FORMATION AND MAINTENANCE OF SPIRAL STRUCTURE

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ABSTRACT. I briefly review different mechanisms for forming and maintaining spirals, such as modes, edges and grooves, driving by bars, tidal interactions and local responses. Some of their observational consequences, and in particular the existence of a leading component in nearby galaxies, are discussed.

1 Introduction

The problem of the formation and maintenance of spirals has been with us for some time. If spiral arms were material structures, they would wind up because of differential rotation. Thus density waves were introduced as a solution to this winding dilemma (Lindblad, 1959 and references therein; Lin and Shu, 1964 and 1966). However this remedy brought soon new headaches, since Toomre (1969) showed that a packet of tightly wound waves will propagate radially from corotation towards the Lindblad resonances where it will be absorbed. Thus it became obvious that it is necessary to continuously replenish, drive or stimulate the spirals. I will here discuss briefly five possible ways for doing so, giving more emphasis to recent developments. For more thorough and complete reviews see e.g. Toomre (1977) or Athanassoula (1984).

2 Modes due to feedback cycles and amplification at corotation

The work of Toomre (1969) and Mark (1974) showed clearly that a wave should be shielded from the inner Lindblad resonance (hereafter ILR) in order to avoid being absorbed. This can be achieved either if its pattern speed is higher than $(\Omega - \kappa/2)_{max}$, or if the velocity dispersion increases abruptly inwards at a radius which is larger than that of the ILR. Then any wave travelling inwards would be reflected on this "barrier" before reaching the lethal ILR. In either case the damping from the ILR would be confined to the very small contribution of stars on very excentric orbits. Yet this is not the only source of energy loss. The dissipation of the gas, present not only at the Lindblad resonances, is an important damping factor (Kalnajs, 1972; Roberts and Shu, 1972). Thus mode cycles should necessarily comprise an amplifier in order to keep the spiral going.

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Two amplification schemes have been so far proposed. In the WASER (Wave Amplification via Stimulated Emission of Radiation; Toomre, 1969, Mark, 1976a, b, c, 1977) an outgoing long trailing wave stimulates the emission of two short trailing waves. One of them propagates outwards towards the outer Lindblad resonance (hereafter OLR) while the other propagates inwards and is reflected at the Q barrier into a long trailing wave which propagates towards corotation and closes the cycle. The amplification thus achieved is very small, and negligible in the case of hot discs.

The second one, the SWING (Toomre, 1981), draws on the amplification of a wave when swinging from leading to trailing (Goldreich and Lynden-Bell, 1965, Julian and Toomre, 1966, Toomre, 1981). The closure of this cycle, providing fresh leading waves, can be made by a reflection of the trailing wave at a sharp edge, or at the center of the galaxy (Bardeen, 1975). The SWING involves regimes in which the standard WKBJ approximation (which assumes that the wave is tightly wound) is in trouble. Its analytical treatment is thus non trivial and has been explicitly worked out so far only in the case of the shearing sheet (Pellat et al., 1990). The SWING amplifier is very powerful and can give important amplification rates. Thus several modes based on it have been found so far (e.g. Zang, 1976; Toomre, 1981; Bertin et al., 1989).

Since the fastest growing mode dominates the evolution, that is the relevant one for comparing with observations. There has been a lot of pessimism about whether modes could explain the observed grand design spirals, chiefly because of their very high growth rates. These could be lowered with the help of a halo (however this solution is limited if one does not want to privilege spirals of higher number of arms m), by increasing the stellar velocity dispersions or because of nonlinear effects. Furthermore it should not be forgotten that all these mode calculations do not include, not even schematically, the dissipation by the gaseous component. Yet a balance could be reached between the energy dissipated in the shocks and the energy obtained from the amplification.

3 Edges and their effects

Edges or sharp gradients can induce spiral structure. This can be understood as due to two basic ingredients, the nonaxisymmetric instabilities of isolated thin rings (Maxwell, 1856; Lindblad, 1958; Papaloizou and Lin, 1989; Sellwood and Kahn, 1990) and the response from the disc (Julian and Toomre, 1966). The instability makes clumps which rotate with roughly the same angular velocity as the material in the ring. These clumps may drive hefty spiral responses, similar to the responses to the giant molecular clouds discussed in section 6, provided the disc mass and velocity dispersion allow large swing amplification rates. The number of arms favoured is a compromise between the two ingredients. Indeed ring instabilities have higher growth rates at high m values (Papaloizou and Lin, 1989) while the disc responds best for m = 2 or 3 for realistic disc parameters. (The maximum disc amplification that can be wrung from a given disc depends on $X = r\kappa^2/2\pi G m\mu$, and for $\Gamma = -d\ln\Omega/d\ln r = 1$, has a maximum around X = 1.5 (Toomre, 1981)).

Toomre (1981, 1989) in a stability analysis of the Gaussian disc found amidst the other modes an edge mode which he called D mode. This has a corotation resonance near the edge of the disc, as expected from the above discussion. Toomre demonstrated on the

one hand the dependance of such modes on the abruptness of the edge by experimenting with different outer density cut-offs of the exponential and of the V = constant disc, and on the other their independence from the feedback loop by freezing the center of the Gaussian disc. Edge modes with similar properties can be easily found in numerical simulations (Athanassoula unpublished). Edges in observed galactic discs have been found photometrically (van der Kruit and Searle, 1981). Whether they are sharp enough to provoke edge modes and how the sharpness is maintained, still remains to be worked out.

Sellwood and Kahn (1990, see also Sellwood, 1989 and 1990) invoke a groove not in the density but in the angular momentum distribution. Of course the two would be the same for the case of cold discs (Lovelace and Hohlfeld, 1978). Both sides of the groove will form clumps, like in the case of an edge. However if the phase of the clumps on the two opposite sides are different they will attract each other in pairs, thus exchanging their angular momenta, as is nicely illustrated and discussed by Sellwood and Kahn. Their numerical simulations further showed that the compromise between the two main ingredients of this instability (instabilities in thin rings and the response of the disc) give, in warm discs, higher growth rates for m = 2. One still has to worry about the reason for forming such grooves in the angular momentum distribution. Sellwood and Lin (1989) saw such grooves form naturally in their simulations of low mass Keplerian discs. Each groove caused an instability with corotation near the radius of the groove. After the instability had grown to a spiral of sizeable amplitude it scattered particles off its Lindblad resonance thus creating new grooves there, which would in turn create new instabilities etc. (The whole process could be closely related to the emission of waves at resonances as discussed by Sygnet et al., 1988). Unfortunately observational tests of this theory seem to be exceedingly difficult. It is thus essential to check the existence of the instability cycle found by Sellwood and Lin in realistic hot discs (since grooves must not only form but also have sufficiently abrupt edges for them to be effective) in order to assess the relevance of this interesting mechanism for real galaxies.

Fridman (1989), inspired from shallow water experiments (e.g. Fridman et al., 1987), discussed the case where the rotation velocity, the density and the sound speed showed a discontinuity at the same radius. For the idealised case where these three quantities can be considered constant, both before and after the radius of the discontinuity, and in the limit of very small or very large Mach numbers allowing for analytical solutions, he showed that such discontinuities could indeed generate instabilities. The formation and persistence of such triple discontinuities in real galaxies has not been so far demonstrated. Nevertheless, at least as far as the rotational velocity is concerned, it is possible to check for such gradients in the observations.

4 Driving by bars

Several simulations of non-self consistent gaseous responses to bar-like or oval potentials have been made (Sanders and Huntley, 1976, Sanders, 1977, Sanders and Tubbs, 1980; Van Albada, 1985; etc.) showing clearly that the response is spiral. Thus a spiral forcing is not a necessity for obtaining a spiral response. A self consistent, but linear, calculation (Athanassoula, 1980) showed that gaseous spirals are more tightly wound than stellar

ones and that the thin gaseous arms are embedded in the broad stellar ones for most of their extent. Furthermore the potential of the spiral arm provides a considerable part of the total forcing and therefore should not be neglected in the calculations. In all the above cases either the pattern speed of the bar had been assumed from the onset to be equal to that of the driven spiral (e.g. Athanassoula, 1980) or the self consistency was neglected (Sanders and Huntley, 1976; Sanders, 1977; Sanders and Tubbs, 1980, etc) in which case the equality of the pattern speeds followed naturally. However this need not always be the case.

In several N-body simulations (e.g. Sellwood, 1985) more than one mode have been observed of which the one with the lowest pattern speed has an ILR, and, according to what was discussed in section 2, should not have existed. Tagger et al. (1987) and Sygnet et al. (1988) noted that in all these cases the region of the offensive ILR was the same as that of corotation of the faster rotating mode. They thus explained the existence of the slow wave by the nonlinear coupling of the two modes between them and with their beat wave. This coupling, although constrained only to the narrow region around the two resonances, is particularly strong because of the resonance overlap. This would thus lead to the possibility of having spirals with a different pattern speed than that of the bar that drives them. Sygnet et al. (1988) discussed the implication of this for real galaxies, noting that this might account for the fact that in certain barred spirals the dust lanes are observed on the inner (concave) side of the spiral arm. However they were reluctant to believe that this could happen for galaxies like NGC 1300, where the arms join very smoothly to the bar, because different pattern speeds will result in random relative orientation of the two components. However that pessimism was unwarranted since the spiral may continually break from the bar and reconnect to it, as shown in the simulations of Sellwood and Sparke (1988).

5 Tidal spirals

In order to understand tidal spirals we have to consider two extreme cases. That of satellites on circular orbits and that of unbound companions.

a) Satellites on circular orbits provide a periodic forcing. It is thus reasonable to expect the pattern speed of the excited spiral to be equal to that of the driving and resonances to be of primary importance. If the satellite is direct then the $m = 2$ component of its forcing will conspire with the $m = 2$ ILR and a two armed spiral wave will be excited. On the other hand if the satellite is retrograde then the only possible resonance is the $m = 1$ ILR. Thus an $m = 1$ wave will be excited, which is furthermore leading (Athanassoula, 1978). Since this is a very unorthodox spiral structure several numerical simulations have tested it (Noguchi and Ishibashi, 1986; Thomasson et al., 1989) and have shown good agreement with the theoretical predictions.

b) In the case of unbound passages it is not clear whether the spiral will have the same pattern speed as the companion at its pericenter or not. In order to test this I made a number of N body simulations using J. Sellwood's N body code (Sellwood, 1981). More information on these can be found in a forthcoming paper and in Athanassoula (1990). Figure 1 of Athanassoula (1990) shows a simulation of the driving of a spiral by a companion in what can be loosely termed a "stable" galaxy: one which if unperturbed

would show no spiral features - either in the density plots or by Fourier analysis - for a time considerably longer than that of the simulation. Note that the driven spiral is transient and its propagation towards and absorption at the ILR agree very well with the analytical calculations of Toomre (1969). I measured its pattern speed in three different ways and found it compatible with that of the companion at pericenter. As a second experiment I tried forcing an "unstable" disc. A spiral was again excited but its fate was quite different from that of the previous example. It did not propagate towards the ILR to be absorbed there but rather evolved into a bar. The pattern speed of the spiral was the same as that of the bar it evolved in to, but it was not compatible with that of the companion at pericenter. Instead it seemed to be compatible with the pattern speed of one of the modes that would develop in the same disc if this were to evolve unperturbed, as I could show by a further numerical simulation. Thus the main effect of the companion in this case was to excite, much before its due time, an instability that would develop anyway. These two different behaviours being now clear I wondered what would happen in intermediate cases. I thus submitted a disc, with properties intermediate between those of the "stable" and "unstable" discs of the above examples, to a passage of an external companion. A spiral was forced which after a while died out, very much like that of the "stable" case. After that followed some dull time, during which not much could be seen in the simulation, and then a new spiral formed, grew and evolved into a bar. The pattern speed of the first spiral episode was compatible with that of the companion at pericenter, while the second spiral and the ensuing bar had a different pattern speed, presumably that of the perturbation that would evolve in the undriven disc.

From all the examples described above, and many more corroborative simulations, it is clear that companion driven spirals are short lived, not exceeding a life time of the order of a few times 10^9 years. On the other hand nothing prohibits a later encounter to form a new spiral which will in turn die out, etc. This could continue only as long as the heating of the disc due to the consecutive spirals is balanced by the cooling due to star formation from fresh gas.

A spiral driven by a satellite will also evolve and eventually die out. This is due to the fact that the radius of the satellite's orbit will change because of the dynamical friction and of exchange of energy and angular momentum between the satellite and stars around the ILR of the parent disc (Tremaine, 1981; Quinn and Goodman, 1986). However the time scale involved may well be longer than in the case of a companion, although detailed simulations are necessary to give a quantitative estimate.

6 Ragged spirals and local responses

Most spirals do not have a "grand design" structure as M51 or M81, but show a more ragged structure. Attention to such "swirling hotch-potch of pieces of spiral arms" was focussed by Goldreich and Lynden-Bell (1965) and Julian and Toomre (1966).

Julian and Toomre worked out the response of a disc when forced by an orbiting mass or clump, like a giant molecular cloud. The wake thus formed is a trailing spiral with an excess mass much larger than that in the driving clump and is a driven steady density wave. It can be easily visualised by following the trajectories of particles orbiting

near the driven clump. The inclination of the spiral depends on the shearing rate in the sheet.

Toomre (1990) discussed an N-body realisation of such a shearing sheet, where each of the particles can be considered at the same time as driving and being driven. The impression one gets from the evolution of this simulation is that of a "kaleidoscope of spiral features". These features can be understood and explained as the superposition of the wakes of the individual particles.

7 An observational search for the leading component

A necessary ingredient for the SWING feedback cycle discussed in section 2 is the existence of a leading component. It is thus important to establish whether such a component exists in real galaxies. It may be easily spotted on isodensity contours of a given multiplicity m. Figure 1b shows the result obtained by adding on the spiral of figure 1a its mirror image (i.e. leading if that of figure 1a is trailing) at 30% of its amplitude. The superposition of the trailing and the leading component shows a very characteristic interference pattern with maxima roughly 90° apart. Thus one promising way of looking for leading components is to search for such maxima using photometry of nearby spirals. Elmegreen et al. (1989) mention the existence of maxima in M 81 and M 100. In M 81 they are approximately 120° apart and in M 100 approximately 100° and 140°. No other relevant information could be found in the literature.

I thus tried to look for such maxima along the spiral arms in the data obtained by Considère and Athanassoula (1988) from the Fourier decomposition of the light distribution in 16 nearby disc galaxies. Four out of those galaxies were either flocculent or ringed and technical problems prohibited analysing the data for a fifth one. I was thus left with a sample of 11 galaxies with some spiral structure. I found the maxima along the m = 2 components of the density and the angle between them. Figure 2 shows the contours of the m = 2 component of the light distribution for NGC 598. The stars mark the position of the local maxima. They definitely give the impression of being at roughly 90° apart. However, instead of discussing each galaxy individually, which would lead to very small number statistics, I found it more convincing to make a cumulative histogram of the $\Delta\theta$ values between two successive maxima, for all galaxies in the sample. The result is given in figure 3. Although the sample is very small a χ^2- or Kolmogorov-Smirnov test shows that the distribution of the angle differences has a very small probability of being consistent with random. Thus the search for the leading component seems to be on a good track. However it should be noted that the bin containing most of the values is not centered around 90° but around roughly 65°. This shift from 90° could be explained in two different ways. Figure 1c shows the result obtained when adding 90% of the spiral in figure 1a to 10% of its mirror image. Note that the difference in angle between two consecutive maxima is now smaller than 90°. This can be understood by realising that for small ratios of leading to trailing amplitudes the variation of the density along the spiral has to be taken into account when predicting the positions of the maxima. A second alternative is if the leading and trailing spirals do not have the same wavenumber.

The reason one would expect, at first guess, these two wavenumbers to be the same is that the Lin-Shu-Kalnajs dispersion relation (Lin and Shu, 1966; Kalnajs, 1965) as well as the equivalent one for the gas, show a symmetry between leading and trailing waves, i.e. if, for a given ν (r), $k(r)$ is a solution of the dispersion relation then $-k(r)$ is also a solution. However this symmetry can be easily broken by the presence of resonances, dissipation, non linear effects or the presence of an external forcing. Figure 1d shows the result obtained when adding 70% of the spiral in figure 1a to 30% of a spiral with twice the wavenumber and opposite winding. It is thus clear that a substantial difference between the wavenumbers of leading and trailing components could account for a shift of the maximum of the peak of the histogram from 90°.

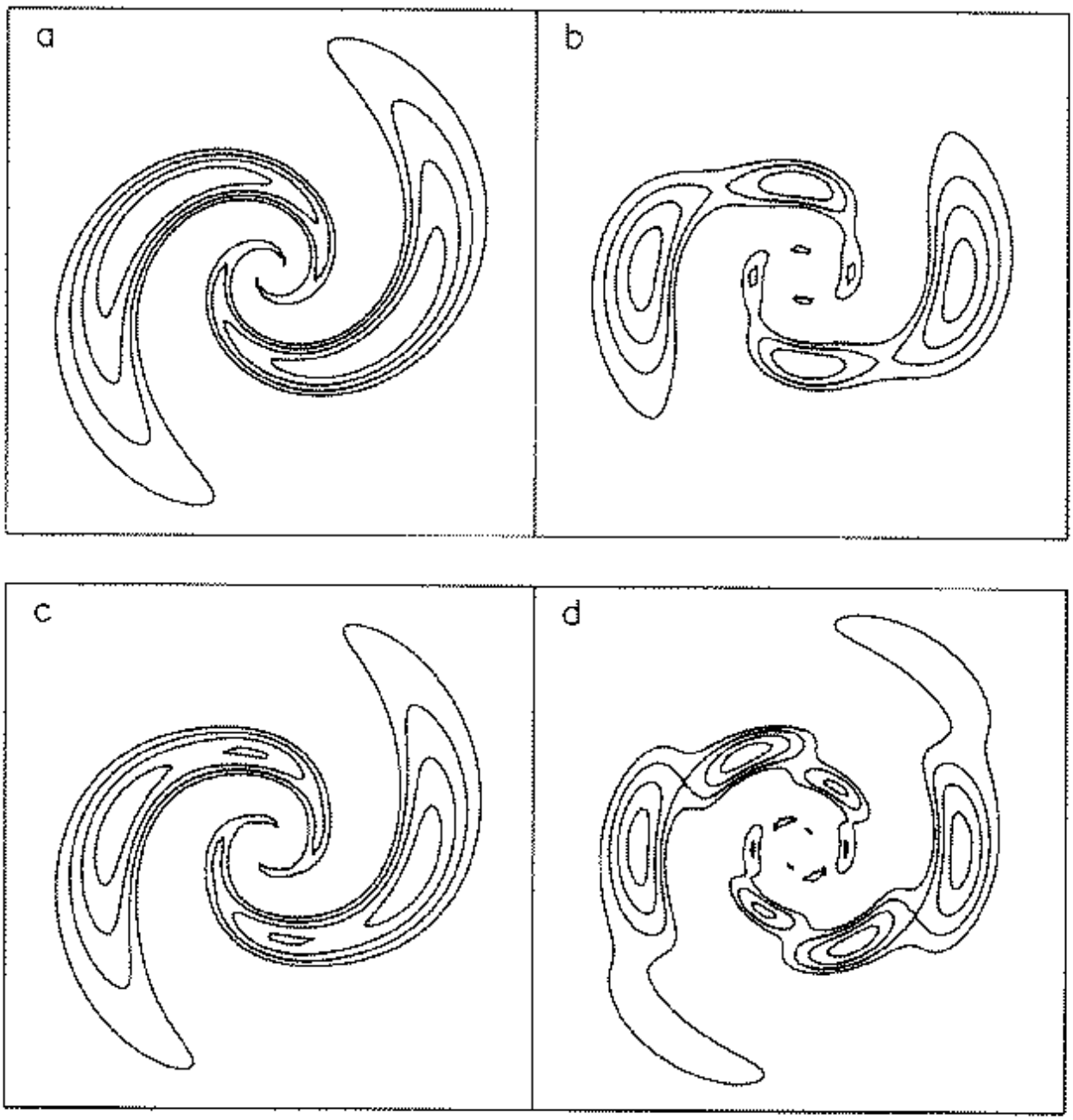

Figure 1. Superposition of trailing and leading spirals (a) 100% trailing (b) 70% trailing and 30% leading (c) 90% trailing and 10% leading (d) 70% trailing and 30% leading with twice the wavenumber.

Such a difference can also be argued from the Fourier spectra of the galaxies given in figure 5 of Considère and Athanassoula (1988), where several peaks can be seen on the leading sides but not necessarily at the positions of the maxima on the trailing side. There are thus at least two possible explanations for the shift of the peak of the distribution from 90°. Which one is dominant may vary from galaxy to galaxy. Furthermore the amplitude of the shift need not be the same for each galaxy, resulting in a spread in the histogram. If the trailing spiral is more tightly wound than the leading one, then the angle difference is larger than 90°, the opposite being true if it is more open. Thus, if the shift in maximum is due to the different wavenumbers of the leading and trailing components, the leading component, in the present sample of galaxies, is on average more tightly wound than the trailing one.

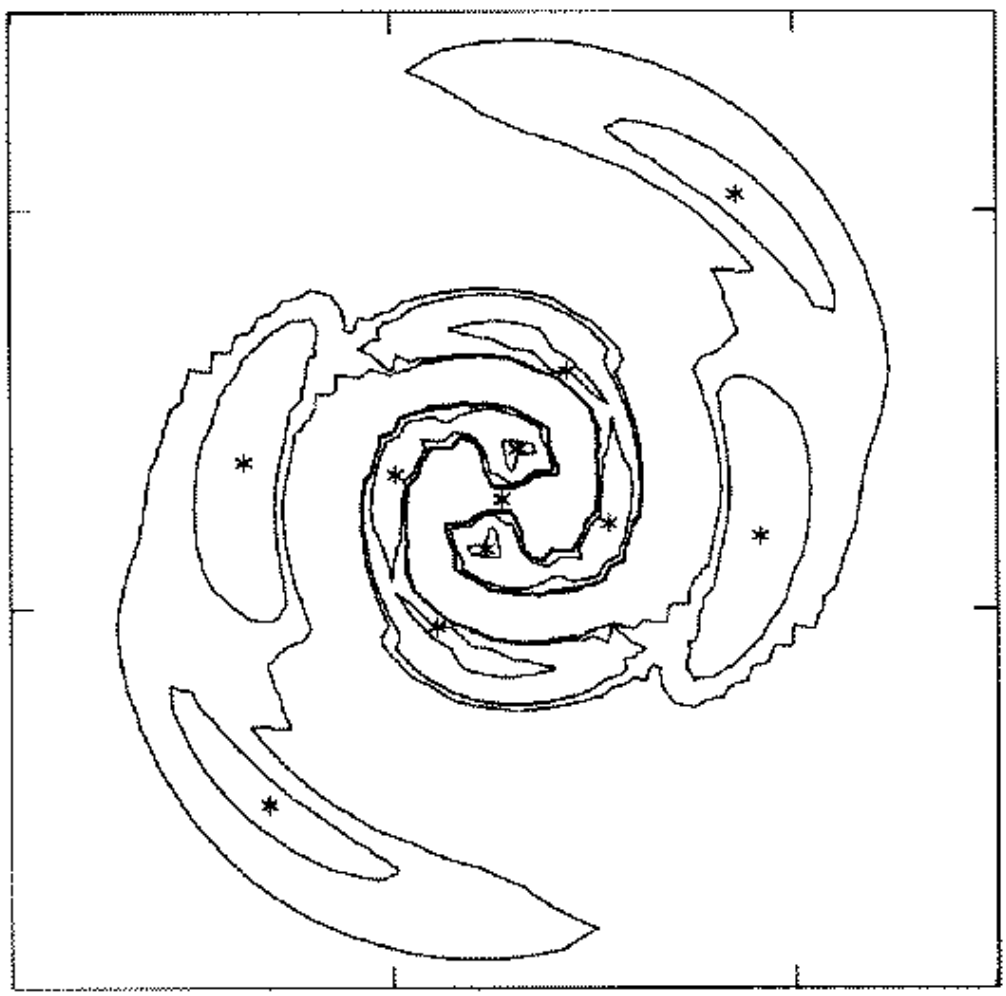

Figure 2. Contours of the m = 2 component of NGC 598. The stars mark the positions of the maxima along the arm and the center of the galaxy.

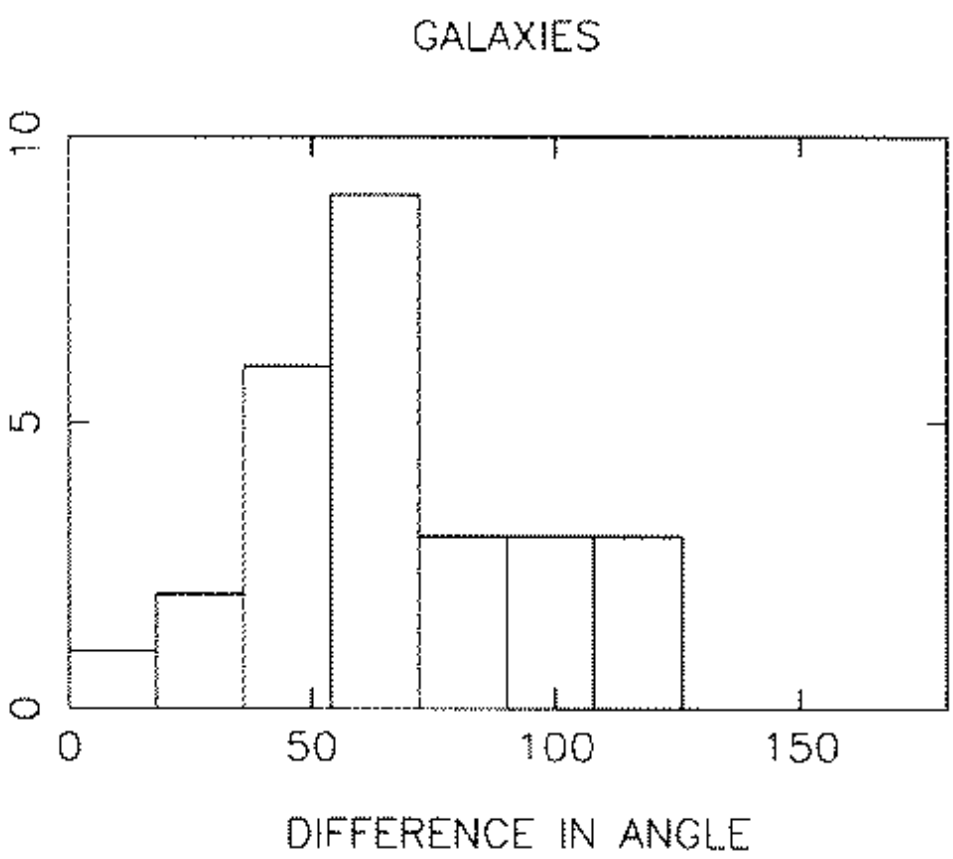

Figure 3. Histogram of the angle differences between two successive maxima in the m = 2 component for all galaxies in the sample discussed here.

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Discussion

R. Buta - May I present a photograph and color index map of the southern spiral galaxy NGC 4622, whose morphology seems very relevant to your retrograde encounter simulations. This galaxy has two relatively normal-looking outer arms which seem to terminate in a near circular ring. Inside the ring there appears to be a leading arm which was recently recognized by Byrd, Thomasson, Donner, Sundelius, Huang and Valtonen (1989, *Cel. Mech.* **45**, 31), who also made some related models. Deborah Crocker and I imaged the galaxy in B and I and we find that, while the two outer arms and half of the ring are clearly distinguishable in B−I, the leading arm and inner disk show no significant color differentiation. Are these the kinds of characteristics you would expect from your models?

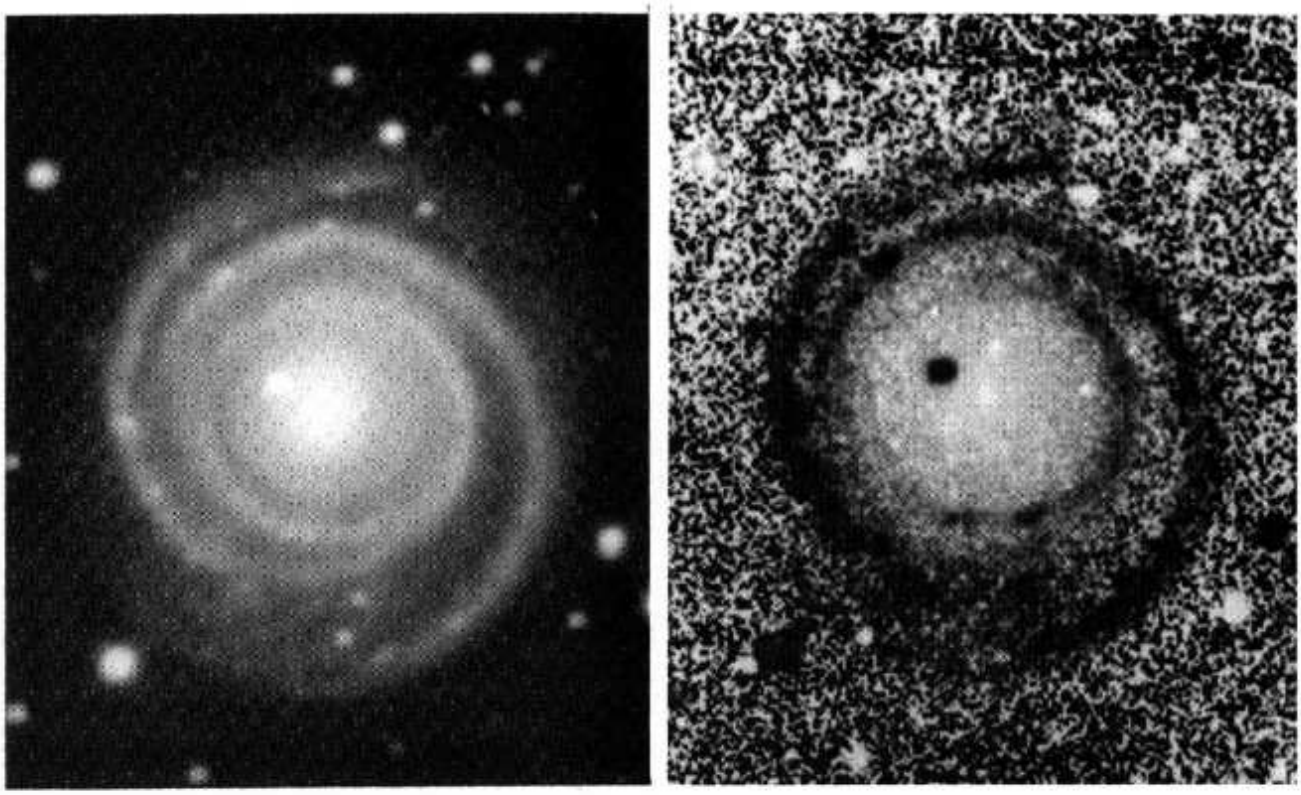

Figure 4. B-band CCD image (left) and B−I color index map (right, where the sense dark to light is blue to red) of NGC 4622, obtained with the CTIO 1.5-m telescope in February 1990.

E. Athanassoula - I would expect the m = 1 spiral to be mainly confined to the region surrounding its ILR, and the m = 2 to be dominant further out, where the tidal forcing is greatest. This is, I believe, indeed the case for NGC 4622. I can unfortunately say nothing about the colours without doing any detailed modeling.

F. Combes - In the case of driving by a companion, is there a particular relation between the external spiral corotating with the companion, and the inner density-wave (bar)? Is there for instance conjunctions of resonances (ILR and CR) or a better efficiency when that occurs?

E. Athanassoula - In most of the examples I discussed in section 5, there was, at any given time, only one pattern speed present. On the other hand in many other simulations there have been more than one mode present and then resonance overlap is very common. The physics of this has been discussed by Tagger et al. (1987) and Sygnet et al (1988).

I. King - Theoreticians are much enamored of density waves with low m, but we also have flocculent spirals, which probably do not have a density wave. How are we to understand them dynamically?

E. Athanassoula - Indeed flocculent spirals exist and are actually much more numerous than grand design ones. However I would not readily concede that they do not have density waves. The type of local responses discussed in section 6 could well explain the spiral structure in galaxies like NGC 2841 and NGC 5055.

Evangelia Athanassoula during her talk. In the foreground Ron Buta shows a picture of one of his favorite galaxies.