A CONFRONTATION OF DENSITY WAVE THEORIES WITH OBSERVATIONS

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ABSTRACT

It would be a mistake to think that the density wave theories of spiral structure have reached the maturity where they can make unconditional predictions which can be tested. On the contrary, they are still very dependent on observations for help and guidance.

1. INTRODUCTION

I have been taught to believe that a theory is a theory only if it is capable of being falsified. A good theory should propose observations which can unequivocally contradict it, and this element of risk is essential in order to have a confrontation. A sifting of the observational data in search of features which can be explained by a theory, and the subsequent tabulation in two columns, separated by a line, one labelled "observation", the other "theoretical interpretation", may be a good advertisement for it, but it does not constitute a confrontation.

When I turn to what is commonly referred to as the density wave theory, I find it very difficult to think of an observation which could contradict it. There seems to be an overabundance of uncertain parameters, and "as yet imperfectly understood mechanisms", which allow plenty of room to manoeuver around any tight spot posed by observations. Under these circumstances we are not dealing so much with a confrontation between theory and observation, as with a reconciliation.

In this paper I will discuss my perception of the status of the theory, and speculate about the direction in which I expect it to progress. Observations can and will play an important role in determining future developments, but the sort of data that are of the most importance pertain to the structure of the disk which is supposed to support the density waves, and are extremely hard to obtain. One actually has to turn the problem around and ask what spiral structure tells us about the disks, and in order to be able to do this, more

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attention will have to be devoted firming up the dynamical foundations of the theory itself, which are not as firm as one would like to think.

2. DENSITY WAVES AND WKBJ DENSITY WAVES

There are two distinct approaches to the subject of density waves, and in order to understand how this has come about and what the distinctions between the two are, I must sketch a brief history. It will be very rough, and if you wish to find out who did what and when, I recommend the forthcoming review article by Toomre (1977).

It is safe to say that all parties in the field agree or at least hope that the underlying stellar disk is sufficiently close to an axisymmetric equilibrium, so that any deviations can be treated as small perturbations of it. It is also agreed that Newtonian gravitation is the dominant force.

From the assumed symmetry of the equilibrium it follows that the perturbations will take the form of density waves. Each wave is sinusoidal in the azimuthal direction, rotates without shear at a fixed angular rate which is known as the pattern speed, and it may also grow or decay in time. The radial structure, pattern speed and growth rate of each wave or mode is determined by an integral equation which depends on the equilibrium structure. The growing modes of finite disks are discrete, can be singly excited, and one rejects all equilibria as unrealistic, unless the largest growth rates are sufficiently low. The amplitudes of the modes are not specified, except to the extent that they should not be too large. Roughly speaking, this implies that the largest acceptable amplitude for the density perturbation should decrease with the length scale of the mode, which makes the largest scale modes the most interesting ones since their effects should be more easily observed.

It is also agreed that one should at first try to describe the effects of the density wave in the stars on the gas in an iterative fashion: compute the non-linear response of the gas due to the stellar force field, and then consider, at most, only the effects of the induced density Fourier component which has the same angular periodicity as the stellar forcing field. The out-of-phase component is the more interesting one of the two, since it describes the energy and angular momentum transfers between the two subsystems, which relate to the question of growth and decay of the waves.

A difference arose on the question of how one should tackle the rather complicated integral equation which determines the modes. At a rather early stage C.C. Lin scented the possibility of developing an analytical theory of density waves, provided that the underlying perturbed potential was in the form of a tightly wrapped spiral. In this case one could make use of the rapidly varying phase to develop asymptotic or WKBJ solutions and neatly sidestep the complications of the integral equation. It was also necessary to have analytical expressions for the equilibrium orbits, which in general are too complicated to be of much use, but could be approximated by epicycles provided the eccentricities are sufficiently small.

The WKBJ theory, worked out by Lin and Shu, is sometimes referred to as the "local theory", for in the lowest order of approximation one pretends that the galaxy is uniform over the distance of a wavelength or so, and therefore requires that the wave be self-supporting at each radius. It is then left to the higher order terms to piece these locally constructed waves together to form the grand design, calculate group velocities, pattern speeds, etc.

The tightly wrapped potential hypothesis allowed W.W. Roberts (1969) to work out a tidy asymptotic theory for shock formation in the gaseous component, which has stimulated theories of star formation and given a fairly concrete picture of what a spiral arm should in this case look like.

In making this great leap forward, Lin and his co-workers are not now only facing the observers in the front, but have exposed their rear to the sniping of those they left behind. This of course was anticipated (Lin 1967). But what was not, was the possibility of simulating disk galaxies in numerical experiments on large computers. These simulations showed that disk galaxies did not behave in a manner which could be described in the framework of WKBJ theory. Self-gravitating disks do not form long-lived spiral structure, instead they are prone to large-scale two-armed instabilities which heat up the disk. The end product of this evolutionary phase is usually a finite amplitude wave in the form of a bar.

The numerical simulations certainly convinced me to give up my original plan of pursuing mode calculations with an epicycle version of the integral equation and epicyclic equilibrium distributions, since epicycles became less and less adequate as one approached the center. In order to keep the orbit approximation one had to exclude the center, but this is where the instabilities in the simulations seemed to occur!

The use of finite eccentricity orbits has made the equilibrium and mode calculations quite lengthy, and while I have not yet succeeded in constructing stable disks, it has been possible to identify the causes of the fastest growing instabilities and to substantially dampen them by simply including retrograde orbits in the central parts. The cure for the instabilities points to models with fairly hot centers, where pressure plays as significant a role as rotation in opposing the gravitational field.

It should be recalled that the possibility of disks being able to support tightly wrapped spiral waves is only a working hypothesis (Lin 1967), albeit a very reasonable one. But even if it turns out to be correct, the spiral modes will not be of much interest if the disk has faster growing instabilities which will dominate the evolution.

After all, many of the numerical simulations started with the very same disks used to illustrate WKBJ waves. My contribution to the sniping stems in part from doubts about the chances of being able to suppress the large scale instabilities and at the same time keep the tightly wound ones. If the explanation for the latter is the outward transfer of angular momentum as suggested by Lynden-Bell and Kalnajs (1972), then as they also pointed out, whatever a spiral wave can do, a more open one can do it better. If one has to increase the pressure in order to stabilize the bar type instabilities, it does not appear likely that one is going to decrease the scale of the dominant mode.

Further sniping stems from the role of the gas in the WKBJ theory, which is, as Oort (1962) has stressed, the key element for the presence of spiral structure. For very tight spirals, gas is a liability, since it damps the waves. However it can be made to work for you, if you have stable negative energy modes, such as bars, which are allowed to interact with it (Lynden-Bell 1975; Kalnajs 1973). This has led me to my own working hypothesis, namely to assume that a stable bar mode will eventuate when one manages to produce a stable disk, and to see how it interacts with the gas. While this does not encompass the whole range of observed spiral structure, it seems to be a direction in which some progress can be made.

3. WHY GAS?

Gas differs from stars in one unique respect: it can dissipate energy. If you believe that spiral structure is a long lived phenomenon, and hope to explain it by stars alone, you will have to rely on a relatively few so called resonant stars to keep it going, since spirality implies a redistribution of angular momentum, and the resonant stars act as sources and sinks (Lynden-Bell and Kalnajs, 1972). The trouble is that these sources and sinks have a finite capacity, and if they absorb too much they start giving it back, and vice versa. Gas does not have this problem, and will shock easily, particularly so near the Lindblad resonances. The reason for this is that in a steady field it tries to settle down in periodic orbits, but since these orbits intersect (in space) around the resonances, it cannot avoid running into itself.

This verbal theory is best illustrated by a simulation of forced gas response, presently pursued by P. Schwarz at Mt. Stromlo. The gas is assumed to be in clouds, which collide inelastically, loosing a good fraction of their relative motion in each encounter. The forcing is due to a rotating bar, reminiscent of the sort of thing one obtains in numerical simulations. The bar is turned on slowly over a period of two bar revolutions, and the distribution shown in figure 1 at the end of the third revolution persists for a further 4 to 7 revolutions before it dissolves. The reason for its demise is that the torque exerted on the gas tends to depopulate the intersecting periodic orbits by pushing the gas outwards past the outer Lindblad resonance. The end state is a nearly closed ellipse with its major axis along the bar. The locus of the shock, or rather of the collisions, coincides with the density maxima.

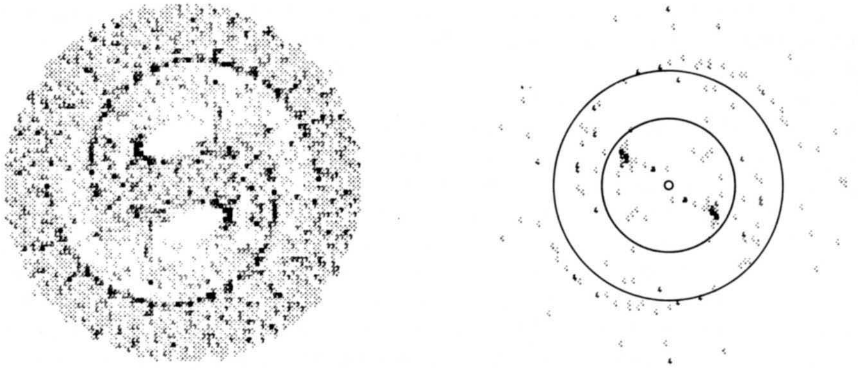

Figure 1. Quasi-stationary distribution of gas clouds driven by a bar (left), and the locus of the cloud collisions (right). The major axis of the bar is in the horizontal direction and the circles denote corotation and outer Lindblad radii.

While this is not the first demonstration that bars can force spiral patterns in dissipative gas, it is the one I understand best. The problem of making the pattern last is not unique to bar-type forcing, it occurs also when the field is spiral.[1] There are still a number of avenues to be explored before one is forced to the conclusion that the gas in the disk has to be replenished on a time scale of a billion years if spiral structure is to persist longer than that. But this is a distinct possibility.

4. THE PROBLEM OF Q'S, HOT DISKS, BULGES AND HALOES. IS Q=1?

I was instructed by the organizing committee to "concentrate on observable effects and avoid controversy of interest only to theoreticians". There is one issue that may arguably fall outside these guide-lines, but since it has far-reaching consequences, particularly for the WKBJ theory, it must be mentioned. It stems from our inability to construct cool self-gravitating equilibrium disks, which Toomre (1974) termed as a "near scandal" when he first reviewed it. The problem is still with us, but only in a slightly different form.

For nearly a decade since Toomre's WKBJ type analysis of the axisymmetric stability of disks (Toomre 1964), it was thought that once the fast-growing axisymmetric instabilities were taken care of by a sufficiently high radial velocity dispersion, the disks would be at most mildly unstable to non-axisymmetric perturbations. The ratio of the magnitude of the actual velocity dispersion to the minimum needed for

[1] For comparable azimuthal field strengths, the spiral field is at least as efficient in pushing the gas out past the Lindblad resonances as the bar.

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stability Toomre denoted by Q. He also remarked that the observed parameters near the sun seemed to indicate that Q is close to 1, which no doubt helped to fuel the myth that "realistic" disks ought to be just barely stable in an axisymmetric sense. Thus it was somewhat of a surprise when the early numerical simulations by Miller, Prendergast, and Quirk (1970) showed up bar-like instabilities which proceeded to heat up the disk substantially above the Q=1 level. At that time the heating was not taken too seriously in view of the seemingly rough nature of the numerical work. The subsequent calculations by Hohl (1971, 1973), which were impeccable in this respect, confirmed the bar-instabilities and their associated heating. It was Ostriker and Peebles (1973) who first collected all the then available evidence and pointed out the shocking fact that the kinetic energy in the form of random motions has to exceed the rotational part by about a factor of 2.6 in order that a self-gravitating disk be stable. The typical values of Q associated with such largely pressure supported disks were of order of 4, with the lowest values around 2, and the tendency was for Q to increase with radius. Such values correspond to a velocity dispersion at least double of that observed near the sun, which led Ostriker and Peebles to propose the existence of haloes. A halo, which would be called a bulge if its radius was smaller than some characteristic disk scale length, can and will reduce the absolute level of random velocities needed to make the disk stable. This is almost self-evident, for by postulating that only a fraction of the equilibrium force field in the plane of the galaxy is provided by the disk, with the remainder coming from the rigid halo, you end up with a lower surface density and hence can afford to decrease the velocity dispersion and still remain stable. However if we insist on using Toomre's Q as a thermometer, its scale shrinks in proportion with the surface density, and there is no evidence that a halo reduces Q. On the contrary, I found that Q actually is increased by the presence of a stabilizing halo (Kalnajs 1972). The far more realistic simulations by Hohl (1976) designed specifically to study the stabilizing effects of a halo could not reduce Q below 2 around the solar radius.

The value of Q is quite important for WKBJ waves, and is implicitly assumed to be 1.0. If Q rises above 1.0, there is a region around corotation where the WKBJ waves cannot propagate, and as Toomre (1974, 1977) has stressed, that region spreads rapidly with Q, so that by the time Q reaches 2 the waves are squeezed out of existence. The reason why one wants propagating waves near corotation is that the proposed amplification mechanism which is necessary to keep the waves going, depends on the communication of angular momentum across this region (Mark 1976). The best available estimate of Q from observations in the solar neighbourhood puts the value at 1.5, with an uncertainty in the range 1.2 to 2.0 (Toomre 1974). While one might just manage to keep the WKBJ waves going with Q=1.2 by marshalling all the higher order corrections, Q=1.5 is a very serious problem for WKBJ waves, and with Q=2.0 they are ruled out.

The precise value of Q is not of great concern to the more general type density waves. The numerical simulations show that bar like instabilities are still present when Q is in the range 2 to 4. My own analytical studies, which agree well with the early stages of the simulations, confirm the persistent nature of the bar modes, although for historical reasons I have confined myself mainly to selfconsistent disk models with Q's in the range 1 to 1.5. Figure 2 illustrates the

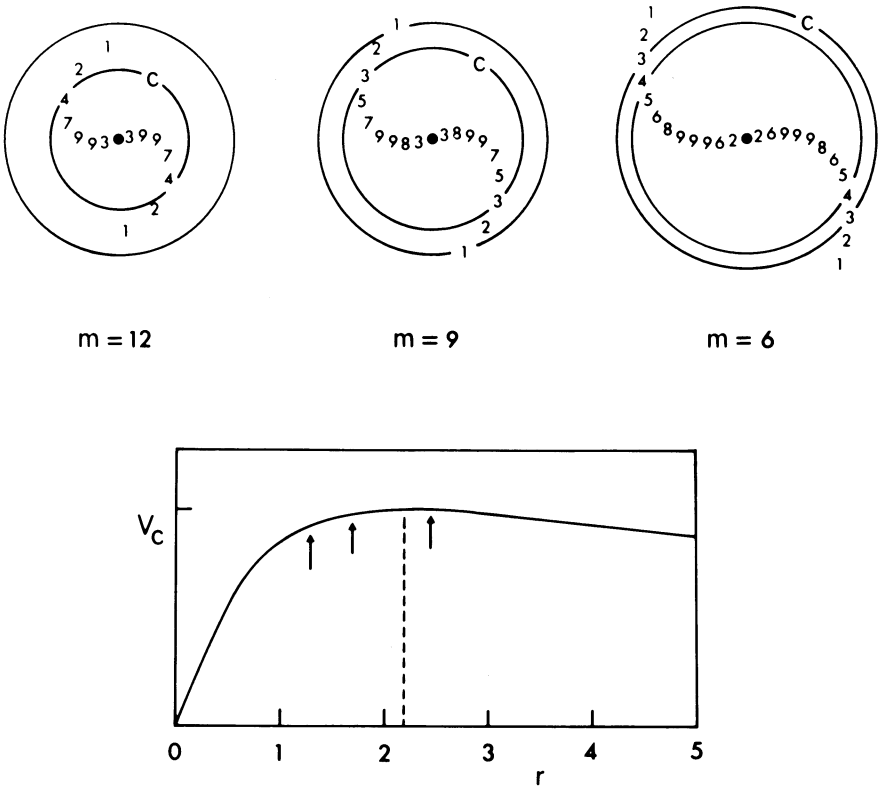

Figure 2. The lines of constant phase of the dominant mode potentials of three isochrone/m models (above), and the rotation curve of model (below). The circles labelled by C are the corotation radii, which are indicated by the arrows on the rotation curve. The unlabelled circles indicate the location of the maximum of the rotation curve.

appearance of the dominant two-armed modes of the isochrone/m models[2]. The relevant parameters of the three modes are found in Table 1. The pattern speeds and growth rates are expressed in units of the central

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[2]The distribution functions (Kalnajs 1976) include a retrograde component, which is a function of $J_1+|J_2|$, and matches up continuously with the direct part at $J_2=0$.

Table 1

	m = 12	m = 9	m = 6	m = 8	m = 8/1.5
Q_{center}	1.10	1.26	1.50	1.32	1.98
$Q_{corot.}$	1.00	1.14	1.46	1.22	1.83
Q_{gl}	.99	1.16	1.39	1.23	1.84
Pattern Speed	.59	.47	.34	.43	.26
Growth rate	.42	.29	.15	.25	.04
Corotation	1.32	1.73	2.45	1.90	3.03

rotation rate. The global Q, or Q_{gl} can be thought of as that factor by which the surface density should be multiplied in order to make the disk marginally stable to axisymmetric perturbations. The stellar disk instabilities are remarkably similar to those discovered by Erickson (1974) in his study of "softened" gravity disks.

As in the case of the simulations, the instability is mainly a central phenomenon; the potential peaks roughly at a distance of three mean epicycle radii from the center, and the spiral form is due to the inability of the outermost stars to keep up with the forcing field because of its sizable growth rate. The pattern speeds are fast in the sense that corotation falls well within the galaxy.

The last two columns in Table 1 illustrate the effects of a "halo" on the m=8 model. The "halo" takes the form of allowing only 2/3 of the disk to participate in the oscillation, which corresponds to a Q in the vicinity of 1.9. In this case the instability is fairly mild: if one were to place the sun at r=3.7, the e-folding time would be 200 million years.

One might argue that an apparent success of WKBJ waves would prove that Q must be very close to 1.0, at least in the vicinity of corotation. If so, then why? The best argument advanced so far why this might be the case is that corotation occurs in a region where the gas density dominates over stars, and because gas can cool, Q could hover just above 1.0 (Lin 1970). This would mean that corotation should be near the outer edge of the galaxy. Thus a determination of the pattern speed is of considerable interest.

If the interaction between the bar and gas is to grow spontaneously, a substantial part of the spiral structure must lie outside corotation. For this to be the case, corotation must be in the middle of the galaxy. The best chance of determining the pattern speed is from studies of the observed HI motions in external galaxies.

5. MOTIONS IN EXTERNAL GALAXIES

The most important observational consequence of a density wave is the density fluctuation and associated velocity field induced in the gas. The WKBJ theory does make a very strong prediction about the tangential velocity and the degree of compression of the gas. It stems from the fact that the azimuthal component of the spiral field can be neglected and therefore angular momentum is conserved. Consider a circular equilibrium flow, as illustrated by frame 1:1 in Figure 3.

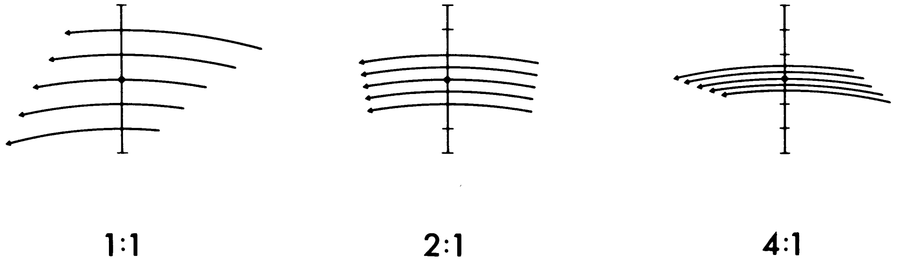

Figure 3. The effect of a radial compression on a sector of gas located at the radius where the rotation curve has its maximum. The uncompressed flow (1:1) shows differential rotation, which is arrested when the compression ratio is 2:1, and reversed when the ratio becomes 4:1.

Because of differential rotation, the gas that at some time in the past was contained inside a sector, shears out into a trailing feature. If for some reason the same patch of gas were to experience a uniform compression by a factor $(2\Omega/\kappa)^2$ (which at the maximum of the rotation curve is 2), the conservation of angular momentum would speed up the outer streamline with respect to the inner one in such a manner that the sector would appear to rotate at a uniform angular rate, as shown by frame 2:1. If the compression ratio were to be 4:1, the sense of shear would be reversed (and one might start to worry about the stability of the flow!). Thus it should be clear that as long as the forces are predominantly in the radial direction, one expects to see streaming motions on either side of an arm, irrespective whether it is leading, trailing, on the inside, or on the outside of corotation. The result is also independent on the rate at which the gas was compressed. The streaming motions will translate into wiggles in the 21cm velocity maps, and will be correlated with the position of the arm. The information about the WKBJ pattern speed is contained in the radial motion, in the sense that the motion in the arm is toward the center inside corotation, and outward outside, if the arm is trailing. In the leading case the radial component is reversed. After both components are combined and the resultant velocity field is convolved with a finite beam, the result is a sinusoidal wiggle. It is the phase of the wiggle with respect to the arm or shockfront which tells us where corotation is.

The same sort of relation between the tangential velocity and compression appears to hold, at least qualitatively, in the case when the arm is forced by a bar. This can be seen in Figure 4 which shows

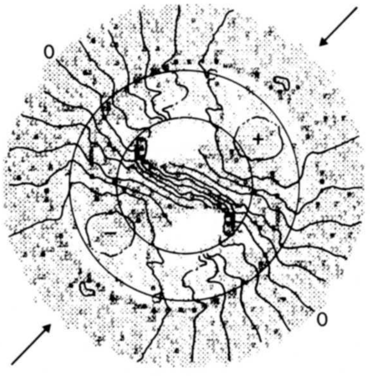

Figure 4. The velocity map of the gas cloud simulation shown in Figure 1. The true major axis is at 45 degrees to bar and indicated by the arrows. Also shown are the corotation and outer Lindblad resonance radii.

the velocity map superimposed on Schwarz's gas clouds. (Some of the smallest scale wiggles are due to the discrete nature of the clouds - the total number is 4000 and the mean per beamwidth is 3). In this case even the radial motion is in the same sense as predicted by the WKBJ theory.

Not too long ago hopes were high that one could, with the help of density waves, unravel the complexities of the 21 cm line profiles from the Galaxy, and learn something about the waves in return. These hopes visibly subsided once the magnitude of the task became apparent, and with the advent of aperture synthesis telescopes, external galaxies have replaced our own as the test bed.

Of the half-dozen nearest galaxies which have been observed with sufficient resolution to be possible candidates for a confrontation, M 33 and M 81 are the likeliest. The others can be excused for a variety of reasons, such as having too many arms, bad orientations, suffering from tidal effects, etc. The first observations of M 33 at Cambridge did not reveal any likely WKBJ pattern (Wright *et al.* 1972; Warner *et al.* 1973). The galaxy has been reobserved with a tenfold increase in sensitivity, but the data are yet to be reduced.

Visser has just given a detailed report on his model fitting of WKBJ patterns to the 21 cm observations of M 81 carried out by Rots (1975). I am not trying to belittle the effort that has gone into this comparison, when I say that you did not witness a confrontation. It is a convincing demonstration that we are dealing with a density wave of some sort, but if one were to argue that the good fit on the east side indicates that the corotation must be at 11 kpc, the discrepancy on the west side suggests that perhaps 5 kpc is the correct place, and vice versa. The galaxy is clearly asymmetric as a result of the tidal effects of the nearby companions as shown by van der Hulst, and I do not know which side is least affected, or how to go about correcting for such effects.

If I were to make a similar study, I would plot the theoretical convolved density and velocity fields on top of each other, and search for qualitative features which distinguish between being inside or outside corotation, and then try to discern these in the observations. As noted above, the distinction between the two cases depends on the relation between the shock and the phase of the wiggle. That relation is easily lost if one compares a theoretical velocity field with an observed density, since it is most unlikely that the latter will coincide with the theoretical one over the length of the spiral arm. Figure 4 illustrates how sensitive the phase relation can be.

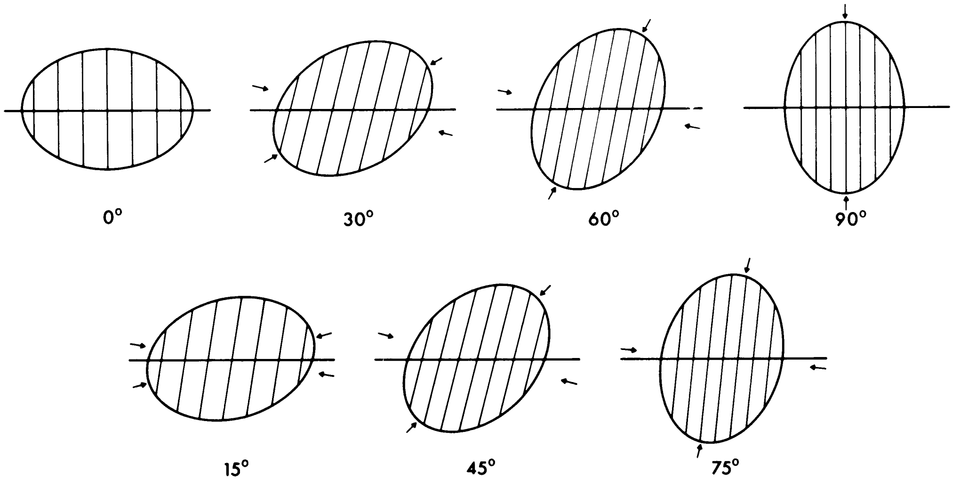

Figure 5. The velocity maps of the gas flow induced by a stable bar mode in a uniformly rotating stellar disk, shown for seven orientations of the bar.

One feature that is not very sensitive to detail is the tilt of the lines of constant radial velocity inside corotation, produced by a bar. This can be seen in Figure 4. The reason why it appears to be incorruptible is due to its large scale, and the fact that the streamlines are elongated in the same direction as the bar. The simplest illustration of this effect is provided by a stable bar mode of a uniformly rotating stellar disk. Figure 5 shows the velocity maps due to the motion of cold gas for various orientations of the bar. The bar is shown as it would appear viewed face on, and the major axis is in the horizontal direction. The arrows indicate the bar and kinematical major axes. There is a simple formula in this case which relates the angle v between the normal to the velocity contours and the true major axis, with the angle b between the bar major axis and true major axis,

$$\tan v = - a \sin 2b \,/\, (1 - a \cos 2b)$$

and

$$a = 0.75\, e \,/\, \omega \ .$$

Here e is the ratio of the bar minor to major axes, and ω is the pattern speed expressed in units of the disk rotation rate. The amplitude of the mode has been chosen to make $e = 1/6$, and the pattern speed is 1/2, hence $a = 1/4$.

Figure 5 shows that the only way a bar can go unnoticed is if $b = 0$, since in this orientation it can be confused with an inclined disk. It is also worth noting that the true major axis lies always somewhere between the kinematical and bar axes, and therefore a compromise between the two will be closer to the truth than the choice of one or the other. The 21cm observations of NGC 4151 (Bosma *et al.* 1977a) and NGC 4736 (Bosma *et al.* 1977b) show the sort of behaviour illustrated above.

6. PHOTOMETRY

The naive approach to star formation in a WKBJ shock would predict an increase in the width of a spiral arm in proportion to the difference between the angular rotation rate and the pattern speed. Thus Schweizer's measurements of the arm half-widths in different colours and as a function of radius (Schweizer 1976) should have been sufficient to determine the pattern speed. But they show no systematic trend. Wielen has just pointed out a possible explanation for the failure. There is another parameter, the velocity at birth of the stars which can make arms fat, and thus spoil the expected progression of dust, gas, young stars, old stars. While another seemingly simple method for determining the pattern speed has evaporated, nevertheless quantitative photometry of this kind is invaluable in providing the magnitudes of the spiral force fields. It would be nice if one could obtain a more direct determination of the stellar contribution to the arm light.

7. CONCLUSION

Implicit in the above ramblings is a warning, directed particularly to observers, not to spend too much time interpreting their results in terms of this density wave model or that. It is almost certain that the models will be obsolete next year, and the time spent in forcing the least-squares solutions is far better spent in gathering more data,

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and searching for features that appear to be sufficiently universal to require an explanation. To give an example: now that the WKBJ people are beginning to think in terms of modes, you can look forward to cooler and hence less massive disks, and proportionately more massive haloes. The reason for this is that whereas before one would fit just the short-wave branch of the dispersion relation to the data, now the longwaves must also be added. When the two are combined, the pattern becomes more open, and in order to restore the fit, the disk must be cooled.

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DISCUSSION FOLLOWING REVIEW II.4 GIVEN BY A.J. KALNAJS

LIN: There are (roughly speaking) two classes of mass models for galaxies: (1) those with a spheroidal component and a disk with a "hole" in the middle (cf. Einasto), and (2) those without a spheroidal component. Dr. Kalnajs has been stressing the second class of models. In this case, the system is likely to develop into an open spiral, or even a bar. The parameter Q is likely to be high. In the first case, the asymptotic theory can be applied to yield spiral patterns of relatively small pitch angles [see Mark's comment below].

MILLER: You mentioned that the dispersion relation, especially near corotation, is affected if $Q > 1$. You also mentioned that Q is re-defined in the presence of a halo. Is the Lin-Shu dispersion relation affected by a halo in any way beyond that implied in the definition of Q?

KALNAJS: No, the dispersion relation is local and depends only on local parameters. It knows nothing about the global distribution of material which determines some of these parameters.

STROM: To what extent does the observation of wave patterns in disks (from near IR observations of the underlying disk stars) allow you to check the wave generation mechanism? Do you believe that wave patterns observed in Schweizer's galaxies represent density wave patterns? Is there any case where you see a bar-like instability in his galaxies?

KALNAJS: I don't know how to distinguish between a self-supporting wave in the sense of the WKBJ theory, and a forced spiral due to a bar near the center.

Yes, I do believe that there are density waves in Schweizer's galaxies, and that there could be a bar in the center of M81.

WAXMAN: What effect does spiral structure excited by a bar have on the bar itself; and therefore, how long can we expect the bar to maintain the spiral structure?

KALNAJS: It can either amplify or damp it. In the situation I illustrated, the bar is a negative angular momentum mode in the stellar component, and because of the energy loss the spiral structure in the gas orients itself so as to pull the bar backwards and thus amplifies it. The spiral structure decays in this case because the colliding gas gains angular momentum and moves out.

OORT: Referring to your remark about Visser's confrontation of the M81 observations with spiral-wave theory I felt that you were asking too much. I think that it is already an important accomplishment that in one case a good representation has been obtained of the various observed characteristics with a theory of spiral structure.

TOOMRE: What is it you still question about the wave in M81 (whose existence I would have thought Visser, Rots, Shane and others have now demonstrated beyond all reasonable doubt)?

KALNAJS: I do not question the presence of some sort of a density wave in M81. It is just not clear to me whether it is a WKBJ type wave or the effect of a large-scale global mode in the stars.

VISSER: First I want to say that my model of M81 does not prove that other models are impossible and that density-wave theory has to be correct in all its consequences because of this model. On the other hand, I have to point out that the model is not so perfect as it seems. If the velocity perturbations of the model are as best as possible in phase with the observed wiggle, there is a phase shift of the observed spiral arms with respect to the model arms. The phase shift can be as large as 22^o (11^o in azimuth).

SCHWEIZER: How massive must the bars which you use be to produce the spiral patterns you are interested in? Do you need bar-disk contrasts of factors 3, or can you do with 10% to 20% contrasts? In M81, there just isn't much room for a massive bar, if the light distribution is at all indicative of the mass distribution.

KALNAJS: One needs a very modest field in the vicinity of the outer Lindblad resonance to produce a spiral shock. For the example I just cited, the total field strength is just a bit over 3% of the axi-symmetric component. Such a field can be produced by a small large-contrast bar, or a large small-contrast one. We chose the former, without having any particular galaxy in mind.

FREEMAN: Is there a problem understanding the spiral structure in systems like M33 where the disk obviously has no hole at the center, there is no bar and the bulge is quite insignificant?

MONNET: In the center of M33 there is indeed a bulge with a mass of about 2% of the total mass of the galaxy.

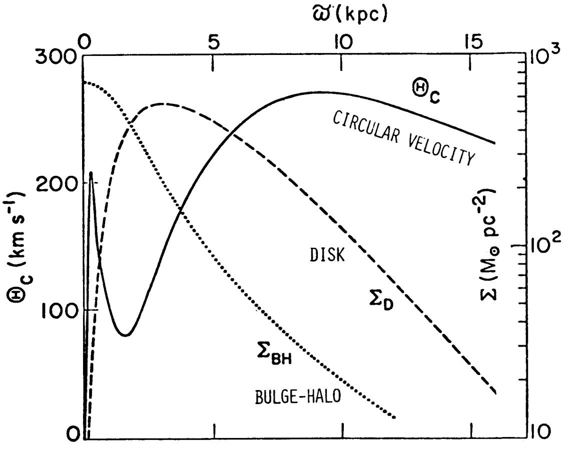
LIN: I would just like to make one simple general statement, namely we do not pretend that we have a theory about every spiral galaxy.

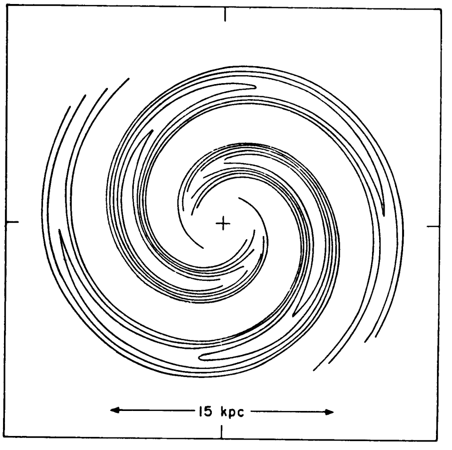
FREEMAN: But M33 is the simplest galaxy you'll possibly ever see up close!

LIN: Is it? No, it has quite a complicated disk structure.

MARK: DISCRETE SPIRAL MODES IN DISK GALAXIES

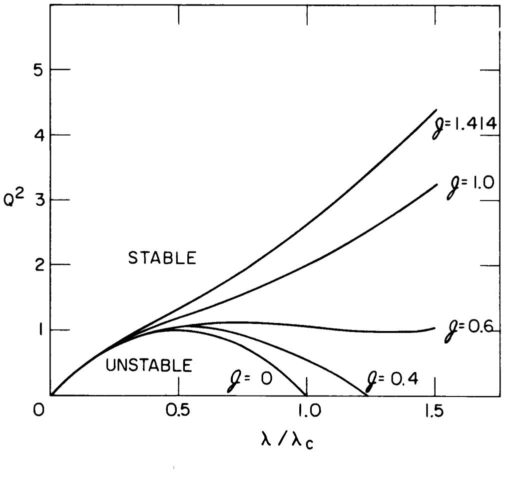
Discrete spiral modes are calculated based on stellar dynamics, according to the most recent form of the asymptotic theory of density waves. These self-excited modes are maintained wave systems which no longer propagate in the radial direction. They are expected to grow to observable amplitudes in a few billion years, and several of them may coexist in a given galaxy. A quasi-stationary spiral structure may be found in many galaxies due to a balance between wave amplification and certain dissipative processes, such as shocks. The theory can be applied to realistic galaxy models. Shown in the left figure below are the rotation curve and the mass distribution of a galaxy model which resembles M31 in many respects. Shown in the right figure are the perturbation density contours for the lowest two-armed spiral mode. For each individual spiral mode, their radial density distribution in the stellar arms is qualitatively similar to that observed in nearby galaxies (for example by F. Schweizer). Details will appear in a forthcoming publication (Bertin et al., Proc. Nat. Acad. Sci., USA).





BERTIN: GROWTH OF SPIRAL WAVES IN DISK GALAXIES

A local dispersion relation for spiral waves in a gaseous disk is derived. In addition to the well-known parameter $Q = \kappa a/\pi G\sigma_0$, another dimensionless parameter $J = 2m(\pi G\sigma_0/\kappa^2 r)/\sqrt{(1/s - 1/2)}$ is found to be important in characterizing the growth of spiral waves. Here a is the acoustic speed, σ_0 is the surface density, m is the number of spiral arms, κ and Ω are respectively the epicyclic and circular frequency, r is the radial distance from the galactic center, and $s = -d\ln\Omega/d\ln r$. Specifically, for stability against disturbances of local wavelength λ, $Q^2 > 4[\lambda/\lambda_c - (\lambda/\lambda_c)^2/(1 + J^2\lambda^2/\lambda_c^2)]$ where $\lambda_c = 4\pi^2 G\sigma_0/\kappa^2$. The marginal stability curves are shown on the Figure for various values of J. For axisymmetric disturbances, $J = 0$ and the curve resembles that of Toomre (1964, Ap.J. 139, 1217). The diagram indicates that non-axisymmetric waves are more difficult to suppress than the axisymmetric ones, in general agreement with the work by Goldreich and Lynden-Bell (1965, M.N.R.A.S. 130, 125) and by Julian and Toomre (1966, Ap.J. 146, 810).



The details of this work, together with the role of J in the growth of spiral modes, will be given in a forthcoming paper (Lau and Bertin, in prep.).

LIN: You might have added that for large values of J, one needs a higher value of Q for stability.

W.W. ROBERTS: GALACTIC SHOCKS IN OPEN-ARMED NORMAL SPIRALS AND BARRED SPIRALS

In the steady state gas dynamical studies of the late 1960s (Fujimoto, 1968, I.A.U. Symp. No. 25, 435; Roberts, 1969, Ap.J. 158, 123) the dark dust lanes, which are observed along the inside edges of spiral arms, were identified as tracers of large-scale galactic shock waves which form in the gas. Thought also to be tracers of the shock phenomenon were the strikingly narrow and rather straight dust lanes often observed along the leading edges of the bar structures in barred spirals (see Lin, 1970, I.A.U. Symp. No. 38, 377). More recent two-dimensional, time dependent, numerical hydrodynamical calculations have been carried out by Sorensen et al. (1976, Ap.Sp.Sci. 43, 491), Sanders and Huntley (1976, Ap.J. 209, 53), and Huntley et al. (1977, in prep.) for the response of rotating disks of gas to bar-like perturbations in galactic gravitational fields. All of these time-evolutionary calculations evolve through a state in which the viscous, differentially-rotating disk of gas forms a central gas bar with two trailing spiral waves and exhibits features resembling shocks.

Here, in cooperation with J.M. Huntley and C.C. Lin, we discuss an approach in which we have been able to generalize the steady state gas dynamical studies for tightly-wound normal spirals to include normal spirals with open spiral arms and barred spirals with prominent bar structures in the inner parts. The response of the gas to a barred spiral-like perturbation, for example, is calculated by means of an analysis which enables the two-dimensional flow to be broken up into two physical regimes. In regime I where the gas flow is highly supersonic, the flow is determined through an asymptotic approximation that neglects secondary terms proportional to the square of the dispersion speed, such as the transverse gradient of pressure. In Regime II near and within the bar (and spiral arms) the flow is determined through an asymptotic approximation that neglects the small variation of the velocity, density, and pressure along a shock with respect to their variation normal to the shock. The composite picture for the steady state flow of gas is constructed by joining the two regimes of flow in the transition layer between regimes.

This composite picture is illustrated for one case, model A, in Figure 1. Arrows on two of the gas streamlines (left panel) indicate the clockwise sense of gas circulation about the disk and through the shocks (----) which form near the potential minimum (——) of the barred spiral perturbation. A photographic simulation (right panel) of the gas density distribution illustrates the strong compression of the shock on the inside edge of each gas arm.

Figure 2 illustrates the corresponding results for a second case, model B, in which the flow equations contain a "friction type" term

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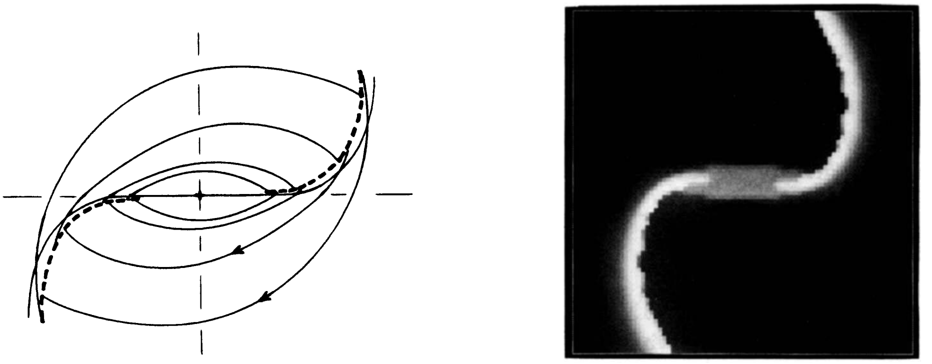

Figure 1. Gas streamlines and gas density distribution for model A.

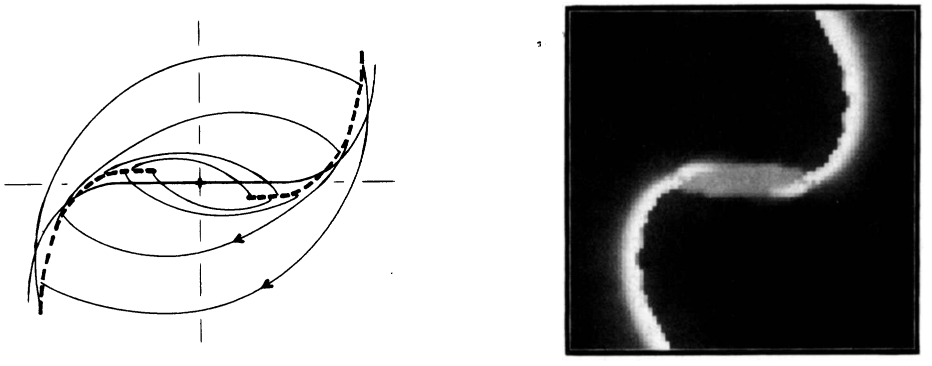

Figure 2. Gas streamlines and gas density distribution for model B.

that simulates "gaseous friction" in the inner parts of the disk. The forward shift of the shock onto the leading edge of the bar in model B produces an offset similar in some respects to the offset exhibited by the dark dust lanes observed on the leading edges of bars.

ALLEN: Did I understand correctly that your model has a gas density contrast between the arms and the interarm regions of about 20?

W.W. ROBERTS: Yes, that is correct.

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