FORMATION OF RINGS AND LENSES

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1. RINGS

Both inner rings and outer rings are frequently observed in disk galaxies (de Vaucouleurs, 1963 and 1975). As an example, Fig. 1 shows NGC 2217 in which both occur. Further examples, e.g. NGC 2859 and NGC 3081, can be found in the Hubble Atlas (Sandage, 1961), the Revised Shapley Ames Catalogue (Sandage and Tammann, 1981), and in the morphological study of nearby barred spirals by Kormendy (1979). In this talk I will concentrate on some theoretical questions concerning rings, and in particular on their formation.

Schwarz (1979, 1981) studied the response of a gaseous disk to a rotating bar potential. He models the gas by "clouds" which can collide inelastically, thereby losing an important fraction of their relative motions. A spiral is formed which extends roughly from corotation (hereafter CR) to the outer Lindblad resonance (OLR). Due to the torque exerted by the bar, this spiral evolves into a ring at the OLR. Schwarz associates this kind of ring with the outer rings frequently observed in external galaxies. Depending on the value of the pattern speed used in the calculations, a second ring was sometimes formed. This occured near the ultra harmonic resonance (UHR) where $\Omega_p = \Omega - \kappa/4$, and/or the inner Lindblad resonance (ILR). Schwarz associated these rings with the observed inner rings.

The problem with Schwarz's calculations is that the time scale for ring formation is very short. Indeed, the rings form in just a few bar rotations, yet a large percentage of observed galaxies do not have rings. Schwarz proposed three possible ways out, favouring the third one :

a. The mass distribution in his model bar differs from that in real galaxies
b. The cloud collisions have not been correctly modelled
c. The gas between CR and OLR is replenished by mass loss from stars or by infall.

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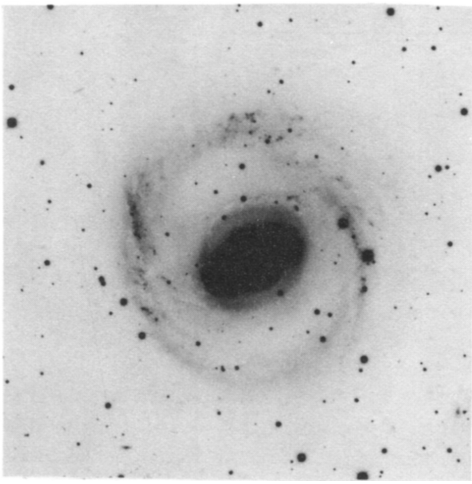
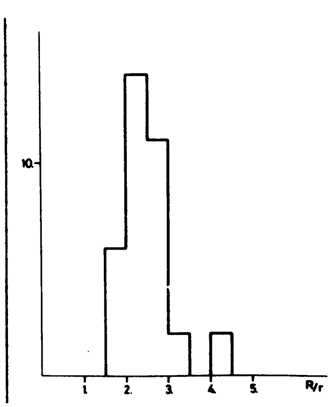


Figure 1. NGC 2217 (Prime focus, CFHT 3.6 m by Athanassoula and Bosma)

One of the virtues of Schwarz's model is the definite prediction that rings will form at resonances. Athanassoula et al. (1982, hereafter ABCS) tested this prediction by analyzing data on the sizes of rings and lenses as given in the catalogue of de Vaucouleurs and Buta (1980) for 532 galaxies. For galaxies having both outer and inner rings,the ratio of the two sizes, R/r, was formed and histograms were made of the R/r frequency distribution for both barred and non-barred galaxies, as shown in Fig. 2. Clearly the two histograms are very different. The barred galaxies have a peak around R/r = 2.2, while the non-barred galaxies have a rather flat distribution. The form of the barred spiral histogram can be explained (cf ABCS) if outer rings form near the OLR and inner rings near the CR or the UHR. Thus, this statistical analysis agrees nicely with Schwarz's prediction.

Two further points can be made here. First, rings in barred spirals seem to avoid the ILR (at least the regular inner and outer rings ; nuclear rings are not discussed here). Since Schwarz claims he found rings at the ILR in his models, maybe the existence of this resonance should be



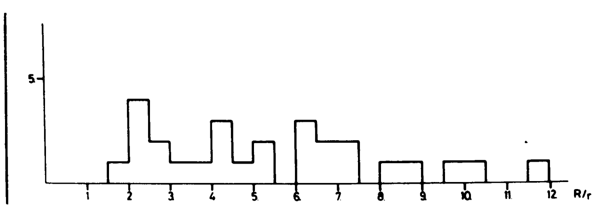


Figure 2. Histograms of the ratios of the outer ring to inner ring major diameters for barred galaxies (left) and non-barred galaxies (above).

questioned (see also Van Albada and Sanders, 1982). Second, rough knowledge of the rotation curve at the distance of the outer ring and of its diameter allows calculation of the pattern speed in barred galaxies with outer rings. Inner rings are less useful in this case since at that distance the velocity field can be highly perturbed by the bar.

The form of the histogram for SA galaxies is more difficult to explain. One possibility is that rings in SA's are not associated with resonances. However this is hard to accept in view of the continuity of some of the properties along the "families" SB-SAB-SA. Furthermore, Schwarz showed that a non-barred, but spiral forcing was as efficient in forming rings, which were again associated with resonances. An alternative explanation is that in SA galaxies more resonances come into play. In the histogram of R/r we would then have a superposition of several peaks which, together with the small numbers involved, leads to the observed flat distribution. The question remains then, why we don't observe SA galaxies with three large rings.

In Schwarz's models, the orbits between CR and OLR are unstable and their eccentricity increases with time. A similar result, for a different form of the potential, was stressed by Contopoulos and Papayannopoulos (1980). They found that the main families of periodic orbits for strong bars are unstable between CR and OLR, but stable around the OLR. This behaviour, they conclude, explains the appearance of rings ; the instability of the main periodic orbits between CR and OLR leads to a depletion of that region while the stable orbits around OLR trap quasi-periodic orbits around them (e.g. Arnold and Avez 1967). Nevertheless they correctly note that only knowledge of the distribution function i.e. of the number of particles following a given orbit can definitely settle the question.

However, the main families of periodic orbits between CR and OLR are not unstable in every model of a barred galaxy. A counterexample has been discussed by Athanassoula et al. (this volume and 1982), who used a nonhomogeneous prolate spheroid to model the bar, and a power law rotation curve to model the axisymmetric background. They found that if the length of the bar equals the corotation radius (CR as defined by the axisymmetric background), the main families of periodic orbits between CR and OLR are stable for reasonable values of bar eccentricity and of ratio of bar to disk mass. They are followed by regular invariant curves on all surfaces of section. The way to introduce stochasticity (i.e. unstable orbits) in this model is to allow the bar to extend beyond corotation.

Thus, depending on how mass is distributed between the axisymmetric background and the bar, the models may have stable or unstable periodic orbits between CR and OLR. It then becomes crucial to know what the relevant mass distributions in real barred galaxies are, and whether they differ in galaxies with rings and without rings. Rather than exploring all the theoretical possibilities, it seems more sensible to turn to observations. With this aim in mind, Athanassoula and Bosma (1982) have taken a number of plates of galaxies with bars or ovals, with and without rings. From the light distribution and various assumptions about the M/L ratios, they plan to derive the potential function of the bar in the galaxy plane. A calculation of the main families of periodic orbits or, better still, of the gas response to these potentials should shed more light on the ring formation process.

2. LENSES

A lens is a shelf in the luminosity distribution of a galaxy occuring between the bulge and the disk. A typical example is NGC 1553 (Freeman, 1975). Further examples (e.g. NGC 3245, NGC 4150, NGC 4262, etc) can be found in the Hubble Atlas (Sandage, 1961) and the Revised Shapley-Ames Catalogue (Sandage and Tammann, 1981).

Kormendy (1981) would like to further subdivide objects fitting the above description and distinguish between those located in early type galaxies (SO to Sa), which he calls lenses, and those located in later types (Sb to Sm), which he calls ovals. This distinction would, according to Kormendy , be based on their different kinematical properties. I believe that further work is needed to show whether such a distinction is real and necessary. I will thus, for the purposes of this review, not distinguish between the two, but use the terms lenses and ovals alternatively.

The ABCS statistical study showed that lenses have axial ratios between 0.5 and 1. Hence an important fraction of them are eccentric enough to have sizeable nonaxisymmetric forces, thus qualitatively resembling bars. There are further links or similarities between bars and lenses. Kormendy (1979) has noted that for galaxies with both a bar and a lens, the major axes of the two components have the same length and position angle (hereafter PA) in 17 out of 21 cases he studied. This he terms, "the bar fills the lens in one dimension". Furthermore, for NGC 5383, the only galaxy with both a bar and a lens for which a M/L estimate is available for both components (Duval and Athanassoula, 1982 and this volume),the values were found to be the same within 30 %. This argues for similar stellar populations in the two components and a common origin or link in their formation.

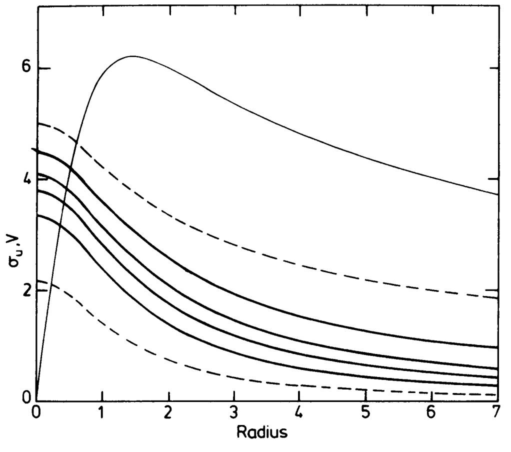
The following scenarios have been put forward for the formation of lenses : Bosma (this volume) thinks that lenses are primary components, formed as part of the disk formation process. The outer edge formed where the initial gas density dropped low enough so that star formation stopped abruptly. This process would then account for all sharp outer edges in lenses and disks.

According to Kormendy (1979, 1981) lenses are secondary components formed by secular evolution of a bar to a more axisymmetric state. This could be due to the interaction of the stars in the bar with a very rapidly rotation bulge.

Let me put forward here yet a third scenario. According to it, lenses like bars, are due to instabilities of galactic disks. The difference in eccentricity between the two components is due to the different amounts of random motions initially present in the disk, i.e. the different initial distribution functions.

This hypothesis is based on the results of numerical simulations (Athanassoula and Sellwood, this volume). We studied the effects of velocity dispersions on the stability of galactic disks. The aim was to find out whether, and if so by how much, velocity dispersions reduce the growth rate of the bar instability and whether disk stability could be reached with little or no help from a halo. The initial mass distribution was identical for all runs, namely a Toomre n = 1 disk (Toomre, 1963). The initial velocities of the 40.000 particles used in the simulations were taken according to distribution functions calculated analytically. Starting therefore from initial conditions that are stationary solutions of the Boltzmann equation, i.e. much closer to equilibrium than is usually done with other starting conditions, we have less reason to fear that imprecise initial conditions provoke bar instability. We let the runs evolve and the stellar density distribution change shape due to the bar instability. A bar or oval was invariably the end product of the evolution. Its shape however, differed systematically from one simulation to the next depending on the velocity dispersion in the initial distribution function.

Let me first discuss the results of four simulations whose radial velocity dispersions, $\sigma_u(r)$ are given by full curves in Fig.3. The particular set of distribution functions were taken from Kalnajs (1976). A quantitative measure of the resulting bars or ovals was obtained by fitting ellipses to the isodensity contours in the bar using a software package by M. Cawson (1982). The ellipses approximate the isodensity contours very well in the bar region in nearly all cases, while their eccentricity changed little with radius. Only when we used the coolest of the four distribution functions were the isodensity contours somewhat box shaped and the eccentricity of the best fitting ellipse less representative. In Fig. 4. we plot the mean eccentricity of the bar isodensities, 1 - b/a with b and a the minor and major axes of the bar or oval, as function of the mean mass averaged Q (i.e. the ratio of actual dispersion to what is required to prevent axisymmetric instabilities, cf. Toomre, 1964) in the initial disk. A very clear trend shows up in the sense that initially colder disks evolve into thin bars, and initially hotter disks evolve into fatter ovals. Other series of runs confirm this trend. We make here the comparisons in terms of the dimensionless parameter mean Q rather than in σ_u, although the latter might be more appropriate in case initially different mass distributions are to be compared. We also used the dispersion of velocities in the initial distribution functions, since, after the bars or ovals have formed, all quantities depend on the angle as well as the radius, thus making comparisons more difficult and less meaningful. Note that the differences between the dispersions of velocities of the four models are largely reduced as the runs evolve, since the initially cooler models heat up more than do the initially hotter ones. However a detailed comparison is too lengthy to be included here.



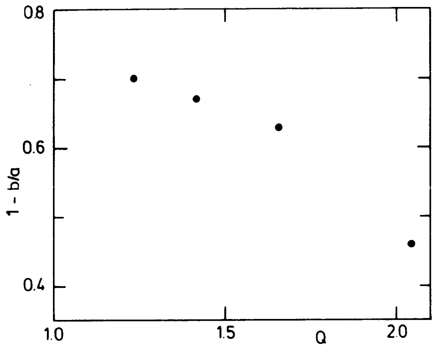


Figure 3. Velocity dispersions (thick and dotted lines) and circular velocity (thin lines)

Figure 4. Mean eccentricity of the bar isodensities as a function of the mean mass averaged Q.

One of the previous runs was analysed by dividing stars into two groups : the hottest half and the coldest half. At the beginning of the simulation all stars at a given energy were divided into two halves i.e. those with the largest angular momentum and those with the smallest. Since we tagged each star, we could follow the evolution of each group separately, and found that the above trend still applied very well ; that is, the coldest half had isodensities well approximated by eccentric ellipses, and the hottest half had near circular isodensity contours. Furthermore the PA of the major axes coincided to within the (small) measuring errors.

We also studied the evolution of disks in which two populations were initially present, each with its own distribution function f(E,J). Several such cases were run, all leading to similar conclusions, so we will only present one example here. In this particular run, 50 % of the stars followed a cool distribution function and 50 % followed a hot one. Their corresponding radial velocity dispersions are given by the dotted curves in Fig. 3. As expected the hotter population formed a near circular oval, while the cooler one evolved into a much narrower bar. The ellipses fitted to the isodensity contours are given in Figure 5. The PA and, to the extent they could be defined, the lengths of the major axes of the two components are the same.

The basic trend which can be observed from these runs is that the final ellipticity of the bar or oval depends on how hot the initial distribution function was. Cool systems make thin bars while hot systems make fat ovals.

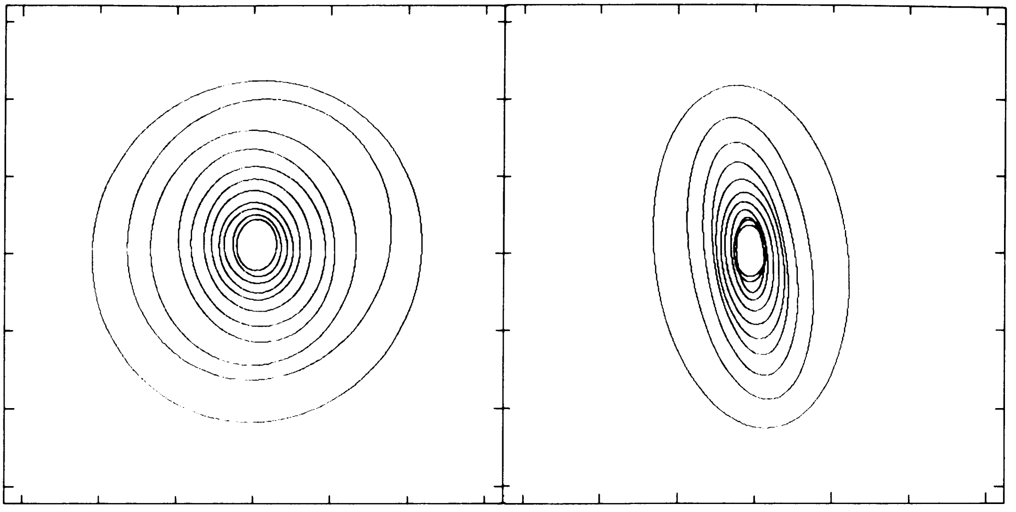


Figure 5

These results may well be relevant to the formation of lenses. Indeed if lenses are so similar to bars, the main difference being their shape, it may well be that their formation process is the same, i.e., that they are both due to an instability of the galactic disk. The differences in shape would then be due to the different amount of random motions initially present in the disk. In cases where, for whatever reason, two distinct populations were present, the coolest one would form a bar and the hottest one a lens, the major axes of both components having the same PA and approximately the same length in agreement with Kormendy's maxim. Furthermore the velocity dispersions in our models are in the same range as those borne out by the observations of Kormendy (1981) and Bosma and Freeman (1982).

Several interesting questions arise if lenses are indeed as hot as suggested by the observations (Kormendy, 1981) and our scenario. In particular, the coexistence of a relatively sharp edge and large velocity dispersions (which do not necessarily extend out to the edge) has to be investigated further. Some lenses seem to be devoid of structure while disks with sharp edges might be prone to unstable edge modes (Toomre, 1981). However, a detailed study of the influence of sharpness and velocity dispersion at the edge on the occurence of edge instabilities has not been done yet. Finally, lenses, and bars also, are thin in the z direction (Tsikoudi, 1980, Burstein, 1979), while being hot in the plane. Such large anisotropies in the velocity distribution pose another interesting theoretical problem.

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DISCUSSION

SANDAGE : It is true that the galaxies NGC 2217, NGC 5101, NGC 5566, and other similar early type Sa galaxies that you showed at the beginning have very large external "near" rings of star formation. Yet these structures are not true rings. They are segments of spiral arms (m = 2) very tightly wound, but clearly separated from each other after each winding of ∿ 180°. The same happens in the well-known Sa galaxy NGC 3185 where, on low resolution plates a completed ring is strongly suggested, yet the structure is, in fact, two spiral segments. This feature, present in a subset of ∿ 30 Shapley-Ames early Sa galaxies resembles Schwarz's Figure in the lower right of this diagram which you showed. (See Ap.J. 247,77, Figure 10).

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The question is : what happens much later in the Schwarz sequence as time proceeds ? Can a true closed ring be formed of old stars such as in NGC 2859 or NGC 4736 ? Invariably, when these true closed rings are seen, and there are some even in Shapley-Ames galaxies, they have red colors and a very smooth intensity distribution, indicating stellar ages of at least 10^9 years.
If, then, your answer is yes, are there later "Schwarz true ring" forms stable for 5 to 10 orbital periods ?

KENNICUTT : The models discussed here can account for the narrow gaseous rings seen in the outer parts of galaxies, but many galaxies seem to possess very broad stellar rings, extending over many kpc in radius, and occuring in both barred (NGC 3945) and non-barred systems (NGC 4736). Do you think that this latter type of ring is a distinct phenomenon dynamically, or do you think that these models can provide insights into them as well ?

ATHANASSOULA (to both SANDAGE and KENNICUTT) : In the evolutionary sequence I showed (Figure 10 of Schwarz 1981), only the gaseous component feels the bar and responds to it. The response is initially a two-armed spiral. During the evolution there is an outward flux of particles from the region between CR and OLR to the OLR. Thus this region is depleted and the response becomes more ring-like and less spiral-like with time. Exactly where one should draw the line between the two, I don't know. The gas particles will follow more and more closely a small range of periodic orbits around the OLR. Thus collisions will be minimized and further evolution in the model stopped. However, the subsequent evolution in real galaxies is less obvious. Schwarz's calculations do not include all physical processes which can be of importance in the formation of stellar rings. One plausible hypothesis is that, because of the high gas concentration, rings are regions of enhanced star formation and thus a stellar ring will be formed at the same position as the gaseous one. Whether and for how long the gaseous ring will be maintained will depend on several, not very well understood, parameters like the rate of star formation in the ring and whether new gas will be added to it from the region between CR and OLR. The maintenance of stellar rings can also be questioned since in all N-body (i.e. stellar) simulations, rings seem to be transients. If however this structure is maintained while the stellar population ages and acquires higher dispersion of velocities by mechanisms analogous to those discussed by Schwarzschild and Spitzer (Astrophys. J. 114, 385 and 118, 106), then this can account for the redder and relatively broad stellar rings.

VAN WOERDEN : The distinction between rings and completely wrapped-up spirals is semantic. Schwarz's time sequence of evolution of a spiral pattern shows that structures may develop which morphologically cannot be distinguished from rings.

MILLER : Rings in N-body simulations are very unstable if they contain much mass. Stellar rings, especially those in outmost regions of galaxy images, are likely to contain enough mass to cause trouble even if they have low surface brightness.

ATHANASSOULA : Rings have often formed in the numerical N-body simulations described above as well as in previous ones (e.g. Sellwood, Astron. Astrophys. 99, 362), but they were always transient. I have not looked into how the mass in the ring may influence its lifetime. However, I do not know to what extent these results can be extrapolated to real galaxies, since there can be a number of differences. In particular the dispersion of velocities and the amount of softening present in the models can be of great importance.

HUNTER : What resonances do you have in mind that might be responsible for the formation of rings in non-barred spirals ? In the absence of a bar, there is no obvious pattern speed to use in calculating the location of the outer Lindblad resonance.

ATHANASSOULA : Anything rotating and nonaxisymmetric can provide a pattern speed. Bars, ovals or spirals seem the obvious candidates. In fact Schwarz (Astrophys. J. 247, 77) pointed out that a spiral potential can produce rings in time scales comparable to those of bar forcing.

JORSATER : Contopoulos (Astron. Astrophys. 81, 198) suggested that bars end at corotation. However in your discussion of rings you presented results of orbit calculations in a model with a substantially longer bar. Could you comment on this ?

ATHANASSOULA : Because of the rather centrally condensed density distribution in the bar, only 10-15 % of the bar mass was actually outside corotation in the examples shown. Also note that the bar introduces a sizeable nonaxisymmetric force so that the very definition of corotation is not unique. Athanassoula et al used, for simplicity, the background axisymmetric rotation curve and did not include the axisymmetric contribution of the bar in their definition of CR.

KENNICUTT : Lenses often exhibit very sharp outer cutoffs in their radial distribution. How can such a sharp transition be produced from a protogalaxy that must have possessed a much smoother radial distribution ?

ATHANASSOULA : The question holds true for both bars and lenses since they both have rather sharp cutoffs. Neither the scenario presented here nor that of Kormendy claims to answer it. According to Bosma's scenario, the lens stops where the density of the initial gas dropped low enough so that star formation stopped abruptly.