roy (1994) reviewed the question of abundance gradients in HII regions of barred and normal galaxies. They found that:

- barred galaxies show weaker abundance gradients than normal spirals, particularly for galaxies with Hubble types later than about Sb.
- among the intermediate and barred galaxies, the [O/H] abundance gradients are weaker for galaxies with *longer* bars (in terms of the ratio of bar semi-length to disk scale length).
- the abundance gradients are weaker in systems with *more elliptical* bars.

These observations all indicate that gas mixing across the disks is more efficient for stronger bars.

Friedli et al. (1994) made 3D simulations of the effect of gas flows and star formation on the abundance gradients. They showed how the bar induces a strong large-scale inflow-outflow field, which rapidly reduces an initially imposed radial abundance gradient.

This is an important issue of general relevance to galactic chemical evolution, because it now seems possible that many of the normal (SA) galaxies have been through one or more barred phases which may have significantly affected their star formation history and chemical evolution.

3.2. Dust Lanes, Shocks and Gas Flows in Bars

Within the bars, the gas flows induce large-scale shocks that lie more or less along the bars. These shocks are usually associated with the spectacular dust lanes that are so often seen within the bars of barred galaxies. The properties of the gas flows and shocks are sensitive to the dimensionless pattern speed and strength of the bar. Athanassoula (1992) has reviewed this subject. Some of the important conclusions are:

- shocks arise in the gas if the x_1 orbits have loops or large curvature at their apocenters.
- the shape of the shock depends on the parameters of the bar and the disk: for shocks that are offset from the major axis of the bar, the presence of the x_2 family of orbits (and hence of an ILR) is required over a sufficiently large region of the bar.
- therefore the shock or dust lane properties can be used to constrain the dynamical parameters of models. For example, shocks with a realistic appearance require that the radius r_L of the Lagrangian points near the ends of the bar satisfies $r_L = (1.2 \pm 0.1)\, a$, where a is the bar semi=length.
- the predicted velocity jump of the gas across the shock increases with increasing axial ratio a/b and increasing quadrupole moment of the bar.

4. Magellanic Systems

The Magellanic barred spirals are characterized by a second asymmetry: the bar is offset from the center of the disk (the offset is usually along the minor axis of the bar), so that the potential is no longer bisymmetric. The prototype of the Magellanic systems is the LMC and many are known among the bright galaxies. They were a major research interest for de Vaucouleurs, who recognized that the Magellanic systems are not just irregular but are a well defined class of disk galaxies (see de Vaucouleurs & Freeman 1972). Their importance includes the intrinsic dynamical interest of the offset bar geometry, the question of whether they are transient or long-lived systems, and whether they come from $m = 1$ instabilities of their disks or result from interactions.

A morphological feature of the Magellanic systems is the asymmetric spiral structure, with one major spiral arm plus one or more minor arms starting from near the ends of the offset bar. NGC 4027 (e.g., Phookun et al. 1992) is a nice example. Colin & Athanassoula (1989) used a simple model of the potential, in which the offset bar is in synchronous rotation about the center of the disk (so that the potential is time-independent in a frame rotating with the bar), and showed how a strong one-armed response develops in the gas.

The offset bar phenomenon appears to be associated with tidal interaction (e.g. Odewahn 1994): most Magellanic galaxies have nearby companions which are 2 to 3 magnitudes fainter (e.g. LMC/SMC, NGC 4618/4625). This is reminiscent of other work on enhanced bar formation in encounters (see §2.3). An apparent exception is NGC 55, a large edge-on Magellanic galaxy in the nearby Sculptor group, for which the nearest companion is more than 150 kpc in projected distance and is at least 7 magnitudes fainter.

The Magellanic systems are of particular interest because the LMC is our nearest neighbor galaxy and it is possible to study it at a level of detail that is not possible for most other galaxies. For example, just to mention some examples close to home:

- the Australia Telescope HI mosaic project is imaging a 10° × 12° field centered on the LMC, with an angular resolution of 40 arcsec or 10 pc.
- the MACHO project, in the process of monitoring the brightness of about 15×10^6 stars, is producing very large numbers of particular kinds of stars (e.g. clump giants, cepheids, RR Lyrae stars) distributed all over the LMC.
- the AAT with the 2-degree field spectroscopic facility will provide opportunities for very large stellar spectroscopic programs on the LMC, such as studies of the stellar population and dynamics of the bar, disk heating and chemical evolution in the Magellanic environment, and the dynamics of the metal-poor population in the LMC (RR Lyrae stars, giants).

As another possible application of the HI and stellar kinematical data, one could use the Tremaine & Weinberg (1984) method on many strips in the LMC, to see if the bar of the LMC has a well defined pattern speed Ω_p. This might indicate that the asymmetric Magellanic structure is not transient on dynamical time scales (my thanks to Bruce Elmegreen for discussions leading to this suggestion).

At this stage, our theoretical understanding of the Magellanic phenomenon remains rudimentary. Given the exceptional observational opportunities provided by the LMC, more work on the dynamical theory of Magellanic systems would be very welcome.

5. The Galactic Bar/Bulge

In 1964, de Vaucouleurs classified our Galaxy as a transition barred spiral, SAB(rs)bc. This classification caused some mirth at the time but we now realize that it is probably close to correct. The evidence for an inner bar/bulge is now strong (for a recent review, see Gerhard 1995) and includes:

- the longitude asymmetry seen in the near-infrared DIRBE images of the inner Galaxy.
- the bulge IRAS sources, Miras and clump giants are all brighter in the mean on the positive galactic longitude side of the galactic center.
- the longitude-velocity distribution of molecular gas has the characteristics of the gas flow associated with a bar.
- the very large optical depth to microlensing (about 3×10^{-6}) reported by the OGLE and MACHO teams is indicative of a bar-like distribution of stars in the galactic bulge.

Dwek et al. (1995) have recently modelled the infrared light distribution observed for the galactic bulge. They favor a Gaussian density distribution of the form

$$\rho(\mathbf{r}) = \frac{M}{8\pi abc}\exp(-s^2/2)$$

where M is the mass of the bulge,

$$s^4 = [(x/a)^2 + (y/b)^2]^2 + (z/c)^4$$

and the x and y axes lie in the galactic plane. For their best model, they find that $(a, b, c) = (1.5, 0.6, 0.4)$ kpc, with the x-axis inclined at 13° to the sun-(galactic center) line and pointing into the first quadrant. It is striking how similar the vertical scale height for the DIRBE bulge is to the vertical scale height of about 300 pc for the old galactic disk (this is seen more directly from the exponential models of Dwek et al. which are an excellent fit to the infrared light distribution over most of the bulge). This may provide support for the view that the bar/bulge formed through instability of the galactic disk, after the disk itself was already present. Zhao (1994) has constructed a rapidly rotating ($\Omega_p = 60$ km s^{-1} kpc^{-1}) Schwarzschild model to fit the Dwek et al. density distribution and the observed stellar kinematics in the bulge. This is one of the few rapidly rotating bar models now available, and it will have many applications.

The presence of the galactic bar/bulge suggests several aspects of the evolution of the Milky Way in which the effect of the bar should be fully considered. They include

- gas infall and chemical enrichment of the inner bulge.
- the chemical evolution of the galactic disk.
- the serious possibility that the bulge formed *after* the disk
- the heating of the inner stellar disk by the bar and bar-forming process.

6. Some Questions

Here are just a few issues associated with the barred galaxies which I find particularly interesting:

- Why do only 30% of the disk galaxies have strong bars?
- Are the dark coronas relevant to the presence or absence of bars in disk galaxies?
- What are SAB galaxies: are their bars forming, dissolving, or evolving?
- What is the dynamical nature of the lenses?
- What is the role of bar formation and evolution in the formation of the different kinds of small peanut-shaped bulges, small spheroidal bulges and large spheroidal bulges which are seen in edge-on galaxies?

Another issue concerns the numerical simulations of bar formation, evolution and destruction. These simulations mostly start from an equilibrium disk and follow the evolution of the bar that forms from the instabilities of this disk. It would be interesting in the foreseeable future to make full high resolution simulations of hierarchical galaxy formation, and study the bar formation and evolution in this *non-equilibrium* process.

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Discussion

Z. Tsvetanov: You mentioned several times that approximately 30% of galaxies have bars. However, this assumes that bars are strong enough to be easily seen. Could it be that all galaxies do have bars, only most of them are so weak that they are below our detection limit?

K. Freeman: Recent near-IR imaging by several authors shows that some galaxies which are apparently un-barred in their optical images do show bars in the near-IR. But it seems unlikely that all galaxies have bars.

D. Pfenniger: There is certainly a strong bias against barred systems in any census of the barred spiral fraction, because most edge-on systems are not classified barred.

K. Freeman: The method of Kuijken and Merrifield (1995) (for detecting edge-on bars) is particularly interesting in this context.

A. Bosma: You mentioned as a possible origin of lenses in ordinary (SA) galaxies that they are the remnants of bar-destruction, in which bar-supporting orbits are converted to chaotic orbits. In such a scenario, how do you keep the sharp edge so characteristic of lenses?

K. Freeman: I could only speculate that there is a fairly well-defined upper limit to the Jacobi integral for stellar orbits in the bar which might then translate to a fairly well defined outer edge to the lens following the destruction of the bar.

J. Sellwood: The alignment of rings relative to the bar indicates that they are clearly associated with bars. Yet we can also find evidence that the coupling of bars to outer spirals is weak, because the spirals can have different pattern speeds. Does this not suggest that outer rings are transients formed at the time of the bar, but dissolving slowly, or when a new spiral pattern appears in the outer disk?