The Evolution of Galaxies on Cosmological Timescales
ASP Conference Series, Vol. 187, 1999
J. E. Beckman, and T. J. Mahoney, eds.

Observations of Barred Galaxies

Johan H. Knapen

University of Hertfordshire, Department of Physical Sciences, Hatfield, AL10 9AB, UK

Abstract. We review general observational properties of bars in galaxies, and relations between bars, their dynamics, and (circum)nuclear activity. We consider new measurements of bar fractions and of the distribution of bars with host type, bar strength, and bar pattern speeds. Bars redistribute material radially, leading to flattened abundance gradients and a diminished degree of disk-wide twofold symmetry in the distribution of star-forming regions. We discuss recent results on statistical correlations between bars and AGNs in samples of active and non-active galaxies, and on circumnuclear regions of star formation in the cores of barred galaxies. Finally, we review the limited, but promising, work published to date on bar fractions at cosmological distances, and list a number of issues where further observational progress should be expected.

1. Introduction

Bars are common structures in disk galaxies. Just over half of all galaxies are barred (Sellwood & Wilkinson 1993; §2), a fraction that only goes up slightly when near-infrared (NIR) rather than optical images are used for the classification, contrary to claims that the use of NIR imaging substantially increases bar fractions. The main observational characteristics of bars in the optical and NIR are an elongated light distribution, pairs of curved dust lanes which show up in broad-band or color-index maps, and characteristic isophote twists. Radio and millimeter observations often show gas concentrations in the central regions, with some emission along the dust lanes. Kinematic evidence for gas streaming along the main body of the bar can be seen in H I or millimeter line emission (e.g., Bosma 1981; Knapen et al. 1993).

Gas response to the barred potential is delayed, creating an offset leading shocks inside the corotation radius. Enhancements in the gas surface density are observed where such shocks occur. Generally, this is believed to be where the dust lanes are observed in the optical/NIR, although Beck et al. (1999) claim from polarimetric radio continuum observations that the shock fronts are significantly offset from the dust lanes in the bar of NGC 1097, the first galaxy for which such data could be obtained. An important consequence of the elongation of the dominant stellar orbits and (given the high stellar mass fraction) of the mass distribution, is that the gravitational potential of a barred galaxy is non-axisymmetric. Through shocks in the gas which dissipate energy, such a potential naturally provides a mechanism for angular momentum loss in inflowing gaseous material. Bars can thus be expected to channel gas from the disk of a galaxy to the central kpc regions (e.g., Shlosman, Begelman, & Frank 1990; Athanassoula 1992; Sellwood & Moore 1999). Channeling of gas by a hierarchy of stellar and gaseous bars (Shlosman, Frank, & Begelman 1989) is frequently invoked to explain the occurrence of central or circumnuclear starbursts, or AGN activity (see §4).

The astrophysical importance of bars lies both in their common occurrence in disk galaxies, and in their ability to facilitate gas inflow. In this paper, recent observational results on selected aspects of barred galaxies are reviewed. Related theoretically or observationally oriented reviews include those by Sellwood & Wilkinson (1993) which concentrates on the dynamics of barred galaxies, by Buta & Combes (1996) on ring galaxies, and several reviews in the proceedings of the 1995 Alabama meeting (e.g., Elmegreen 1996; Freeman 1996; Roy 1996). In the present volume, Friedli (p. 88) reviews the birth, aging, and death of bars, whereas Shlosman (p. 100) discusses the dynamical evolution of central regions of disk galaxies. This review is more observationally biased and complements those by Friedli and Shlosman.

This paper discusses selected basic observational properties of bars where recent progress has been reported in the literature (§2), radial mixing due to bars (§3), and the relation of bars to Seyfert or circumnuclear star formation activity (§§4 and 5). Bar fractions at cosmological distances are discussed in §6. The summary (§7) includes a brief list of open questions and ideas for future work.

2. Basic Bar Properties

2.1. Are All Galaxies Barred?

How common are bars in galaxies? And does this bar fraction go up, possibly to 100%, if observations are considered at NIR wavelengths and/or very high resolution? In other words, are all galaxies barred at some level? Although new bars are being found in well-known galaxies such as NGC 1068 (NIR imaging by Thronson et al. 1989) or Centaurus A, for which Mirabel et al. (1999) claim that the bisymmetric structure observed in dust emission at mid-IR and submillimeter wavelengths is indicative of a gaseous bar, it is far more difficult to obtain reliable statistics that can help answer the questions raised above.

Sellwood & Wilkinson (1993) compiled statistics on bar fractions using data from three major catalogs, and found that whereas the bar (SB) fraction was roughly constant across catalogs and morphological types, at 25–35% of disk galaxies, the intermediate (SAB) fraction was as high as 25% in the RC2 (de Vaucouleurs, de Vaucouleurs, & Corwin 1976), but substantially lower in the other two catalogs analyzed.

Studying the distribution of morphological classification in the RC3 catalogue (de Vaucouleurs et al. 1991), Knapen, Shlosman, & Peletier (1999a) confirm an overall bar fraction (including intermediate type, X) of between 50% and 60%. Figure 1 shows this bar fraction as a function of morphological type and ellipticity (or inclination) of the host galaxies. Several interesting trends can be noted. 1) About 35% of all galaxies are classified as B, or barred, and this fraction is remarkably constant across morphological types ranging from

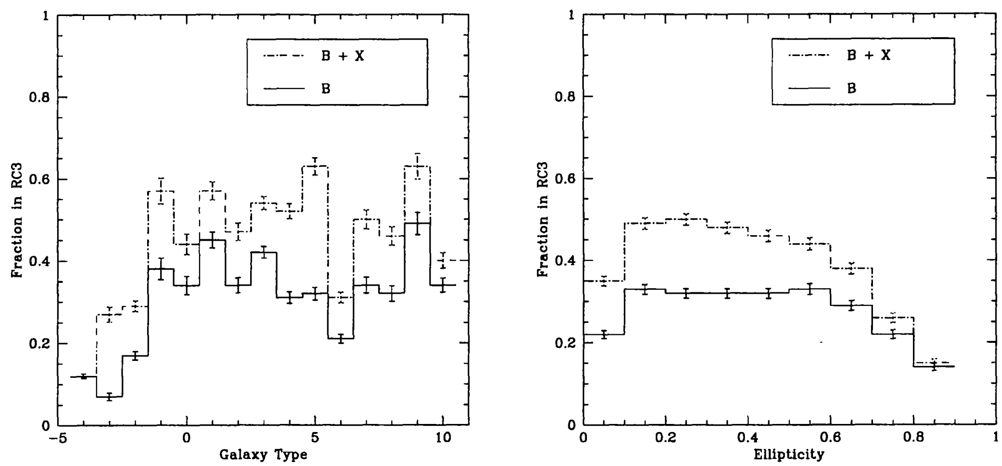

Figure 1. Bar fractions as determined from the morphological classifications in the RC3 as a function of morphological type (*left panel*) and ellipticity ($1 - b/a$; *right panel*). B and B+X fractions are shown separately. Data from Knapen et al. (1999a).

type=–1 (S0) to type=10 (Sm). 2) The total barred fraction (B+X) is roughly constant at a level between 50% and 60%, again over the full range of types. This also shows that the ratio B/X, strong to intermediate bars, is constant (at about 2). 3) The B fraction is constant with ellipticity up to $\epsilon \sim 0.6$, whereas the X fraction is constant up to $\epsilon \sim 0.4$. This effect can be interpreted simply as one of selection: it is progressively more difficult to distinguish bars from morphology alone in more inclined galaxies, and this effect is more noticeable for less well defined, presumably weaker, bars.

So between one half and two thirds of all disk galaxies contain a stronger or weaker bar, as based on the classification in the RC3, with about twice as many galaxies being classified as B than as X.

This determination is based on morphological classification from optical plates exposed in blue or visual light, which deliver galaxy images with a resolution of a few arcsec, and with often overexposed central regions. Being dominated by an older stellar population, in contrast to, for example, spiral arms, bars are most readily detected in the NIR. It is thus somewhat surprising that the bar fraction in spirals goes up by only about 10 – 15% when NIR digital images are used for the classification, even when these are at subarcsec resolution (e.g., Mulchaey & Regan 1998; Knapen et al. 1999a). These studies are as yet based on small samples of objects as compared to the RC3, and results from more extensive NIR surveys or even complete sky surveys should be used for confirmation.

Certainly not all spirals are barred in the conventional sense. Small-scale bars, nested within primary bars or not, are discovered at high resolution in the NIR or using adaptive optics techniques (e.g., Regan & Mulchaey 1999; Erwin & Sparke 1999; Combes et al., in preparation), but not in all galaxies (e.g., Laine et al. 1999a; Regan & Mulchaey 1999). However, small-scale oval distortions, miniature bars on scales smaller than tens of parsec, or non-axisymmetries due to structures other than bars or ovals, e.g., spiral arms, may have some or all of the dynamical effects ascribed to bars, but would not normally end up in statistics on bar fractions.

2.2. Bar Strength

Whereas the parameter bar strength can be defined rather easily theoretically, it is hard to determine observationally, and is usually measured as, for example, the axial ratio or length of the bar. Sandage & Tammann (1987) and de Vaucouleurs et al. (1991) catalog barred galaxies as either "AB" or "X" for intermediate bars, or "B" for truly barred galaxies, but these classifications are not strictly delimited by bar strength as measured more quantitatively from digital images. Several quantities have been used as indications of bar strength, e.g., the fraction of total luminosity in the bar (e.g., Sellwood & Wilkinson 1993), or the length of the bar relative to the total galaxy size.

Martin (1995) used the simple but very useful measure of the so-called apparent bar ellipticity. In equivalence with the usual classification of elliptical galaxies, this parameter is defined as $\epsilon_b = 10(1-b/a)$, where b/a is the apparent ratio between the bar minor and major axes. Thus a galaxy without a bar will have $\epsilon_b = 0$, one with a bar with a high axial ratio, presumed to be a strong bar, $\epsilon_b = 8$. Martin (1995) studied the lengths and axial ratios of the bars in a sizable sample of galaxies, and found, among other results, that bars in early-type galaxies are longer on average. Martin also confirmed the previously reported (e.g., Athanassoula & Martinet 1980) relation between bar length and bulge diameter, but a large scatter completely hides any correlation of bar axial ratio, or strength, with morphological type.

Some interesting correlations with bar "strength" have appeared in the literature over the past few years. For example, high star-formation activity seems to occur in galaxies with strong bars (but not all strongly barred galaxies have a high star-formation rate; Martin 1995; Martinet & Friedli 1997). Aguerri, Beckman, & Prieto (1998) find a very weak relation between bar strength and the location of the corotation radius ($R_{\rm CR}/R_{\rm bar}$), which remains to be confirmed.

2.3. Bar Pattern Speed

The pattern speed of a bar is one of its most defining and important properties, and its determination is critical for a detailed study of bar dynamics. Unfortunately, measuring bar pattern speeds remains a difficult task in practice. Elmegreen (1996) reviewed observations of bar pattern speeds and their implications, and this section will only discuss more recently published results.

In general, there are three main ways of measuring the pattern speed of a bar. First, with data from high signal-to-noise long-slit spectra of bars, the Tremaine–Weinberg method (based on the continuity equation) can be used for stellar bars (Tremaine & Weinberg 1984). Gerssen, Kuijken, & Merrifield (1999) used the method to obtain a value for the pattern speed for the early-type barred galaxy NGC 4596 (SBa), placing the corotation radius just outside the bar ($R_{\rm CR} = 1.2R_{\rm bar}$).

Secondly, morphological information can be used to deduce the location of resonances, which in combination with a rotation curve leads to a pattern speed determination. Fourier techniques are often used in this respect. Aguerri et al.

(1998) performed a Fourier analysis of optical images of ten barred galaxies and found $\bar{R}_{\rm CR} = 1.2\bar{R}_{\rm bar}$. Using morphology in another sense, Elmegreen, Wilcots, & Pisano (1998) studied streaming motions from an H I map of the SABd galaxy NGC 925 and found the remarkably large value of $R_{\rm CR} = 3R_{\rm bar}$. Canzian (1998) has studied the extent of spiral structure and relates it to the location of the main resonances for the unprecedented number of 109 galaxies, including almost 60 barred spirals, and about 40 ringed spirals. A result of interest to the present discussion is that Canzian plots the distribution of a parameter describing the extent of the spiral, and finds a peak for barred and for ringed spirals at a position indicating that the corotation resonance occurs at, or just outside, the end of the bar. This is under the assumption that bar and spiral are resonantly related, implying that the spirals can extend only between corotation and the outer Lindblad resonance. Canzian finds a considerable number of barred spirals where the spiral extends further into the disk than expected in this picture, which may indicate that weak bars do not quite end near corotation, or that bars and spirals are not resonantly related in all galaxies.

Thirdly, one can construct families of numerical models for a galaxy with varying pattern speeds, and from a comparison of the observed and modeled morphology certain pattern speed values can be excluded and a preferred value determined. Lindblad, Lindblad, & Athanassoula (1996), for example, compare their numerical gas simulations with morphological observations of NGC 1365 (SBb), and find $R_{\rm CR} = 1.2 - 1.3R_{\rm bar}$. For NGC 1300 (also SBb), Lindblad & Kristen (1996) find that two models represent the galaxy morphology, with $R_{\rm CR} = 1.3$ and $2.4R_{\rm bar}$. Laine, Shlosman, & Heller (1998) find $R_{\rm CR} = 1.1R_{\rm bar}$ for NGC 7479 (SBbc), in agreement with the value obtained previously from modeling and morphology by Sempere, Combes, & Casoli (1995).

The main problem with pattern speeds remains that it is very hard to determine them observationally. Several methods are now regularly used in the literature, but the error analysis is often not convincing, and individual results must be critically examined. In spite of this, there is a consensus, with rather few exceptions, toward $R_{\rm CR} = 1.1 - 1.2R_{\rm bar}$, or bars ending just before the corotation radius. This result continues to confirm the bar-aligned orbit theory (e.g., Contopoulos 1980). There are no significant trends of pattern speed with, for example, the bar strength or morphological type of the host galaxy.

3. Radial Mixing Induced by Bars

3.1. Abundance Gradients

Several studies published over the past decade have provided ample evidence that radial abundance gradients are flatter in barred than in non-barred galaxies, as reviewed by Roy (1996). Martin & Roy (1994) even found a trend of stronger bars having flatter gradients. Flatter abundance gradients in barred galaxies have been interpreted as evidence for radial mixing in the disk, induced by the bar.

In a recent study, Dutil & Roy (1999) extend the study of abundance gradients to early-type galaxies. This has only now been done because abundance gradients are usually measured from line ratios in individual H II regions, which are most plentiful and most easily observed in later-type galaxies. Dutil &

Roy find that the abundance gradients in early-type galaxies are shallower than those in non-barred late-type galaxies, but similar to strongly barred late-type galaxies. They interpret this in terms of late-type non-barred galaxies (Sd, Sc, Sbc) developing a strong bar, and evolving via SBb and SBc types into earlier-type (Sa, Sb) galaxies. Theoretical arguments can be found to support such an evolution (e.g., Martinet 1995).

3.2. Symmetry in Star-Forming Regions

Rozas, Knapen, & Beckman (1998; see also Knapen 1992) studied the two-fold symmetry of star-forming regions along the two main spiral arms in a dozen galaxies, and found an anti-correlation between symmetry and bar strength. The sample galaxies are all grand-design spirals, and are thus two-fold symmetric in their spiral arm shapes, but it is the symmetry of the "pearls on the string", the H II regions along the spiral arms, that is considered here. An example of strong symmetry is M51, where all the main star-forming complexes can be identified with a counterpart some 180° away in azimuth but at the same galactocentric radius, and whose locations can be identified with the locations of density-wave resonances (Knapen et al. 1992). Measuring this degree of two-fold symmetry quantitatively and relating it to the presence and strength of the large-scale bar of the host galaxy, led Rozas et al. (1998) to their conclusion that apparently bars destroy global symmetry in the distribution of star-forming regions.

The anti-correlation between bar strength and degree of symmetry of the star-formation regions within two-armed spirals is interpreted along the same lines as the abundance gradient results, namely as a result of radial mixing in barred galaxies, which destroys the disk-wide symmetry in the location of star-forming regions that was present originally as a result of the global density wave.

The sample used by Rozas et al. (1998) is small, but if their conclusion on bars and symmetry can be confirmed generally, the technique might be used for detecting bars through Hα or FUV imaging, possibly to substantial redshifts because the bar itself, mostly devoid of recent star formation, would not have to be detected.

4. Bars and Nuclear Activity

Since theoretical arguments indicate that bars are efficient vehicles for gaseous inflow from the disk (Shlosman et al. 1990; Athanassoula 1992), gas accumulation can be expected in the central regions of barred galaxies. The inflow is slowed down towards the center (more so in the presence of inner Lindblad resonances—ILRs), and nuclear star-forming rings and disks can be formed. Massive nuclear disks and nuclear rings are themselves subject to non-axisymmetric dynamical instabilities, which drive the gas further in by means of gravitational torques, leading to the formation of nested bars and fueling stellar and nonstellar activity in the center (Shlosman et al. 1989). As a result, a direct observational relation between the occurrence of a bar, and of (circum)nuclear activity might be expected. Gaseous nuclear bars are expected to be short-lived, probably around 10^7 yr, and are therefore challenging to detect. Besides, their observational characteristics are as yet completely unknown.

Previous observational work strongly suggests that central starburst hosts are preferentially barred (e.g., Heckman 1980; Balzano 1983; Devereux 1987), but the issue has been much more controversial for Seyfert galaxies. After early claims of higher bar fractions in Seyferts (e.g., Adams 1977; Simkin, Su, & Schwarz 1980) had been criticized (e.g., Balick & Heckman 1982) for not having a sufficiently well defined control sample, only recently has more work appeared on the subject.

Ho, Filippenko, & Sargent (1997) compare the morphology as obtained from the RC3 of active galaxies, including Seyferts and LINERs, as identified from their spectra, with that of non-active galaxies. Although the source of their classifications (the RC3, thus optical plate material) can be criticized, their active and control samples were well matched (unlike, for example, those used by McLeod & Rieke 1995; Moles, Márquez, & Pérez 1995; or Hunt & Malkan 1999). Ho et al. conclude that the bar fractions in AGN and non-active galaxies are equal. Using new NIR images of Seyferts and of a matched control sample, Mulchaey & Regan (1997) determine bar fractions, and although they find that more galaxies are barred than in the Ho et al. study (as expected through the use of NIR array imaging), they find no evidence for enhanced bar fractions in their active sample.

Peletier et al. (1999) obtained NIR K-band images at subarcsecond resolution of the complete CfA sample of Seyferts, and of a well-matched control sample. From a morphological analysis of these data, Knapen et al. (1999a) find that, whereas about 60% of their non-active galaxies are barred, almost 80% of the Seyfert galaxies are barred (after excluding from the analysis those galaxies that are too small to study their morphology, interacting, or edge on). Given that the statistical uncertainties in these numbers are about 8%, the significance of this result—that slightly more, though by no means all, Seyfert hosts are barred—is at the 2.5σ level, and needs further confirmation using larger samples. The differences between the Seyfert bar fractions as found by Mulchaey & Regan (1997) and Knapen et al. (1999a) can be explained by the higher spatial resolution of the latter study ($\sim 0\farcs7$ vs. $\sim 1\farcs5$), and the strict use of a set of well-defined criteria to determine the presence of a bar.

It is possible that a direct correlation between bars and nuclear activity might exist for bars at smaller scales, but this remains to be confirmed (the study by Regan & Mulchaey 1999, who used *HST* NIR and optical imaging to see whether small bars occur particularly often in Seyfert cores, can only be regarded as a first step due to the limited sample size and to the use of ad hoc criteria for the presence of small-scale bars, assuming that they have the same morphological characteristics as large-scale bars). Miniature spiral arms seem to be common (e.g., Laine et al. 1999a and references therein; Regan & Mulchaey 1999), and are being found in both Seyferts and in non-active galaxies, but whether they are more common in the active galaxies, is, for the time being, an open question. In any case, the radial mass flow they excite may be too small for fueling purposes.

5. Bars and Circumnuclear Star Formation

Circumnuclear regions (CNRs) of enhanced star formation in barred galaxies are relatively common, and are believed to occur in response to gas accumulation between or near ILRs (see Shlosman, this volume, p. 100). There, gas inflow along the bar is slowed down, and the resulting high gas density can lead to spectacularly enhanced star formation. The star formation can result from the spontaneous gravitational collapse of gas clouds if these become Jeans-unstable (e.g., Elmegreen 1994), from cloud–cloud collisions, or it can be triggered by shocks or density-wave spiral armlets (such as in the case of M100, see Knapen et al. 1995a,b, 1999b).

The importance of star-forming CNRs lies in the fact that they are excellent inflow laboratories, for a variety of reasons. Firstly, the phenomena occurring as a result of the inflow are not as violent as in AGN, where apart from the phenomenology resulting from the inflow itself, one will also observe secondary effects due to the activity, such as gas outflow. Secondly, the angular and physical scales in CNRs are excellent for observational study. At a typical distance of a CNR host galaxy, 1 arcsec will correspond to up to 100 parsec ($\sim$ 70 pc for objects like M100, in the Virgo cluster), which means that ground-based non-corrected observations can resolve individual starburst regions and gas flow patterns (e.g., Knapen et al. 1995a, 1999b), whereas at higher resolution, e.g., using the *HST*, adaptive optics, or VLBI, one can resolve the individual star clusters (e.g., Maoz et al. 1996). In contrast, nuclear starbursts or AGN occur on angular scales much too small to resolve, e.g., the individual energy sources or powering star clusters. Thirdly, CNRs are bright across a wide range of wavelengths, due to their copious massive star formation activity. Gas and stars are easy to observe at high resolution in UV (e.g., Maoz et al. 1996; Colina et al. 1997, using the *HST*), optical, Hα, NIR (e.g., Knapen et al. 1995a), mid-IR (e.g., Wozniak et al. 1998), millimeter (e.g., review by Kenney 1997; Knapen et al. 1999b) and radio continuum emission (e.g., Hummel, van der Hulst, & Keel 1987).

5.1. Optical and NIR Observations of CNRs

Optical and NIR images of ever better quality are being produced, showing more and more detail in more and more CNRs. The results continue to comply with the general picture sketched above, but evolutionary sequences, if any, are still to emerge clearly. The main problem in the detailed interpretation of optical/NIR imaging is to disentangle the combined effects of young and old stars, and cold and possibly hot dust. Multicolor imaging can help, but additional spectroscopy is necessary to pin down, for example, populations or ages of the stars (e.g., Ryder & Knapen 1999). This area has only recently started to receive the attention it needs.

A major step forward in imaging has occurred thanks to the availability of high-resolution imaging techniques. In ground-based work, resolutions of $\sim 0\farcs7$ are standard nowadays (e.g., Elmegreen, Chromey, & Warren 1998; Pérez-Ramírez et al. 1999). Examples of work based on *HST* imaging, and taking advantage of the high resolution it offers, have been mentioned in the previous section, but, especially in the NIR, ground-based telescopes can be competitive.

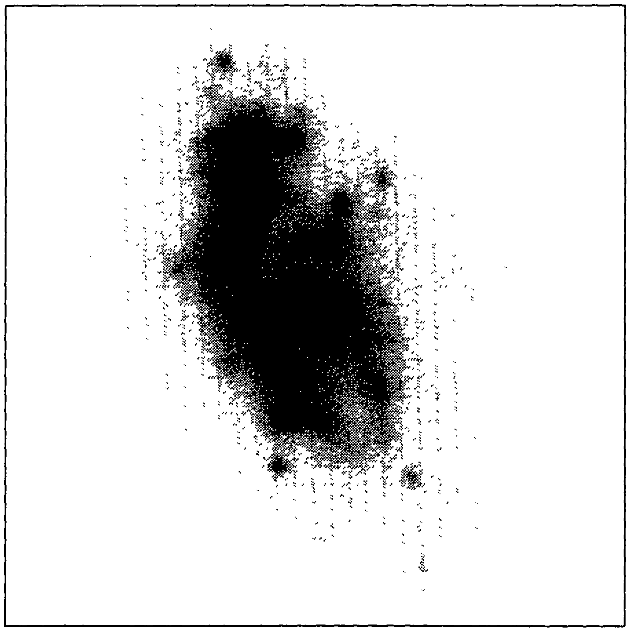

Figure 2. CFHT adaptive optics K'-band image of the circumnuclear star-forming region of the galaxy NGC 2903. The field of view is 21″, the spatial resolution is estimated to be better than $0\farcs3$, and N is up, E to the left.

For example, Ryder & Knapen (1999) used the upgraded UKIRT to obtain images in the J, H, and K bands of the core region of M100 with an angular resolution of $\sim 0\farcs3$, from which over 40 individual emitting knots, presumably star forming, could be identified. Adaptive optics (AO) techniques are also routinely capable of delivering superb resolution, but, until the advent of laser guide stars, only in selected objects due to the limited availability of suitable natural sources to correct the wavefront.

As an example, we mention the results obtained by Laine et al. (1999a,b), who detected a miniature grand-design spiral at scales well below 100 pc within the CNR of the non-active galaxy NGC 5248. Another example is shown in Fig. 2, a K' band image at $< 0\farcs3$ resolution of the circumnuclear region of the (SXT4) galaxy NGC 2903, obtained in October 1998 with the PUEO AO system and the KIR array camera on the Canada-France-Hawaii Telescope, while the natural, uncorrected, seeing was about $0\farcs6$. The image shows a large number of well-resolved individual knots, generally coinciding with Hα emission, and indicating the important contribution of light from young stars to the 2.2-μm emission. We have observed a small sample of CNRs (Knapen et al., in preparation), and most of those are similar to NGC 2903 in that the strong star formation regions in the CNR are obvious in the NIR emission, confirming that K-band emission is not insensitive to a young stellar population, and that any attempt to derive a gravitational potential from NIR images must be accompanied by a discussion of a non-constant M/L ratio (e.g., Knapen et al. 1995a,b, 1999b).

5.2. Gas Density Observations of CNRs

Because the H I surface densities in the central regions of barred galaxies are not high enough to allow high-resolution 21-cm observations, our knowledge of the gas densities in CNRs comes from interferometric millimeter observations, usually in the CO 1→0 line. The CO can be distributed in partial or complete rings, spiral arms, filled exponential disks, or in "twin peaks" (see Kenney 1997 for a review). In M100, leading spiral arms within the CNR have also been observed in CO (e.g., Sakamoto et al. 1995; Knapen et al. 1999b). The main interpretational problem remains the uncertainty in the CO-to-H_2 conversion factor, X, but it is certain that the standard value cannot be used without invoking large uncertainties in the derived gas mass (e.g., Reynaud & Downes 1999). This problem is less severe in kinematic studies, although H_2 present at certain locations in a CNR might not be accompanied by enough CO to be detected, as a result of a locally very high value of X.

Jogee (1998) studied CO emission from the CNRs in a dozen barred galaxies, a sample which included starbursts and non-starbursts in order to study systematic differences between these two classes of objects. Jogee found that whereas the CO in starbursts reaches larger peak surface densities, in non-starbursts it is observed to be either distributed in ring-like structures (e.g., NGC 3351, NGC 4314, NGC 6951), or extended over the central 1–2 kpc (e.g., NGC 4569, NGC 3359, NGC 7479). The total CO flux (interpreted as gas mass through the use of the standard X value) is comparable in both classes, though, with peak molecular gas surface densities three to four times higher in the starbursts. This conclusion does depend on the assumption that the standard value for X can be used.

5.3. Kinematics of CNRs

Detailed observation of the gaseous and stellar kinematics is the most direct way of studying the dynamics of barred galaxies and their central regions. For large-scale bars, H I interferometry gives the best measurements of the gas, though at rather low spatial resolution. Two-dimensional stellar kinematics of large-scale bars is harder to obtain due to the small field of view of the most appropriate instruments, integral-field spectrographs, or the incomplete coverage obtained when using a collection of long-slit spectra. This area remains much in need of further observational advance.

For the CNRs the prospects for observing high-resolution velocity fields are much better, due to the higher flux densities in the main tracers, and the smaller angular size of the area of interest. For the gas, CO interferometry now gives data on gas densities and kinematics in CNRs at spatial resolutions as good as $1''.6$ (Reynaud & Downes 1999), while improvements to telescopes will continue to improve this resolution limit. Ionized gas can be observed with, for example, Fabry–Pérot spectroscopic imaging in the Hα line, which reaches sub-arcsec resolution over a substantial field of view (e.g., Knapen et al. 1999b; Fig. 3).

Integral-field spectrographs, which project individual small regions (comparable to pixels or small beams) of a galaxy image onto a spectrograph, are powerful instruments due to the high resolution achievable and the possibility of making multi-line measurements (giving, for example, stellar and gaseous

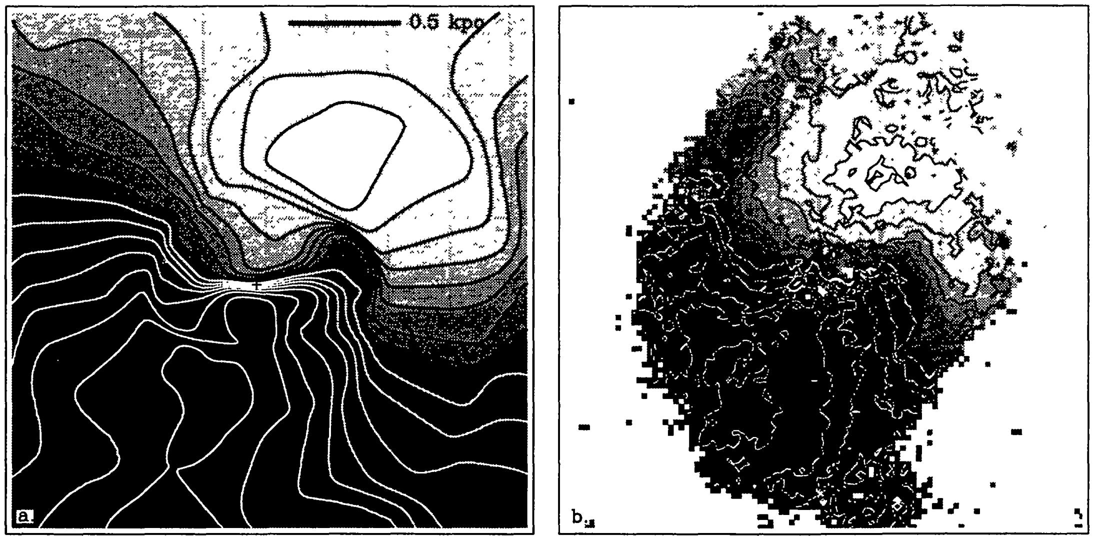

Figure 3. *Left panel:* Gas velocity field for the CNR in M100 as derived from the SPH model of Knapen et al. (1995b). The contour separation is 15 km s^{-1}, and the scale is indicated in the top right-hand corner. *Right panel:* TAURUS Fabry–Pérot Hα velocity field at $\sim 0\farcs7$ resolution obtained with the 4.2-m William Herschel Telescope, shown at the same scale and orientation as the model velocity field. The region shown is 29″ across. N is up, E to the left.

kinematics), but the problem remains the limited number of individual regions that can be observed in an exposure, which translates most directly into a compromise between spatial resolution and field of view. To reach well-sampled sub-arcsecond resolution the field usually remains limited to around 10″ (e.g., Arribas et al. 1999; Colina & Arribas 1999; García-Lorenzo, Mediavilla, & Arribas 1999; Miller et al. 1999).

Kinematic results for star-forming CNRs usually show a rather unperturbed "spider diagram" in the velocity field, indicating predominant disk rotation (e.g., NGC 3351 and NGC 4314: Jogee 1998; NGC 985: Arribas et al. 1999; NGC 5248: Laine et al. 1999b). In some cases there are marked deviations from circular motion, due to gas streaming across miniature spiral armlets in the CNR, and/or along the inner bar (e.g., M100: Knapen et al. 1999b; Fig. 3). However, such non-circular motions are only observable if the position angles of the galaxy's kinematic axis and of the kinematic structures in the CNR are favorably different, and they may only be observable at high resolution due to the small angular scales of most CNRs. Thus, more and better observations are needed to come to more general conclusions as to how common (or uncommon) predominant circular rotation is in CNRs, and what the consequences are for our understanding of the evolution of CNRs and for the star-formation processes within them.

Qualitative and quantitative comparison of kinematic data with numerical modeling is a very interesting area which should allow clearer discrimination between models than the usually performed morphological comparison. Kinematic comparison, however, is not often done, even in cases where kinematic data is available, such as in most studies where modeling is based on interferometric CO data. For M100, we found good agreement (Knapen et al. 1999b; Fig. 3) between the main kinematic features, such as rotation curve shape, and deviations in the velocity field due to spiral arm or bar streaming motions, as observed in Hα and CO, and as obtained from an analysis of our SPH model of the CNR in this galaxy (Knapen et al. 1995b). This qualitative and quantitative agreement forms an important confirmation of the modeling and interpretation in terms of a resonant structure driven by the moderately strong stellar bar.

6. Bars at Cosmological Distances

Studying bar fractions, and perhaps even properties, at cosmological distances can in principle yield direct evidence for or against galaxy formation and evolution models. One such model directly relevant to the topic in hand is that of secular evolution, where bulges are thought to form through the collapse of bars. Better datasets, in particular the Hubble Deep Fields (HDFs; Williams et al. 1996), make high-quality imaging of large samples of galaxies at $0 < z < 2$ available. Among the problems that need to be addressed is that of bandshifting: at $z \approx 2$, we see U light redshifted into I; at $z \approx 4$, far-UV shifts into the I-band. Can redshifted barred galaxies be reliably recognized as such?

The results are very limited so far, but they are exciting and warrant substantial further research. The bar fraction has not been systematically studied in the Medium Deep Survey, but at least some barred galaxies are present (Abraham et al. 1996). Although several barred spirals can be recognized in the northern HDF, van den Bergh et al. (1996) only find one bona fide case at $I > 21$ mag (corresponding to a bar fraction of 0.3%), and six possible ones, as based on a visual inspection of all galaxies. As pointed out by Abraham et al. (1999), however, this result remains controversial because barred galaxies may be undetectable at the levels studied by van den Bergh et al. (1996), due to the combined effects of bandshifting and low signal-to-noise.

From a study of the two HDFs (N and S), Abraham et al. (1999) are able to compile a sample of 18 barred galaxies with low inclination, selected on the basis of their axial ratios and isophote twists. The z-distribution of this sample supports the conclusion reached by van den Bergh et al. (1996) of a significant decrease in the fraction of barred spirals beyond redshift of $z = 0.5$. Abraham et al. (1999) briefly discuss a number of possibilities responsible for this decrease, but do not reach firm conclusions. Further study is required into observational issues like the amounts of dust extinction as a function of redshift, which possibly changes the morphological appearance of galaxies, or into the details of the bar detection mechanisms. Local studies have shown the difficulties in objectively defining whether a galaxy is barred (see §4), and classification of galaxies at substantial redshifts might well be biased to those galaxies that we would call strongly, or obviously, barred at $z \sim 0$.

7. Summary and Open Questions

Barred galaxies are plentiful, and important for a variety of issues, ranging from star formation to central activity and galaxy evolution. There is an enormous amount of observational and theoretical work on barred galaxies, and this review has attempted to present some of the exciting progress being made.

However, there are still many outstanding issues. In this section we will mention a few of the areas where observational progress can be made, leading to a better understanding of bars in galaxies, their origin and formation, and their relation to their host galaxies and the central or circumnuclear activity that may take place in their core regions.

- Most systematic studies of properties of barred galaxies, based on large samples, are still limited because of the use of catalogs based on blue or visual plates, and with poor resolution. There is a need not only for a NIR all-sky survey at decent and uniform resolution and limiting brightness levels, but also of a reliable catalog based upon it. Projects such as the present 2MASS surveys or planned survey telescopes (e.g., the Visible and Infrared Survey Telescope for Astronomy—VISTA) should lead to progress in this area.

- The gaseous kinematics of bars have been observed for a few decades now, and are reasonably well understood. Using Hα or CO observations, spatial resolution has reached comfortably low levels of near or below 1 arcsec, while upgrades to existing array telescopes and especially the planned Atacama Large Milimetre Array (ALMA) will allow much better resolutions. The area of stellar kinematics, however, needs substantial attention. Long-slit spectra are available but cannot show details of two-dimensional velocity fields. Integral-field spectrographs are possibly the way forward, but the field of view is usually still too limited to study large-scale bar kinematics in sufficient detail.

- It has now been established theoretically, as well as observationally, that gas can flow inwards in barred galaxies, toward the active, starbursting, or star-forming central regions. But we need to study the detailed interrelations between the dynamics of the bar and central regions on the one hand, and the star formation resulting from it, but also influencing the kinematics, on the other. Kinematic observations of gas and stars, and NIR imaging and spectroscopy, all at high-resolution, in combination with detailed numerical modeling, are required.

- The study of bar fractions at moderate and high redshift is an emerging area that needs further attention. It can in principle provide important observational inputs and checks to various models of galaxy, bar and bulge formation and evolution, but the various problems related to, for example, identification and completeness require continued scrutiny.

Acknowledgments I am indebted to my many collaborators on various programs, especially John Beckman and Isaac Shlosman. I thank Shardha Jogee, Seppo Laine, Mike Merrifield, Isaac Shlosman, Nial Tanvir, and Jeremy Yates for comments on an earlier version of the manuscript. The Canada-France-Hawaii Telescope is operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique de France and the University of Hawaii. This work is partly based on observations obtained at the William Herschel Telescope, operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

References

Abraham, R. G., Merrifield, M. R., Ellis, R. S., Tanvir, N. R., & Brinchmann, J. 1999, MNRAS, in press (astro-ph/9811476)

Abraham, R. G., van den Bergh, S., Glazebrook, K., Ellis, R. S., Santiago, B. X., Surma, P., & Griffiths, R. E. 1996, ApJS, 107, 1

Adams, T. F. 1977, ApJS, 33, 19

Aguerri, J. A. L., Beckman, J. E., & Prieto, M. 1998, AJ, 116, 2136

Arribas, S., Mediavilla, E., del Burgo, C., & García-Lorenzo, B. 1999, ApJ, 511, 680

Athanassoula, E. 1992, MNRAS, 259, 345

Athanassoula, E., & Martinet, L. 1980, A&A, 87, L10

Balick, B., & Heckman, T. M. 1982, ARA&A, 20, 431

Balzano, V. A. 1983, ApJ, 268, 602

Beck, R., Ehle, M., Shoutenkov, V., Shukurov, A., & Sokoloff, D. 1999, Nature, 397, 324

Bosma, A. 1981, AJ, 86, 1825

Buta, R., & Combes, F. 1996, Fund. Cosmic Phys., 17, 95

Canzian, B. 1998, ApJ, 502, 582

Colina, L., & Arribas, S. 1999, ApJ, 514, 637

Colina, L., García Vargas, M. L., Mas-Hesse, J. M., Alberdi, A., & Krabbe, A. 1997, ApJ, 484, L41

Contopoulos, G. 1980, A&A, 81, 198

de Vaucouleurs, G., de Vaucouleurs, A., & Corwin, H. G. 1976, Second Reference Catalogue of Bright Galaxies (Austin: University of Texas Press) (RC2)

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Buta, R. J., Paturel, G., & Fouqué, P. 1991, Third Reference Catalogue of Bright Galaxies (New York: Springer) (RC3)

Devereux, N. 1987, ApJ, 323, 91

Dutil, Y., & Roy, J.-R. 1999, ApJ, 516, 62

Elmegreen, B. G. 1994, ApJ, 425, L73

Elmegreen, B. G. 1996, in ASP Conf. Ser., Vol. 91, Barred Galaxies, ed. R. Buta, D. A. Crocker, & B.G. Elmegreen (San Francisco: ASP), 197

Elmegreen, B. G., Wilcots, E., & Pisano, D. J. 1998, ApJ, 494, L37

Elmegreen, D. M., Chromey, F. R., & Warren, A. R. 1998, ApJ, 116, 2834

Erwin, P., & Sparke, L. S. 1999, ApJ Lett, in press (astro-ph/9906262)

Freeman, K. C. 1996, in ASP Conf. Ser., Vol. 91, Barred Galaxies, ed. R. Buta, D. A. Crocker, & B. G. Elmegreen (San Francisco: ASP), 1

Garcıá Lorenzo, B., Mediavilla, E., Arribas, S., & del Burgo, C. 1999, ApSS (Proc. The Evolution of Galaxies on Cosmological Timescales, ed. J. E. Beckman & T. J. Mahoney), in press

Gerssen, J., Kuijken, K., & Merrifield, M. R. 1999, MNRAS, in press

Heckman, T. M. 1980, A&A, 88, 365

Ho. L. C., Filippenko, A. V., & Sargent, W. L. W. 1997, ApJ, 487, 591

Hummel, E., van der Hulst, J. M., & Keel, W. C. 1987, A&A, 172, 32

Hunt, L. K., & Malkan, M. A. 1999, ApJ, 516, 660

Jogee, S. 1998, PhD Thesis, Yale University

Kenney, J. 1997, in The interstellar Medium in Galaxies, ed. J. M. van der Hulst (Dordrecht: Kluwer), 33

Knapen, J. H. 1992, PhD Thesis, University of La Laguna

Knapen, J. H., Beckman, J. E., Cepa, J., van der Hulst, J. M., & Rand, R. J. 1992, ApJ, 385, L37

Knapen, J. H., Beckman, J. E., Shlosman, I., Peletier, R. F., Heller, C. H., & de Jong, R. S. 1995a, ApJ, 443, L73

Knapen, J. H., Beckman, J. E., Heller, C. H., Shlosman, I., & de Jong, R. S. 1995b, ApJ, 454, 623

Knapen, J. H., Cepa, J., Beckman, J. E., del Rio, M. S., & Pedlar, A. 1993, ApJ, 416, 563

Knapen, J. H., Shlosman, I., Heller, C. H., Rand, R. J., Beckman, J. E., & Rozas, M. 1999b, ApJ, submitted

Knapen, J. H., Shlosman, I., & Peletier, R. F. 1999a, ApJ, submitted

Laine, S., Knapen, J. H., Pérez-Ramírez, D., Doyon, R., Nadeau, D. 1999a, MNRAS, 302, L33

Laine, S., Knapen, J. H., Pérez-Ramírez, D., Doyon, R., & Nadeau, D. 1999b, ApSS (Proc. The Evolution of Galaxies on Cosmological Timescales, ed. J. E. Beckman & T. J. Mahoney), in press

Laine, S., Shlosman, I., & Heller, C. H. 1998, MNRAS, 297, 1052

Lindblad, P. A. B., & Kirsten, H. 1996, A&A, 313, 733

Lindblad, P. A. B., Lindblad, P. O., & Athanassoula, E. 1996, A&A, 313, 65

Maoz, D., Barth, A. J., Sternberg, A., Filippenko, A. V., Ho, L. C., Macchetto, F. D., Rix, H.-W., & Schneider, D. P. 1996, AJ, 111, 2248

Martin, P. 1995, AJ, 109, 2428

Martin, P., & Roy, J.-R. 1994, ApJ, 424, 599

Martinet, L. 1995, Fund. Cosmic Phys., 15, 341

Martinet, L., & Friedli, D. 1997, A&A, 323, 363

McLeod, K. K., & Rieke, G. H. 1995, ApJ, 441, 96

Miller, et al. 1999, in ASP Conf. Ser., Imaging the Universe in Three Dimensions: Astrophysics with Advanced Multi-Wavelength Imaging Devices, ed. W. van Breugel, & J. Bland-Hawthorn, ASP Conference Series, in press (astro-ph/9906091)

Mirabel, I.F., et al. 1999, A&A, 341, 667

Moles, M., Márquez, I., & Pérez, E. 1995, ApJ, 438, 604

Mulchaey, J. S., & Regan, M. W. 1997, ApJ, 482, L135

Peletier, R. F., Knapen, J. H., Shlosman, I., Pérez-Ramírez, D., Nadeau, D., Doyon, R., Rodriguez Espinosa, J. M. & Pérez García, A. M. 1999, ApJS, in press (astro-ph/9905076)

Pérez-Ramírez, D., Knapen, J. H., Peletier, R. F., Laine, S., Doyon, R., & Nadeau, D. 1999, MNRAS, submitted

Regan, M. W., & Mulchaey, J. S. 1999, AJ, June issue, in press astro-ph/9903053)

Reynaud, D., & Downes, D. 1999, A&A, in press (astro-ph/9904354)

Roy, J.-R. 1996, in ASP Conf. Ser., Vol. 91, Barred Galaxies, ed. R. Buta, D. A. Crocker, & B.G. Elmegreen (San Francisco: ASP), 63

Rozas, M., Knapen, J. H., & Beckman, J. E. 1998, MNRAS, 301, 631

Ryder, S. D., & Knapen, J. H., 1999, MNRAS 302, L7

Sakamoto, K., Okumura, S., Minezaki, T., Kobayashi, Y., & Wada, K. 1995, AJ, 110, 2075

Sandage, A., & Tammann, G. A. 1987, Carnegie Institution of Washington publication 635, A Revised Shapley–Ames Catalog of Bright Galaxies, second edn. (Washington, D. C.: Carnegie Institution of Washington)

Sellwood, J. A., & Moore, E. M. 1999, ApJ, 510, 125

Sellwood, J. A., & Wilkinson, A. 1993, Rep. Prog. Phys., 56, 173

Sempere, M. J., Combes, F., & Casoli, F. 1995, A&A, 299, 371

Shlosman, I., Begelman, M. C., & Frank, J. 1990, Nature, 345, 679

Shlosman, I., Frank, J., & Begelman, M.C. 1989, Nature, 338, 45

Shlosman, I., Peletier, R. F., & Knapen, J. H. 1999, ApJ Lett., submitted

Simkin, S. M., Su, H. J., & Schwarz, M. P. 1980, ApJ, 237, 404

Thronson Jr., H., 1989, ApJ, 343, 158

Tremaine, S., & Weinberg, M. D. 1984, ApJ, 282, L5

van den Bergh, S., Abraham, R. G., Ellis, R. S., Tanvir, N. R., Santiago, B. X., & Glazebrook, K. 1996, AJ, 112, 359

Williams, R. E., et al. 1996, AJ, 112, 1335

Wozniak, H., Friedli, D., Martinet, L., & Pfenniger, D. 1998, A&A, 330, L5