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RESONANCE EXCITATION AND THE SPIRAL-RING STRUCTURE OF DISK GALAXIES

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ABSTRACT

Rings are common in disk galaxies. These rings are either indistinguishable from a pair of tightly wound spirals, or themselves are a part of the spiral structure. Furthermore, their occurrence is seen coincident with a bar in the center. In this paper, we interpret this spiral-ring structure as density waves resonantly excited by a rotating bar potential. The theory gives excellent agreement for the molecular spiral-rings in central parts of nearby disk galaxies, observed by high resolution radio arrays. The same mechanism works for more distant spiral-rings in the outer parts of disk galaxies qualitatively, although the problem is complicated by the coupling of the stellar and gaseous disks.

I. INTRODUCTION

Depending on the size, there are four types of rings in disk galaxies. **The outer and the inner rings** are referred to those which are located respectively at the outer edge and at the middle range of a galaxies (Buta & Crocker 1991). More recent high resolution observations with mm or sub-mm arrays (e.g., Planesas et al, 1992; Helfer and Blitz, 1995; Sakamoto et al, 1995) show that there are rings (spiral-rings) in the central regions in the nearby galaxies. These rings (spiral-rings) are associated with gas clouds and usually not visible in optical observations. Again, there are two sizes for them. The larger ones with a size of 1-3 kpc are now referred as **the central rings** (spiral-rings) and the tiny ones with a size from tens to hundreds pc are referred as **the circumnuclear rings** (spiral-rings). More than often, all these spiral-rings occur in the galaxies in the presence of a bar in the center. The purpose of this paper is to interpret these spiral-rings as density waves driven by a rotating bar in a resonance excitation mechanism.

The idea of generating spiral waves by a rotating bar potential was first seen in the work of 2-D hydro-code calculations to simulate spiral barred galaxies (e.g., Huntley et al 1978). The mechanism of generating spiral density waves by a bar was not known until late 70's when Goldreich and Tremaine (1979) attributed such a phenomenon to a resonance excitation mechanism, which they applied successfully to interpreting the structure of Saturn's rings. A comprehensive theory both linear and non-linear, based on the resonance excitation mechanism, was developed by Yuan (1984) to explain the "3-kpc arm" phenomenon in the Milky Way. The "3-kpc arm" is interpreted as one of a pair of the tightly wound spiral arms generated by a rapidly rotating oval distortion (bar) in the center. This was the first attempt to understand the central spiral-rings problem although it was not posed in the context of the above definitions. An improved linear and nonlinear theory of resonance excitation, with explicit inclusion of self-gravitation and viscosity, was subsequently worked out by Yuan and Cheng (1991). The theory not only proves to be convenient to use but also is verified to agree with the results obtained from advanced hydrodynamic codes based on a second order relaxation method (Jin & Xin 1995; Kuo 1996).

The method described above, however, is a hydrodynamic theory. It applies most ideally to the disks for the central spiral-rings and circumnuclear rings. These disks are made of gas only and completely decoupled from the stellar populations. For the outer spiral-rings and the inner spiral-rings, the problem is not so simple. There the stellar component and the gas component are closely coupled. The responses in stars and gas to a rotating bar potential are different and the difference is most pronounced near the resonance regions where our interest is focussed. Besides, the treatment of stellar response to a bar potential also differs from that of gas, in which one must use the Jeans equation instead of hydrodynamic equations. This complicates the analysis considerably. In fact, no such a solution is available today. Thus, we can only give a qualitative answer to the questions concerning the structure of the outer and inner spiral-rings.

In this short paper, we briefly describe the resonance mechanism and outline the non-linear theory in section 2. We summarize the major theoretical results in section 3, in particular, in reference to the central spiral rings of NGC 1068 and M 100. Qualitative results related to the outer and inner spiral-rings in which stellar and gaseous components are strongly coupled are found in section 4. A few general remarks are given in section 5 concerning the future observational tests of the theory.

II. RESONANCE EXCITATION AND THE NONLINEAR THEORY

Particles, be it a star or a fluid element, in a disk galaxy can be excited resonantly by an external bar potential if the rotation speed of the bar potential, Ω_p, is related to the epicyclic frequency κ of the star or fluid element and the local angular speed, Ω, by

$$\Omega_p = \Omega(r)\pm\frac{\kappa(r)}{2}.$$

The locations at radius r where the above relation is satisfied are called the outer and inner Lindblad resonances respectively for the upper positive sign and lower negative sign. Because of the long-range nature of the bar force, particles at the resonances are self-organized into long spiral trailing waves, propagating towards the co-rotation, where

$$\Omega_p = \Omega(r).$$

These waves, however, will be reflected back as short trailing waves before reaching the corotation, according to the linear density wave theory, at the Q-barriers which divide the wavy region from the evanescence region. It is these short trailing waves that forms the spiral-ring structure we observe in disk galaxies.

The pattern of these short trailing waves, in particular, the extent they can propagate, is our primary concern. It is directly related to the questions such as whether rings are parts of the tightly wound spirals, and why spirals are often observed on the both sides of the ring. The answer to these questions depends very much on the fact whether the waves are in the gaseous disks or in the stellar disks. In the stellar disks, the waves cannot propagate beyond the Lindblad resonances and therefore they tend to form rings there. In the gaseous disks the waves can propagate freely beyond them, but their extent is limited by the viscous attenuation. Such a difference obviously has great impact on our results. It separates problems of **the outer and inner spiral-rings** from the **central and circumnuclear spiral-rings**. For the spiral-rings in the central regions or circumnuclear regions, the stars and gas are completely decoupled and only a thin gaseous disk exists. We can formulate the problem there by using gasdynamical equations. As for the outer and inner spiral-rings, the stellar disk and the gaseous disk are fully coupled. There we must use stellar dynamics (Jeans equation) for stars and gasdynamics for the gas, and treat the problem simultaneously. Furthermore, we must deal a situation in which the waves in the stellar disk stop at the Lindblad resonances while the waves in the gaseous disk continue to propagate beyond them. The complete solution for the latter problem, unfortunately, is not yet available. We can only use the linear dispersion relation to extrapolate our results. For a gaseous disk, a comprehensive non-linear theory has been developed. Not only we understand the underlying physical mechanism, but also we can quantify our results to compare with the observations. In what follows we outline this non-linear theory and refer the derivation elsewhere (Yuan & Cheng 1989; Yuan & Cassen 1994).

The theory is based on a Lagrangian formulation in which we seek steady state solutions of perturbation displacement (r_1, ϕ_1) from the original location (r_o, ϕ_o), in a frame rotating with the bar potential $A_1(r)\cos(2\phi)$. The great advantage of using the Lagrangian formulation lies on the fact that the equation of continuity and the Poisson equation can be simplified, in the asymptotic limit of tightly wound spira waves, i.e., $|kr|\gg 1$ with k being the radial wavenumber. They can be expressed as follows:

$$\sigma(r,\phi)(1+\frac{\partial r_1}{\partial r_o}) = \sigma_o(r_o),$$

$$\frac{\partial V_d}{\partial r} = 2G\int_0^\infty \frac{\sigma(r',\phi_o)}{r-r'}dr'.$$

In the above equations, σ is the surface density, V_d, the gravitational potential of the gaseous disk. With the above equations, we can reduce the entire dynamical system into a single integro-differential equation for r_1. This equation may be replaced by a differential equation in a heuristic approach and solved easily by direct Runge-Kutta integration (Yuan and Cheng 1991). The resulting equation is slightly too complicated to be included here. However, we want to emphasize that the equation is fully non-linear and viscosity and self- gravitation are explicitly expressed in it. Furthermore, since this equation yields r_1 and hence ϕ_1, we can obtain streamlines directly by plotting out (r_1, ϕ_1), instead of going through the trouble of integrating the velocity field as in the Eulerian formulation.

III. THE CENTRAL SPIRAL-RINGS

Recent high-resolution radio interferometry observations in the mm and sub-mm wavelengths have revealed the hidden spiral-ring structure in the central regions of many nearby spiral galaxies. And often such a structure is observed associated with a central bar in infrared. Examples are NGC 1068, M 100, IC 342, etc. This puts them in the same category of the Milky Way, in which the "3-kpc arm" phenomenon has long been suspected to be related to a bar (or oval distortion) in the center (Yuan 1984; Yuan & Cheng 1991). The central bar of the Milky Way has recently been confirmed by radio data and COBE data (Blitz & Spergel 1991; Wieland et al 1994). However, we will not discuss the "3-kpc arm" problem here, but rather concentrate on the recent work of NGC 1068 and M 100.

One of the first problems we have to settle is to decide whether these spiral rings are excited by a bar potential at the outer Lindblad resonance (OLR) or at the inner Lindblad resonance (ILR). This can be achieved easily by reading the velocity data along the spiral arms, according to the theory. The gas in the spiral arms has an outward radial streaming motion in the case of OLR and an inward radial streaming motion in the case of ILR. In our analysis, we find another important morphological difference between these two cases. The OLR spiral pattern tends to be tightly wound, while the ILR spiral pattern, to be open. So far we have three examples available. The central spiral-rings of NGC 1068 and the Milky Way belong to the case of the OLR driving. The central spirals of M 100 belongs to the case of the ILR driving. The direction of the streaming motions and the morphology of the spiral patterns match perfectly with the theoretical predictions.

NGC 1068 is a Seyfert galaxy. The central spiral rings are located at 1.5-2.0 kpc from the center, which are seen in CO and HCN observations. We find that they fit with a picture of a rapidly rotating bar at a rate of $\Omega_p = 227.6\ km\ s^{-1}\ kpc^{-1}$. The OLR is at $r = 1.1\ kpc$ and the strength of the bar field there is about 5% of the mean gravitational field. The detailed comparisons with observations are to be published elsewhere (Yuan and Kuo 1996). The original circular streamlines of the gas in response to the rotating bar are distorted into spiral pattern, where the high density regions are represented by the concentration of streamlines. They are shown in Figure 1, in which we rotate the bar 63^o in agreement with the observed position angle and project the disk 40^o according to the observed inclination angle.

Similar calculations are done for M 100, with $\Omega_p = 39\ km\ s^{-1}\ kpc^{-1}$. This rotating speed of the bar gives an ILR driving at 1 kpc, which generates a pair of open spirals. Again, after adopting a position angle of 153^o and an inclination angle of 30^o, the resulting density distribution and the line of sight velocity distribution are plotted in Figure 2. They are in excellent agreement with the observations of Sakamoto et al (1995), both in velocity and morphology.

Another important result of this study is the rate of net mass flux in the disk. This is directly related to the problem of so-called "fueling the AGN or the starburst". As the bar excites spiral density waves in the disk, it imparts angular momentum, positive or negative, to the disk. This angular momentum will be carried by the waves, then deposited in the annular region where the waves occupy. The gas in the annular region will gain angular momentum and move outward in the case of OLR or lose angular momentum and move inward in the case of ILR. The outward moving gas tends to form a ring near the OLR and the inwarding moving gas either accumulates into an inner ring or heads directly to the center. In both cases, gas density is enhanced and the disk there becomes increasingly unstable. This would lead to massive star formation as seen in the starburst galaxies. In the case of ILR, gas in the disk may even spiral into the center to fuel AGN activities directly. Our estimate is for a disk of $\sigma_o = 200\ M_\odot\ pc^{-2}$ a mass flux of $1\ M_\odot\ yr^{-1}$ may be induced by a bar, which is in the same order of magnitude estimated from the observations in AGN and starburst activities. The time scale for the disk evolution under the bar driven mechanism is about 1 billion years. Therefore, we expect recurrence of such activities in the life of such galaxies.

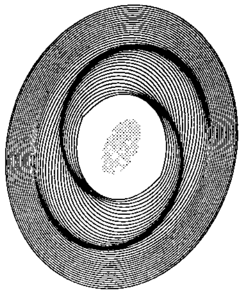

Fig. 1.— Projected streamlines as distorted by a rotating bar, to simulate the observations of the central parts of NGC 1068

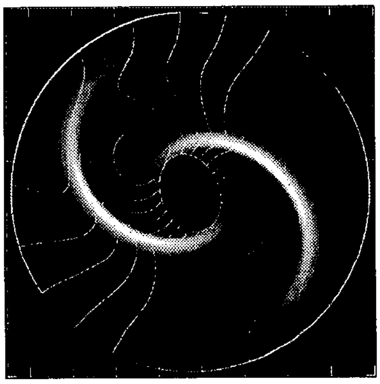

Fig. 2.— Density distribution overlaid with velocity distribution, to simulate the observations of the central region of M 100

IV. OUTER AND INNER RINGS

The problem of the outer and inner rings (spiral rings) involves finding the responses of the stellar and the gaseous disk to a rotating bar potential simultaneously and the possible interaction between them. The problem of finding the response in the gaseous disk is the same as in the previous section. For the problem of the stellar disk, however, not even a linear theory exists. The difficulty is to solve the highly complicated inhomogeneous Jeans equation. Without such a solution at hand, we cannot treat the density wave problem near the resonances. The only thing we can do is to use the results of the gasdynamics for regions elsewhere, but at the Lindblad resonances we consult the results obtained from the joint dispersion relation of stars and gas (Lin and Shu 1968). The results are less satisfactory, but still contain useful information concerning the spiral-ring structure in the outer parts of disk galaxies. We refer our detailed calculations elsewhere (Yuan, Jiang and Lee 1996) and summarize the main results below:

- The spiral-rings are density waves resonantly excited by a rotating bar potential. The ring forms because the stellar density waves cannot propagate beyond the Lindblad resonances.
- The tightly wound trailing spiral density waves of stars and gas, in response to the bar potential, occupy a region bounded by a Q-barrier and a Lindblad resonance. The stellar waves tend to be tangent to the Lindblad circle as they approach it, while the gaseous waves trans-pass it with perhaps some phase change.
- The spiral waves beyond the Lindblad resonance are primarily waves in the gaseous disk, although there may be star formation along the wave crests.
- Stars may gain (OLR) or lose (ILR) from the bar and move toward the Lindblad resonances. This will enhance the ring formation.
- Spiral waves can appear on both sides of the ring. Between the Q-barrier and the Lindblad resonance, the size of the spiral region is controlled by the combined Q value of stars and gas. Beyond the Lindblad resonance, it solely depends on the viscosity of the gas.

V. CONCLUSION REMARKS

In this short report, we discuss the problem of the spiral-ring structure of disk galaxies. We attribute this phenomenon to an interaction between the disk and a rotating bar in a mechanism known as resonance excitation. Spiral waves are generated at the Lindblad resonances and form rings either due to viscous attenuation of the waves in a gaseous disk, or due to the inability to pass the Lindblad resonance in a stellar disk.

For the central and circumstellar disks, we have both analytical solutions and numerical solutions. The results are in perfect agreement with observations. But, for the outer and inner spiral rings, we have only qualitative results based on the extrapolation of gasdynamics and the combined dispersion relation of stars and gas.

From the results of gasdynamics, we conclude that bar-driven spiral density waves at OLR tend to be tightly wound and at ILR, to be open. This morphological difference gives the great advantage of telling the rotating speed of the bar. Since a disk galaxy of high concentration of matter at the center is thought to favor a fast bar and to have OLR near the center, it is likely to drive a pair of tightly wound spirals near the center. On the other hand, a galaxy of less concentration of matter in the center is likely to support a slow bar and to have ILR near the center, hence to generate a pair of open spirals. This theoretical prediction can be tested observationally, since a galaxy of high concentration of matter has a rapidly rising rotation curve in the center while a galaxy of less concentration of matter does not.

Another test is the radial streaming motion. The open spirals have inward radial streaming motions, due to an ILR driving, while the tightly wound spirals have outward radial streaming motion, due to an OLR driving, according to the theory. So far, the Milky Way, NGC 1068 and M 100 all agree with these results. We can check other galaxies and propose more observational tests.

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