Barred Galaxies
ASP Conference Series, Vol. 91, 1996
R. Buta, D. A. Crocker, and B. G. Elmegreen, eds.

Evolution of Bars in Isolated and in Interacting Disk Galaxies

E. Athanassoula
Observatoire de Marseille, 2 Place Le Verrier, 13248 Marseille Cedex 04, France

Abstract. I use N-body simulations to follow the evolution of bars in both isolated and interacting disk galaxies. The pattern speeds of bars evolving in isolated galaxies decline gradually with time, due to transfer of angular momentum from the bar to other components in the galaxy. Both the form and amount of this decline depend on the model used. The fate of a bar in an interacting disk galaxy depends on the mass, central concentration and orbit of the perturber. The pattern speed, form and amplitude of the bar may change, the bar can become off-centered, or, more drastically, it can disappear altogether. Finally I propose a scenario for the evolution of NGC 7217, which could, if proven correct, explain the formation of the rings in that galaxy and also, at least qualitatively, the existence of a retrograde population.

1. Introduction

In this paper I discuss several aspects of the slow secular evolution of bars in isolated disk galaxies, as well as the faster, and often more violent, evolution in interacting or merging systems. I neglect the gaseous component of the galaxy and do not discuss vertical motions and instabilities, since these topics will be covered by other authors contributing to these proceedings. All results presented in this paper are preliminary. In particular, insofar as isolated galaxies are concerned, I discuss only the gradual slowdown of the bar, leaving for a future paper a more extensive discussion of the problem, including the amplitude, form and length of the bar.

2. Slowdown of the Bar in an Isolated Disk Galaxy

It is by now well established that, during the evolution of a barred galaxy, angular momentum is redistributed between, but also within, the various components of the galaxy, leading to a gradual slowdown of the bar. Linear analytical estimates (Weinberg 1985, Hernquist & Weinberg 1992) predict that a strong bar transfers a significant fraction of its angular momentum to the halo in only a few rotation periods. Similarly high slowdown rates were also found in the numerical work of Hernquist & Weinberg (1992), who found that their fiducial bar would lose all its angular momentum in a time of the order of 5 initial bar rotations. On the other hand other numerical simulations (e.g. Combes et al. 1990, Little

https://doi.org/10.1017/S0252921100049940 Published online by Cambridge University Press

& Carlberg 1991) gave considerably longer estimates for the slowdown, i.e. they found that of the order of 30 to 40 initial bar rotation periods are needed to slow down the bar by a factor of two. There is thus an important disagreement between the results of different analyses. Furthermore, one can question whether a linear treatment is adequate for this problem, while the fact that some simulations considered that the bar was rigid, while others are two-dimensional and therefore model the halo as an infinitesimally thin hot disk (Little & Carlberg 1991), may also be responsible for the differences in the results.

I have addressed this problem using fully self-consistent, three dimensional numerical simulations, in which the force calculation is made with the method entailing the fewest approximations, namely direct summation. All simulations were made on our GRAPE system, consisting of five GRAPE 3-AF boards linked via an Sbus/VME bus converter to a Sparc station 10/512. The second processor does on-line analysis of the results in order to reduce storage requirements. This system gives us a sustained speed of 20 Gflops for direct summation and will be described in more detail elsewhere. Direct summation has the added advantage of not constraining the geometry of the system, a property necessary for the simulations of interacting and merging systems described in the next section. The fact that the same method was used to follow the evolution of both isolated and interacting systems allows us to make comparisons between the two. Similar results, but using cartesian or polar grid methods, have been presented at this meeting by R. Fux & D. Friedli and by V. Debattista & J. Sellwood (these proceedings).

In this project, carried out in collaboration with Mattias Wahde, two types of model galaxies have been considered. In the first one (hereafter KTP) 120,000 particles have been used to represent a Kuzmin-Toomre disk and a Plummer halo. The slowdown of the bar was found to be a linear function of time and in a characteristic example corresponds roughly to $\Delta\Omega/\Omega_{init} = -0.3$ in 21 initial bar rotations. When the halo particles were given a forward rotating motion the pattern speed decreased slower, the opposite being true when the halo particles were given a retrograde motion, in good agreement with a straightforward application of Chandrasekhar's formula, but in disagreement with the predictions of Weinberg (1985).

In the second type of model a halo which follows a lowered Evans model (Evans 1993, Kuijken & Dubinski 1994) and an exponential disk were modelled by 180,000 particles. In these models the disk was dominated by the halo at all radii, so the bar took longer to form. As shown for one example in Figure 1 the slowdown is not linear, but rather faster initially and decreasing with time; overall, the pattern speed decreases by $\Delta\Omega/\Omega_{init} = -0.6$ in roughly 46 initial bar rotations. These models confirmed the effect of halo rotation found for KTP models.

Thus the bar slowdown found in our models is of the same order as that found by Combes et al. (1990) and Little & Carlberg (1991), but is considerably less than that found by Weinberg (1985) and Hernquist & Weinberg (1992). Nevertheless it corresponds to a substantial increase of the Lagrangian or corotation radius (r_L). Thus our next step should be to measure the evolution of the bar length (a) and of the ratio r_L/a in order to compare it with observational determinations of the same quantity.

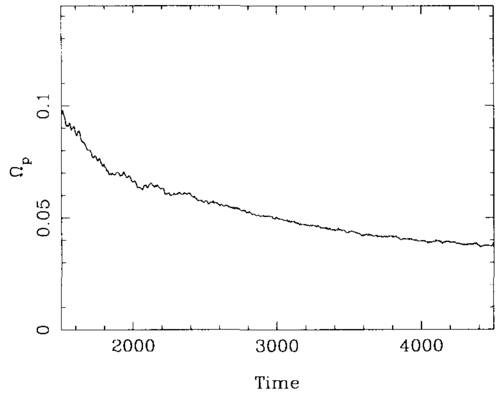

Figure 1. Decrease of the bar pattern speed as a function of time.

3. Evolution of Bars in Interacting or Merging Disk Galaxies

In all simulations described in this section the target galaxy is the KTP model of the previous section and the companion is a Plummer sphere. Over 100 simulations were made using 40,000 particles to model the primary, and the most interesting ones were repeated using 120,000 particles. Three companions have been considered:

- Companion No. 1 is light ($M_c/M_d = 0.1$, or $M_c/M_g = 0.035$, where M_c is the mass of the companion, M_d the mass of the disk and M_g the total mass of the target galaxy) and fluffy
- Companion No. 2 is equally light, but more compact
- Companion No. 3 is more massive ($M_c/M_g = 0.1$), with an intermediate central concentration

Several orbits were considered in all cases. Depending on the companion and orbit chosen, the effect of the companion could be:

- little or none
- complete destruction of the bar
- formation of an offcentered bar
- the possible formation of a lens
- the possible formation of a ring
- the possible formation of a bulge

For lack of space I will discuss here only a few of these possibilities.

https://doi.org/10.1017/S0252921100049940 Published online by Cambridge University Press

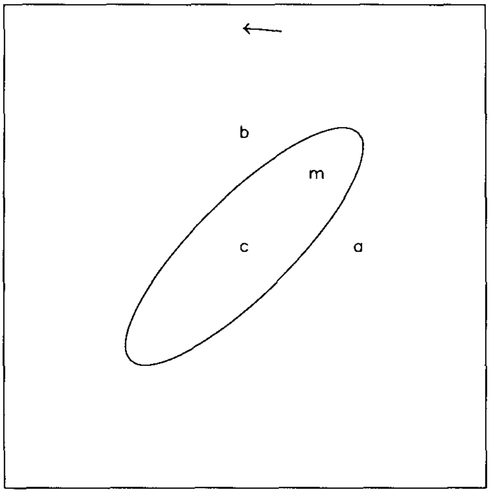

Figure 2. Schematic distinction between four types of impacts, after the bar (**a**), before it (**b**), at its center (**c**), or on its major axis (**m**).

3.1. Passages of the Companion through the Target Disk

Let us start with the results of a small survey including 28 simulations. The perturber was initially located outside the target's halo and its initial velocity was perpendicular to the plane of the disk with an amplitude between 0.5 and 1.2 times the escape velocity v_{esc}. Depending on the position of the impact point with respect to the bar I distinguish impacts "before" the bar (schematically shown by point **b** on Figure 2), "after" it (point **a**), impacts at the "center" (point **c**), or on the "major axis" (point **m**). Before discussing the results of these impacts on the target, I will describe the fate of the companion.

Fate of the Companion The fate of the companion depends to a large extent on whether it is bound to the target galaxy or not. Thus one can distinguish two cases, one in which the initial velocity of the companion is above a value roughly equal to the escape velocity, and one in which it is below it. Of course a more precise division should take into account not only the amplitude of the initial velocity but also the orbit within the target, since a companion can lose kinetic energy by dynamical friction and become bound, but such a fine distinction is beyond the scope of my small sample.

If companion No. 1 (light and fluffy) has an initial velocity less than the escape velocity, then it survives two passages through the disk and ends up as unbound debris, for all except central passages. Such passages cause greater damage to the companion because of the higher density of the disk at the first impact position, and the companion turns into debris already after the first passage.

https://doi.org/10.1017/S0252921100049940 Published online by Cambridge University Press

If companion No. 2 (light and compact) has a velocity less than the escape velocity, then it stays bound, and falls to the center of the target galaxy after having lost 5%-7% of its mass. Finally, if companion No. 3 has an initial velocity less than the escape velocity, then it will encounter the same fate as companion No. 2, but after having lost 20-25% of its mass. In such cases the companion could contribute to the buildup of a bulge component. Of course the percentage of its mass which can contribute to this will depend on its orbit.

If the companion has an initial velocity sufficiently larger than the escape velocity then it escapes, having lost some of its mass, the amount depending on the type of the companion and on its orbit.

Change of Pattern Speed As discussed in the previous section the pattern speed of a bar evolving in an isolated disk decreases with time. The passage of the companion provokes an additional change, which we can measure by continuing the simulations of both isolated and interacting cases for some time after the impact and finding the average difference between the pattern speeds during this time. Unfortunately not all our simulations are fully reduced. Nevertheless, the simulations we have give us a number of interesting results.

The change of the pattern speed depends on the companion's orbit, and in particular on where the impact takes place with respect to the bar, as well as on its mass and central concentration. More centrally concentrated, or more massive companions cause bigger effects. In all cases where an important abrupt change of the pattern speed is noted, the bar is slowed down by the interaction and never speeded up. Changes in pattern speed during interactions have also been measured by Sundin, Donner & Sundelius (1993) who, for 2D simulations of interactions at a distance of a rigid perturber with a disk galaxy, found that for relatively low perturber masses the bar is always slowed down, while for higher masses it can be either slowed down or accelerated.

This change of the pattern speed is accompanied by a corresponding change in the bar amplitude, which, in all cases analyzed so far, was a decrease. The passage through the disk also produces a thickening, which is important in the cases where the amplitude of the bar drops severely. We will have to analyze more of our simulations to see whether it is possible to destroy the bar by such passages, while keeping the disk thin.

3.2. Asymmetries

Offcentered bars, i.e. bars whose center does not coincide with the center of the disk, are not rare, particularly amongst late type galaxies (de Vaucouleurs & Freeman 1972; Odewahn, these proceedings). Although several studies have concentrated on the effects of these asymmetries on the driven spiral structure and on the velocity fields (e.g. Marcelin & Athanassoula 1982, Colin & Athanassoula 1989) very little is known about their origin. Amongst the cases described above there were several examples in which the companion hit on or near the bar and displaced it. One of them, resulting from the impact of a massive companion (No. 3) at a position of the disk similar to that labelled **a** in Figure 2, is represented in Figure 3. The spiral structure in this case is also very asymmetric, with one long spiral arm dominating the morphology, in good agreement with what is observed in several late type galaxies with offset bars.

https://doi.org/10.1017/S0252921100049940 Published online by Cambridge University Press

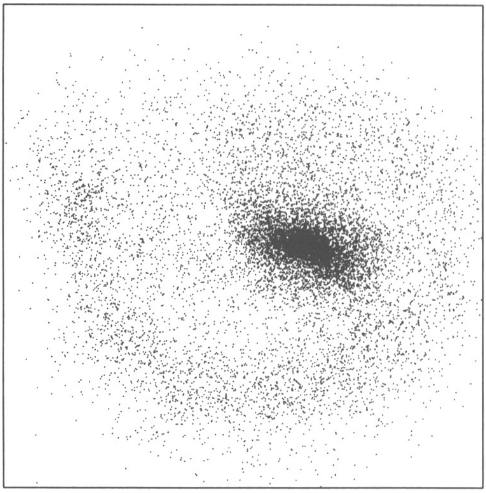

Figure 3. Offcentered bar with an asymmetric spiral structure, resulting from the impact of a massive companion (No. 3) at a position similar to that labelled **a** in Figure 2.

3.3. Destruction of the Bar and Possible Formation of a Lens

In several simulations the interaction led to a total destruction of the bar. The end result of one of these is given in Figure 4. The initial conditions were such that the target galaxy was barred, and the companion was small but rather compact (No. 2) and was placed initially outside the target's halo, on a near-circular orbit in the plane of the disk. The companion spiraled inwards towards the center of the target, its radius decreasing initially slowly, and then faster as it encountered higher density regions of the target. It reached the center having lost less than 10% of its mass and resulted in an important increase of the total central concentration. The destruction of the bar took place rather abruptly around the time the companion reached the center. After that the configuration stayed as in Figure 4, the bar having evolved into a roughly axisymmetric central object, somewhat thicker than the outer disk, but in no way thick enough to be comparable to a bulge. From its size and shape one is tempted to compare it to a lens, although further work, in particular concerning its radial density profile and the possible existence of an edge, is needed to substantiate this hypothesis. Further work is also needed to establish what type of orbits can destroy bars while preserving the disk structure.

4. A Possible Evolution Scenario for NGC 7217

NGC 7217 is an Sb galaxy with three rings: a very conspicuous outer ring, an inner ring, and a nuclear ring clearly seen in Hα. HI is mainly concentrated around the outer ring. From the observed rotation curve Verdes-Montenegro,

https://doi.org/10.1017/S0252921100049940 Published online by Cambridge University Press

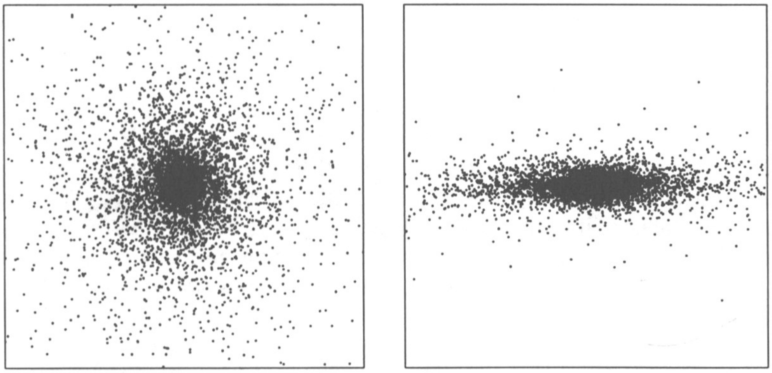

Figure 4. Final stages of a merging between a small companion and an initially barred galaxy. The left panel is the face-on view of the disk, and shows the total demise of the bar. The right panel is the edge-on view, showing that the companion has not unduly thickened the disk.

Bosma, & Athanassoula (1995, hereafter VBA) obtained $\Omega = \Omega(r)$ and $\kappa = \kappa(r)$, and thus found that, if the outer ring is placed at the outer Lindblad resonance, the inner ring should be at the inner ultraharmonic resonance and the nuclear ring at the inner Lindblad resonance. This is actually the standard configuration for the ring positions in barred galaxies (Schwarz 1981, Athanassoula et al. 1982, Buta 1995). NGC 7217, however, is not barred. With the help of *BVRI* photometry VBA found that there is no bar in the inner parts of this galaxy, where, at best, only a very mild oval could be hidden. Similar results were found by Buta et al. (1995), whose simulations of the response of gas clouds, modelled as sticky particles, showed that the response to such a potential is mainly around the inner ring and cannot create a conspicuous outer ring, where most of the gas is concentrated, as is observed in NGC 7217.

Unless H or K photometry reveals a bar totally undetected in I, one has to worry about the origin of the rings and the agent that set the pattern speed for the resonant positions. One possibility is that NGC 7217 had at some point a bar, which formed the rings, and was then destroyed. How viable is such a scenario?

The decay and even total disappearance of a bar can be achieved in at least two different ways. Accumulation of a sizeable amount of mass in the central regions of the galaxy (e.g. by gas inflow) leads to bar destruction (Norman, May & van Albada 1985; Hasan & Norman 1990; Hasan, Pfenniger & Norman 1993; Friedli & Benz 1993; Friedli 1994; Sellwood, these proceedings). An alternative way of destroying a bar is via a strong interaction, as discussed in the previous section.

Will the rings survive after the bar has disappeared? Although not a substitute for a fully self-consistent simulation, the response of gas clouds to a decaying bar can give some insight. Figure 5 shows the result of such a simulation in which, following Schwarz (1981), the gas clouds have been modelled by sticky particles, initially homogeneously distributed in an infinitesimally thin disk. The bar is the same as that used by Schwarz (1981) and is turned on in two bar rotations. As expected (Schwarz 1981) the gas clouds first concentrate in spiral arms and at somewhat later stages of the evolution an outer ring is formed. After 11 bar revolutions the bar is switched off in one rotation period, and the simulation is continued for another 21 rotations of the previously existing bar. With the bar decay the last remnants of the spiral disappear quickly, but the ring remains, its only evolution being that it becomes more circular and thicker. The reason is that the gas clouds in the ring had settled before the bar decay on periodic orbits at the outer Lindblad resonance and after the decay stay there, except for a slow diffusion, which accounts for the thickening of the ring. Since the gaseous ring in NGC 7217 is quite broad, even relatively late stages of the evolution of this simulation are compatible with the morphology of the galaxy, thus showing that a gaseous outer ring could survive the death of the bar by 12 revolutions or more. Of course this simple experiment is not relevant if the bar was destroyed by a strong interaction, since then a more elaborate modelling, including the companion, would be necessary.

There is one more important observational fact to be tied in with this scenario, namely that, as found by Merrifield & Kuijken (1994), NGC 7217 has a substantial percentage of stars on retrograde orbits. Neglecting for the moment the possible effect of a companion, then one may get some insight on the origin of the retrograde orbits with the help of a thought experiment, initially proposed by Lynden-Bell (1978), and later used by Evans & Collett (1994). Consider a pendulum in the presence of gravity. There are two types of orbits: librating, for which the energy allows only a libration around the point of minimum energy; and rotating orbits, which will make complete circles. Now if the gravity was switched off all orbits would become rotating. Depending on the sense of their motion at the time gravity is switched off, these librating orbits will become direct or retrograde rotating orbits. This analogy can be applied to barred galaxies by linking the orbits of the pendulum with the orbits of stars in the galaxy, gravity with the gravitational potential due to the bar, orbits which were initially rotating with loop orbits, and orbits which were initially librating with stochastic orbits. Thus, as the bar potential decays, the loop orbits will continue being loops and keep their sense of rotation, while stochastic orbits will turn also into loop orbits, their sense of rotation depending on the sense of the stochastic orbit during the decay. To substantiate somewhat this thought experiment, I considered a number of orbits in the potential of a barred galaxy and decreased the amplitude of the bar in a certain time interval. The orbits that were retrograde after the demise of the bar were originally either retrograde loops or chaotic in the bar potential. Will there be enough such orbits to account for the percentage found in NGC 7217? This will of course depend on the orbital structure in the bar potential, and in particular on the percentage of stochastic orbits, about which very little is known. Some information can be obtained from Schwarzschild-type orbital analyses (e.g. Pfenniger 1984, 1985), but it is not possible to answer this question fully without self-consistent simulations.

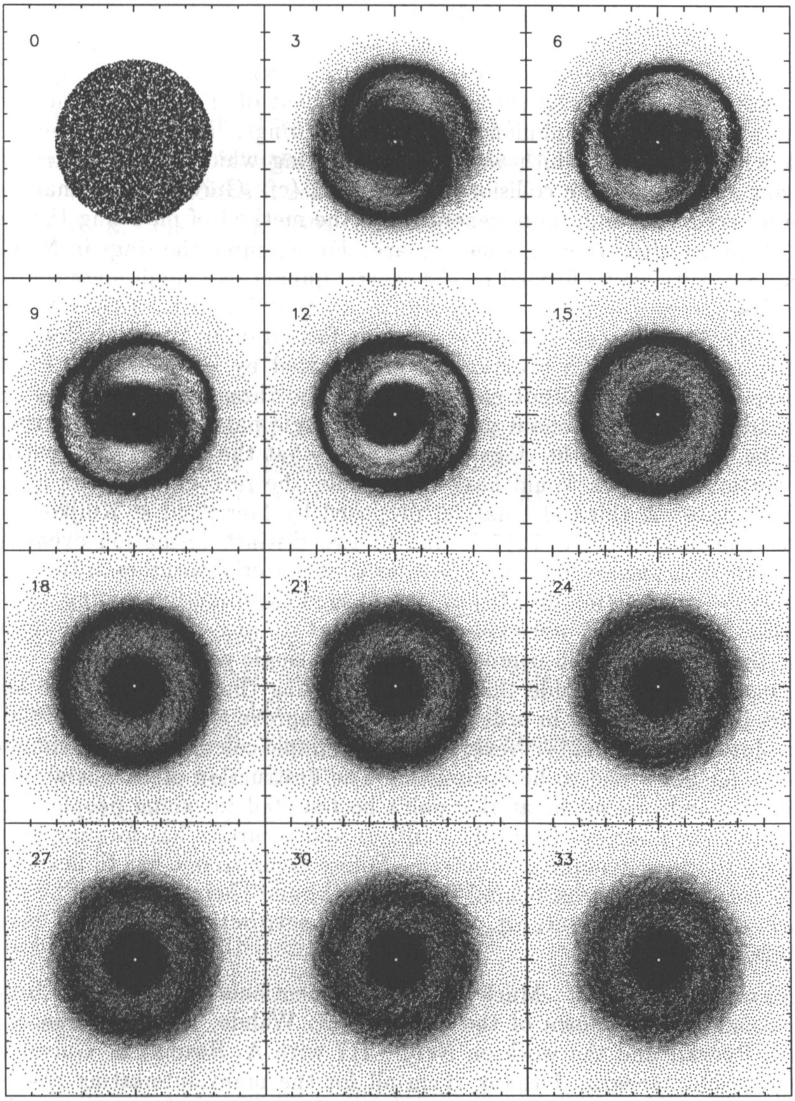

Figure 5. Formation and evolution of a ring in an initially barred potential. Time, measured in units of bar rotation periods, is given in the upper left of each panel. The bar starts decaying at t=11, and has completely disappeared by t=12, while the ring remains for a much longer time.

In the case where a companion triggered the bar decay, the problem becomes more complicated, as one has to include the force from the companion. However some of my fully self-consistent simulations mentioned in the previous section do show after the demise of the bar a substantial fraction of retrograde orbits.

A lot of work is still needed if this scenario is to become a model. For example one has to check whether the amount and radial distribution of retrograde orbits are as observed. One also has to check whether and in what way the cause of the bar decay (be it an enhancement of the central concentration or the passage of a companion) influences the rings. Furthermore one should check whether and in which way the time during which the ring survives the collision depends on the collision scheme used (cf. Guivarch & Athanassoula, these proceedings) and, more generally, on the method of modeling the gas.

There are also other possible scenarii. For example the rings in NGC 7217 could be density waves formed by the central impact of a small mass companion on a non-barred galaxy, in a way similar to that found by Lynds & Toomre (1976), Theys & Spiegel (1977), etc for the formation of ring galaxies by more massive intruders. Such events were investigated by Athanassoula & Puerari (in preparation), but do not guarantee that the three rings will form at radii compatible with the resonant positions of a single pattern speed. Furthermore from the symmetry of the rings one can infer that the impact was central and near-vertical, and one would have to consider the retrograde orbits as due to another cause. A third alternative, proposed by Merrifield & Kuijken (1994), is that the disk of NGC 7217 is due to two distinct formation events. The retrograde disk formed first and at a later time material rotating in the opposite sense to the pre-existing disk fell in, and formed the directly rotating disk. This scenario, however, does not explain, at least at its present state, the formation of the three rings at radii compatible with one single pattern speed.

One can thus conclude this section by saying that a considerable amount of work is still necessary in order to prove or disprove the scenario I propose for the evolution of NGC 7217. Nevertheless the simple calculations and simulations made so far allow one to be optimistic. The destruction of bars is an exciting possibility, and one might at this point be tempted (as some people did after my talk at the meeting) to invoke multiple and recursive bar-forming events as solutions to other dynamical problems. Before doing so one has to bear in mind that a decayed bar leaves behind it a hot disk, and therefore it will be difficult to form a new bar without, e.g., a substantial contribution of new cold material, like infalling gas.

Acknowledgments. Much of the work mentioned above results from collaboration: the slowdown of the bar with M. Wahde, the formation of rings with I. Puerari and the work on NGC 7217 with A. Bosma, B. Guivarch and L. Verdes-Montenegro. I thank them all for the many interesting discussions we have had on these topics. Thanks also to Jean-Charles Lambert for his help with the GRAPE simulation and analysis software and to B. Guivarch for his help with Figure 5. I would like to thank the INSU/CNRS and the University Aix-Marseille I for funds to develop our GRAPE facility.

References

Athanassoula, E., Bosma, A., Crézé, M., & Schwarz, M. P. 1982, A&A, 107, 101

Buta, R. 1995, ApJS, 96, 39

Buta, R., van Driel, W., Braine, J., Combes, F., Wakamatsu, K., Sofue, Y., & Tomita, A. 1995, ApJ, 450, 593

Colin, J. & Athanassoula, E. 1989, A&A, 214, 99

Combes, F., Debbasch, F., Friedli, D. & Pfenniger, D. 1990, A&A, 233, 82

de Vaucouleurs, G. & Freeman, K. C. 1973, Vistas in Astron., 14, 163

Evans, N. W. 1993, MNRAS, 260, 191

Evans, N. W. & Collett J. L. 1994, ApJ, 420, L67

Friedli, D. 1994 in Mass-Transfer Induced Activity in Galaxies, I. Shlosman, Cambridge: Cambridge University Press, 268

Friedli, D. & Benz, W. 1993, A&A, 268, 65

Hasan, H. & Norman, C. 1990, ApJ, 361, 69

Hasan, H., Pfenniger, D., & Norman, C. 1993, ApJ, 409, 91

Hernquist, L. & Weinberg, M. D. 1992, ApJ, 400, 80

Kuijken, K. & Dubinski, J. 1994, MNRAS, 269, 13

Little, B. & Carlberg, R. G. 1991, MNRAS, 250, 161

Lynden-Bell, D. 1978, Observatory 98, 64

Lynds, R. & Toomre, A. 1976, ApJ, 209, 382

Marcelin, M. & Athanassoula, E. 1982, A&A, 105, 76

Merrifield, M. R. & Kuijken, K. 1994, ApJ, 432, 575

Norman, C., May, A., & van Albada, T. S. 1985, ApJ, 296, 20

Pfenniger, D. 1984, A&A, 141, 171

Pfenniger, D. 1985, Ph. D. Thesis, Université de Genève

Schwarz, M. P. 1981, ApJ, 247, 77

Sundin, M., Donner, K. J., & Sundelius, B. 1993, A&A, 280, 105

Theys, J. C. & Spiegel, E. A. 1977, ApJ, 212, 616

Verdes-Montenegro, L., Bosma, A., & Athanassoula, E. 1995, A&A, 300, 65 (VBA)

Weinberg, M. D. 1985, MNRAS, 213, 451

Discussion

J. Palouš: In NGC 7217, what is the degree of symmetry? According to our simulations a very small deviation from symmetry (less than or of the order of 1% in density) is sufficient for multiple ring generation.

E. Athanassoula : Buta et al. (1995) made simulations of the response of gas clouds, modelled as sticky particles, to the potential of NGC 7217. The simulation which "provides the closest approximation to the observed structure of NGC 7217" is given in their Figure 31. It gives an enhancement of the gas density at the location of the nuclear and the inner ring, but very little at the position of the outer ring, where most of the gas in the real galaxy is concentrated.

G. Galletta: I find your explanation of counter-rotation in NGC 7217 very interesting and wonder whether it could also be applied to NGC 4550 which has 50% of stars in counterrotation. It is an edge-on S0 with a companion.

E. Athanassoula : So far the above proposal is a scenario and not a model. In particular I have no quantitative estimate of how much counter-rotation one can get out of a decaying bar. Nevertheless, 50% might be asking too much.

A. Zasov: NGC 7217 is the galaxy where we were able to find a small nuclear bar by kinematical method (cf. my talk in these proceedings). A question arises: can't it be a remnant of the dissolved bar?

E. Athanassoula : It could well be.

R. Buta: I and several other co-workers recently completed a detailed independent study of NGC 7217 (Buta et al. 1995). We found a large stellar halo extending well beyond the outer ring. A bulge/disk decomposition suggested that this is a spheroid dominated galaxy, where the spheroid/disk luminosity ratio is 2.5. Could this explain the retrograde population?

E. Athanassoula : It could perhaps explain some of it, but Merrifield and Kuijken find that the retrograde part does not come from the wing of a hot component, but is rather a distinct component.

M. Merrifield: Our kinematic observations indeed show that there is a distinct peak in the velocity distribution at the negative circular speed, implying a counter-rotating stellar population. This observation is not consistent with a bulge-dominated galaxy, but is it consistent with the scenario you have described?

E. Athanassoula : As you said yourself, it is just a scenario, so I cannot give a definite answer. However my impression is that the orbits that were ergodic in the bar potential, will, after the demise of the bar, give two distinct components, one on the directly rotating side and one on the retrograde side. To these of course you should add the component due to the initially loop orbits, as well as any possible contribution from pre-existing retrograde orbits (trapped around the x_4 family in the bar potential), so the whole picture is rather complicated, and even more so if the bar disappeared due to a strong interaction.

https://doi.org/10.1017/S0252921100049940 Published online by Cambridge University Press