Barred Galaxies
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R. Buta, D. A. Crocker, and B. G. Elmegreen, eds.

General Discussion

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Abstract. This contribution presents a general discussion of special topics on barred galaxies by participants in the meeting.

1. Introduction

During this first conference dedicated exclusively to barred galaxies, many new results have been presented. Since no previous meeting had been dedicated exclusively to this topic, the SOC felt that theorists and observers might benefit from the crosstalk of a general open discussion on various topics. While the summary talks by W. C. Keel and R. H. Miller are useful for synthesizing the whole conference, there remained room for discussing ill-defined and speculative subjects, and also for clarifying misunderstood points. Thus, the SOC set aside 90 minutes on the fourth meeting day for questions and comments in the spirit of a "panel discussion." In this case, however, the "panel" was the audience, rather than a selected group of people sitting at a table in front of the room. A list of possible relevant questions was first set up by the SOC, and then completed by the conference participants.

The result was a much larger number of topics and questions (> 30) than eventual answers. In fact only a few could be discussed. The room acoustics forbidding tape recording, the participants have been asked to write down their interventions on sequentially numbered sheets. A few sheets never came back, and some speakers have been too modest to indicate their name: they will be forever remembered as the famous "Anonymous, XXth century". Below is therefore only the part of the discussion which has been written down on the sheets during and immediately after the discussion. Unable to write down my own remarks during the discussion I have also omitted to include below an unreliable recollection of them.

2. The Discussion

2.1. Shock in the bar and the central mass in NGC 1365

S. Jörsäter: I want to show the shock in the bar in NGC 1365 as measured in a long slit spectrum. A spectrum in my thesis clearly shows a velocity drop of 230 km s^{-1} in radial velocity. The shock seems to be resolved, however. I have also worked out (from velocity data) that NGC 1365 contains 3% of its total mass within 1 kpc = 1/10 bar radius. This is of relevance to the bar destruction issue.

2.2. Can we detect bars in edge-on galaxies, and how thick are bars?

K. Wakamatsu: From surface photometry of the edge-on SO galaxy NGC 4762, we identified sharp edges of the bar and lens component as well as the presumed diffuse outer ring. Our analysis (Wakamatsu & Hamabe, 1984, ApJS, 56, 283) shows the vertical scale height of the bar is $z \sim 150$ pc, i.e. the bar is a very thin system in the disk. We can identify bar systems if we detect sharp edges of bars in early-type barred galaxies. This interpretation has been criticized by Wozniak (1994, A&A, 286, L5).

D. M. Elmegreen: How do you distinguish between a bar end or lens in an edge-on galaxy?

K. Wakamatsu: We discriminated (identified) both the edge of lens and bar because the angle between the line of sight and the major axis of the bar may be favorable to do this job.

J. Sellwood: Somebody should check using the Kuijken & Merrifield procedure whether NGC 4762 observed by Wakamatsu & Hamabe shows any kinematic evidence for a bar.

G. Galletta: Is it possible to detect bars in edge-on galaxies by means of O/H gradient? Some people here discussed the fact that O/H is modified by the presence of the bar.

J. R. Roy: This is going to be difficult because most of the HII regions seen will tend to be at the periphery of the disk (because of extinction), i.e. at constant radial distance. Thus it would probably be difficult to establish a reliable abundance gradient.

T. Hawarden: Looking at the distribution of abundances to find a bar in an edge-on system will be made very hard: if you have enough gas to measure abundances you probably have enough extinction to make it impossible to see in as far as the bar with any reliability.

A. Bosma: For the exactly edge-on galaxy NGC 4013, the Hα velocities indicate that the emission all comes from the same radius. (To J.-R. R., in private: Look at near edge-on galaxies where you do see through the disk over a wider range of radii.)

J. Beckman: Rotation curves for edge-on galaxies at a range of optical wavelengths have shown, by their increasing gradients with wavelength increase, that this technique can be used to explore the extinction profile, and to help with the problem of finding radial dependence of abundances (for example).

R. Buta: On the subject of galactic bars and boxy bulges, I was wondering if the distribution of extents of the boxy bulges might connect them to bars. Viewed broadside-on, a bar is much larger than viewed end-on.

M. Merrifield: Testing whether boxy bulges have the same length distribution as stellar bars is very tricky – boxiness gets very small as a bar is viewed close to end-on. It will be difficult to separate out this selection effect, but should be possible.

J. Sellwood: I believe Kormendy might have already suggested that the luminosity function of bar and boxy bulges might make a useful test to see whether there are similarities. Extinction will be the major difficulty.

Z. Tsvetanov: 1) Identifying bars in external galaxies? It seems to me that it is about time to get to the very basics of the bar definition. That is: what do we call a bar and can we possibly attach "numbers" to estimate its strength? Perhaps one possible approach (as it emerged in our discussions with S. Jörsäter and P. Teuben) is to analyze a relatively small number of barred galaxies with both photometric and kinematical data to calibrate a more practical, purely photometric approach that may involve multiple passbands but could be used for more massive, yet quantitative work.
2) My second comment is about bars-within-bars. In many cases IR imaging is used to reveal small nuclear bars nested in larger "primary" bars. However, the very essence of these observations shows that the two bars have quite different colors, and likely different stellar content. Taking this into account is, therefore, critically important for proper understanding of the formation mechanisms and their co-existence.

2.3. Objectives for future observations of SB's

K. Wakamatsu: It is very important to measure the vertical velocity dispersion of bar and inter-bar regions of nearby face-on barred galaxies. The expected dispersions are about 40 – 80 km s^{-1}. T. Boroson and I once tried to do it at Las Campanas with the Reticon spectrometer. Now, CCD detectors are very useful to integrate more than $\sim$ 10 hours to get good spectra.

A. Quillen: HST should do statistics of bars, Hubble type, length of bar, fraction of bars, etc. for galaxies in clusters at $z = 0.1 - 0.5$.

S. Odewahn: Measuring evolutionary changes in bars using the Medium Deep Survey conducted with HST seems to be a promising idea. Interesting morphological features are clearly visible to $Z \geq 0.3 - 0.5$. Hence, this material should be used to determine how the situation of barred objects changes with time as well as how the morphological characteristics of the bars change with time.

Z. Tsvetanov: I would like to warn you, based on my own experience, not to have too high expectations of mapping velocity and velocity dispersions with HST. It is particularly important for absorption line measurements. The reason being very simple: HST spectrographs have small apertures and there is very little light reaching the detectors.

J. Sellwood: The hypothesis that the 30% fraction of strong bars in galaxies represents a duty cycle of 30% for a barred state in all disk galaxies would predict that HST images of galaxies at redshifts of 0.5 – 1 should show about 30% strong bars. Two caveats: The observed fraction will be affected by the bluer (relative to nearby) equivalent wavelength of the observations caused by the redshift and possibly also by a higher rate of interactions of that epoch.

F. Combes: Evolution of galaxies with time: at high z, surveys see more interacting galaxies, and therefore we should expect more barred galaxies. This will complicate the estimation of the duty cycle of bars.

2.4. Time-scale for ring formation

F. Combes: I wanted to point out, as in my talk, the problems of the simultaneous existence of nuclear and outer rings, which have time-scales of formation of 10^8 and $3 \cdot 10^9$ yr, respectively. Should we not see more "dead" nuclear rings in outer ring galaxies, Ron?

R. Buta: The "dead" nuclear rings are probably there in many cases but have not been recognized as such. This will become apparent as more cases are studied individually.

E. Wilcots: On the subject of "dead" inner rings: do you have colors of such rings? Is there a means of determining the star formation history of the "dead" rings?

D. Friedli: When the stars forming the ring become older, their velocity dispersion increases and the ring will be dissolved (in a few dynamical times?) unless new (low velocity dispersion) stars are formed there.

R. Buta: Colors can provide some information on the star formation history of dead or quiescent rings. For example, based on colors I think there is a "dying" inner ring in NGC 7702, a southern galaxy with a nuclear bar but no obvious primary bar (see ApJ, 370, 130, 1991). The ring is only slightly bluer than its surroundings and includes no HII regions or young associations. The ring has red and blue components with the red component being broader than the blue component. This supports the idea of the velocity dispersion increasing as ring stars age with the likely eventual dissolution of the ring. The time scale for this would likely be faster for a nuclear ring than an inner ring. It is essential to be able to remove the background (bulge and old disk) light from a ring in order to analyze its colors. This is often not possible, especially for a nuclear ring.

*A. Bosma (*to *Buta):* How frequently do you have cases of galaxies with a blue nuclear ring (formed recently according to Françoise) and a diffuse stellar outer ring (i.e. formed in $3 \cdot 10^9$ yr, evolved and diffused after star formation ceases) suggesting the presence of a very long lived bar?

R. Buta: From my list of 64 nuclear-ringed galaxies with D. Crocker (AJ, 105, 1344, 1993), the best examples of bright blue nuclear rings in barred systems with relatively diffuse outer rings or pseudorings are NGC 1326, NGC 3081, NGC 5728, NGC 6782, IC 1438, and IC 4214. In each of these, however, there is some recent star formation in or near the outer rings. Among very detached outer rings, the cases of NGC 1291 and 1543 include "secondary lenses" and secondary bars, rather than blue nuclear rings, but there is still some recent star formation in the outer rings. In ESO 565−11, there is a quiescent outer pseudoring (i.e., no clear recent star formation) and a very knotty, blue nuclear ring (see AJ, 110, 1588). My general impression is that nuclear rings frequently co-exist with clear diffuse, and at least evolved-looking, outer features.

J. Sellwood: The process of rapid bar formation in a disk leads to a strong bar ending near corotation and a strong transient spiral in the outer disk which winds onto the OLR rather quickly. This strong outer spiral sweeps much of the material outside the bar, especially the cool components, into a transient ring at the outer resonance. A dissipative component would probably survive much longer than the stellar rings formed this way, which are quite hot. This rapid process of pseudoring formation, if it occurs in nature, gets over the problem of the long time-scale for ring formation that Combes emphasized. A corollary to this idea is that the bars in galaxies with outer pseudorings could have formed quite recently, and should therefore show systematic differences from those in barred galaxies without rings.

J. Palouš (to F. Combes): The time necessary for ring formation depends on viscosity. Large viscosity means rapid ring formation. Thus lower viscosity inside the galaxy and larger viscosity outside would decrease the difference in the formation times.

J. Kenney: The lifetime of star formation in nuclear rings is probably not that short. Even though there is a high luminosity from star formation in some nuclear rings, there is also a lot of gas. Assuming the standard CO-H_2 conversion and a standard IMF, the gas depletion time scales in the rings in NGC 3351 and NGC 6951 are ~ 2 Gyr.

B. Elmegreen: It seems likely that nuclear rings last as long as the offset dust lanes in the bars, because these dust lanes are a source of gas to feed the rings. In fact this feeding can be somewhat steady, lasting for several $\times 10^9$ yr. The important issue is whether the star formation in the ring is steady, at the same rate as the accretion, or burst-like, going from a low to high rate when a threshold is reached, and then returning to a low rate when the ring gas is partially exhausted. I think the latter case applies, in which case any particular starburst can be young, but the whole ring feature and the persistence of some star formation in the ring, however low, can be very long-lived.

T. Hawarden: As to the inner rings: Bruce Elmegreen may be right and the gas feed rate is roughly the same as long as we can see the dust lanes, but it is certain that the star formation rate varies by at least 2 orders of magnitude even though we can see dust lanes (and even emission from the nuclear ring): NGC 1512 and NGC 1097 both are forming stars, yet NGC 1512 is $\simeq 100$ times fainter. One can find galaxies which look much the same optically but are dramatically different in FIR luminosity (i.e. star formation rates).

Anonymous: It is not enough to have gas accumulation in a (nuclear) ring for star formation. Star formation needs also compression of the gas in the ring. So, it is not surprising that star formation appears to be burst-like. One can imagine that gas accumulates in a ring with no star formation. Eventually, compression occurs, and a burst of star formation occurs. Then, gas continues to accumulate until the next episode of star formation.

B. Elmegreen: I think we can learn about star formation time scales in nuclear rings from analogies with star formation in the disk. In the disk, a large cloud (10^7 $M_\odot$) forms in 10^7 yr and star formation begins at a relatively high rate soon after that in the GMC cores. These GMC cores are pushed around by the star formation, forcing star formation to stop in those regions, but the cores cannot be easily destroyed completely, converting the self-gravitating gas back into diffuse gas. Rather, much self-gravitating gas remains in the neighborhood and this gas continues to house star formation for a relatively long time, forming stars generation after generation. The final result of all this star formation is typically a star complex, containing several aging OB associations and clusters with an age span up to 50 Myr or more. Thus star formation in any one region turns on quickly but turns off slowly. In nuclear rings, we might expect a similar thing, with a quick turn on to hotspots when a threshold density is reached, but a gradual decay to lower and lower levels of star formation after the gas drops below the threshold at the high densities in nuclear rings. The turn-on phase may last only a few million years, but star formation may persist at a decreasing rate for 10 to 100 Myr. This high number is about the gas accretion time. Thus most nuclear rings may contain some star formation, but only 10% may have a really intense burst.

2.5. Precise definition of resonances with non-circular orbits in bars

S. Ryder: In order to compare observationally the variation of $\Omega \pm \kappa/2$ with the observed ring radii, we need the theoreticians to tell us precisely how far inside or outside of resonance the rings will be, perhaps as a function of Ω_p. Also, since rings are intrinsically noncircular, which radius should we use in the comparison - semimajor, semiminor, the average radius, etc.

G. Contopoulos: In the axisymmetric case the resonances are defined exactly, at the points where $\frac{\kappa}{\Omega-\Omega_p} = \frac{n}{m}$. But as soon as a bar perturbation is added one can define only "resonance regions" (Figure 8 of Contopoulos' paper). If n/m is an even integer (e.g. 2/1, 4/1, 6/1) we have gaps along the main family x_1, and if n/m is an odd integer (e.g. 3/1, 5/1) we have intervals of instability along x_1 The theory of bifurcations and gaps is well known (G. Contopoulos, Pgysica 8D, 142, 1983; ApJ, 275, 511, 1983). As the bar strength increases the gaps and the instability strips become larger. Most important are the gaps at the ILR's (2/1 resonances). The characteristic of the x_1 family has large deviations from the unperturbed x_1 characteristic between the two ILR's. Most people define the nonlinear ILR's at the distances where the x_2, x_3 families appear and disappear (see Figure 1 on the following page). But for large perturbations (strong bars) these points approach each other and the two families (x_2, x_3) may disappear. In such a case we may say that the ILR's have disappeared also. But even then one can speak about an "ILR region."

B. Elmegreen: Even though the stellar resonances are broad in radius, it may still be possible to use the non-linear gas response to find morphological indicators of these resonances. The gas response can have much sharper features than the width of the stellar resonances. The gas response may not be centered exactly on the resonance, however.

2.6. Can bars be recurrent?

M. Noguchi: Tidal bars often show recurrent behavior. The bar triggered after the close passage of a companion fades away after a few Gyr and then re-appears after a few Gyr, but with smaller amplitude.

M. Weinberg: A comment to Ron Buta. Our current time-independent dynamical picture does not predict misaligned rings and lenses. Conversely, their existence is evidence for secular evolution and/or recurrent bars. Establishing the frequency of misaligned morphology would be very useful.

R. Buta: From the CSRG it does not appear that extreme misalignment (i.e. 45° bar/ring position angle) could be too common. I do not have a frequency estimate but will try to obtain one at some point. I agree with your comments.

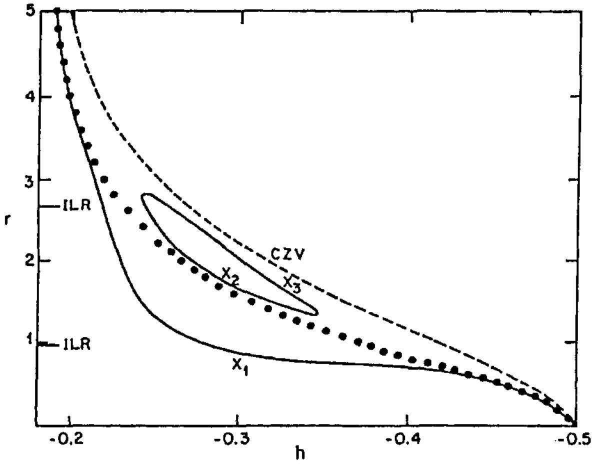

Figure 1. Definition of nonlinear ILR's (Contopoulos)

Anonymous: Bar-lens misalignment may as well be the result of secular evolution. But, what is the mechanism that causes the misalignment? What process is responsible for the breaking of synchronization? (Evolution may be the result, but, what is the cause?)

T. Hawarden:
- A third to two thirds of spirals have bars.
- We can't remake bars soon.
- But bars are very good at collecting gas (in early types) ($2 - 30$ $M_\odot$/yr?). – Therefore they must build central concentrations $>5\%$ of total mass in 5×10^8 to 1×10^9yr. Are we being saved by the ILR?

J. Kenney: No!

2.7. Does Hα from compact nuclei and none from the bar mean fast and efficient inflow?

J. Garcia-Barreto: From my Hα observations we have 32 out of 52 galaxies with gas in the compact nuclei but only the late types show gas *along* their bars. Athanassoula in her two 1992 papers predicts faster gas flow for late types, but 13 observed early-type galaxies with gas in the nuclei do not have gas along their bars, so it means that gas was driven faster. What is happening?

E. Athanassoula: Yes, gas might have gone faster inwards in early-type galaxies because of the potential. Mass density is higher in central regions of these galaxies.

2.8. Do bars drive spiral structure?

R. Buta: I think the observation of alignments between bars and rings, pseudorings means that these features are driven by the bar.

Anonymous: Why don't we hear more clearly what we are supposed to be looking for? For example theorists talk of 30% bar duty cycle. Is there any suggestion of how we may distinguish this situation from 30% of galaxies barred (for instance)?

Anonymous: Irrespective of the formation mechanism of the outer pseudoring, is there an evolutionary mechanism that might cause a difference in the pattern speeds of the bar and of the spiral pattern? In such a case, the bar would initially drive the spiral pattern, but eventually it would break out of synchronization.

M. Weinberg: We have found mechanisms that apply torques between galaxian components. For example, angular momentum can be added from the outer disk to the bar through the OLR. It is possible and it would be interesting to see if this leads to different bar/outer disk pattern speeds.

2.9. On the pattern speed of arms and bar

B. Elmegreen: I think the persistent evidence for long, often symmetric spiral arms in early-type barred galaxies, at a much higher probability than in early-typed non-barred galaxies, indicates that the bars are stimulating the spirals. But this is only for early-type galaxies. Late-type barred galaxies have no tendency to show long symmetric arms. The regular appearance of outer pseudorings is also confined to early-type galaxies.

Steven Jörsäter: I think that there are strong reasons to believe that the pattern speed of the arms and the bar are identical in NGC 1365 as I argued in my presentation. It may well be a different situation in late-type systems, however, the determining factor being the relative mass of the bar.

2.10. Do we understand gas dynamics?

F. Combes: About the percentage of mass contained in the warm and diffuse ISM with respect to the clumpy phase, we can take the example of M51. The arms have been observed in CO with single dishes, and molecular clouds are spread all over the arms. The interferometer shows a concentration along the dust lanes, but even there, the emission is very clumpy and the clumps are coincident with the single dish map. So in conclusion, the dust lane and corresponding shocks are only tracers of the arms and do not represent a lot of mass. They are not likely to influence the dynamics.

Anonymous: Is it possible that the clumpy structure observed that you mention for the arms of M51 could be due to missing short spacings in interferometer maps?

F. Combes: No, it is also seen in single dish maps.

B. Elmegreen: Following Françoise Combes' comment, I think at this point it might be acceptable to introduce the interstellar magnetic field. In 1988 I published a paper on the different motions of diffuse clouds and GMC's at large scale pressure jumps such as spiral wave shocks. The diffuse clouds are well connected by magnetic forces and collisions and they make a thin dust lane. The GMC's are not well connected and they scatter throughout the area. This structure follows entirely from the multifluid nature of the ISM. As a result, spiral arms have dust lanes on their inner edges that are made from a different population of clouds than the GMC's, which make stars in the middle of the arms. Thus star formation looks downstream from the shock front as if there is a time sequence, when in fact the star formation may be unrelated to the shock front. For example, star formation in some spiral arms is offset from the dust lanes by a nearly constant distance, which would correspond to a range of time delays for star formation from 20 Myr to 10^9 yr as a function of radius (higher delays closer to corotation), but such a range in time delays is very unlikely. More likely, much of the observed offset just comes from geometric effects in a multicomponent ISM.

2.11. About gas inside IILR's

Anonymous: Can molecular-gas observers make a case for galaxies which appear to have ILR's but in which the CO gas appears to exist all the way into the center? How common are these cases?

J. Kenney: Yes, there are galaxies with gas inside the IILR. M100, studied by Sakamoto et al. (1995) and Knapen et al. (1995) has a central concentration which clearly seems to be inside IILR. NGC 3504 and NGC 4102, which are young starbursts, have their largest gas surface density clearly inside the OILR, and perhaps also inside IILR, as judged from the fact that the peak of $\Omega - \kappa/2$ is much larger than the bar pattern speed.