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Rotation Curve vs. Central Spiral-Bar Structure in Nearby Galaxies

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Abstract

Most of the nearby galaxies are found to have a central gas-dust disk. Their structures, however, are often obscured by the background luminous star lights. These hidden structures, however, can be extracted from observations by using wavelet methods, after the broad contributions of the Population II stars in the center are removed. The **atrous** wavelet method proves to be extremely useful for such a purpose. We have analyzed the NICMOS and WFPC (WFPC2) data from HST for some 15 nearby disk galaxies without a major bar, for which rotation curves, either by HI or by Hα, are available. We divide our sample galaxies into two groups: one with rapidly rising rotation curves and the other, slowly rising rotation curves. According to the theory developed by Yuan and Kuo (1997, ApJ, 486, 750), the former tends to host a fast nuclear bar (or oval distortion) capable of exciting tightly wound central spirals and the latter tends to give rise to open central spirals which are excited resonantly by a slowly rotating nuclear bar. We use the wavelet methods to search for the central spirals and their morphology in our sample galaxies and test the theory. We find for most of them, the central regions are characterized by spiral or/and bar structures. The majority supports the theoretical prediction. Removing from our list those galaxies which have conflicting data on their rotation curves, or those for which the central structure cannot be discerned by the present method, we present the results for 10 galaxies in this paper.

1.1 Introduction

Recent high resolution observations, either by the HST or by radio interferometry, have unveiled great details of the central regions of the disk galaxies. The majority of the observed nearby galaxies have a gas-dust disk with a size varying from a few hundred parsecs to a couple kilo-parsecs, which is often characterized by the presence of spiral or spiral-bar structures. Since a rotating bar potential can excite spiral density waves, and spiral density waves, in turn, can transport angular momentum between the bar and the disk, the spiral-bar structures are regarded as an evidence of a fuelling mechanism to power the AGN and starburst ring activities, which again are frequently seen in these galaxies and presumably are associated with a supermassive black hole in the center.

While the mechanism of bar-driven density waves and fuelling AGN's and starburst rings has been studied by several authors (e.g., Yuan and Kuo 1997, and references therein), the subject remains controversial (Reagan and Mulchaey 2000). In this paper, we will report further evidence to support the mechanism from analyzing HST data by means of the wavelet methods. In particular, we compare the theory of bar-driven density waves put forward by Yuan and Kuo (1997) with the HST observations to test this mechanism. We present the theory in section 2, the analysis of the observations in section 3, and comparison between the theory and observations in section 4, where we also draw the conclusion of our study.

1.2 The Theory

Spiral density waves are excited at the Lindblad resonances by a rotating bar in the gas disk surrounding the galactic center. A rapidly rotating bar can excite a pair of tightly wound spirals, or ring-spiral structure, at the outer Lindbald resonance (OLR) while a slowly rotating bar, open spirals at the inner Lindblad resonance (ILR). We believe a fast nuclear bar probably results from a Jacobi-type instability for the highly concentrated, hence rapidly rotating, mass of stars in the center, while a slow bar, an orbit trapping mechanism at ILR, for which relatively low concentration of stellar mass in the center is required. Thus the following sequences are in order (Yuan & Kuo 1997):

fast bar↔high concentration of matter at center ↔rapidly rising rotation curve
slow bar↔low concentration of matter at center ↔slowly rising rotation curve

Furthermore, since fast bars excite tightly wound spirals and slow bars, open spirals, we expect the following sequences to be in order:

rapidly rising rotation curve↔tightly wound central spirals with an exterior ring
slowly rising rotation curves↔open spirals with a possible interior ring

There is a possible exception though. For galaxies with a major bar, the spiral waves are possibly excited at the ILR by the major bar, not by a slow nuclear bar. For such cases, galaxies with moderately rising rotation curve can still have open spirals, such as NGC5383. To avoid this complication, we only test our theory among galaxies which do not have a major bar. Another test which cannot be performed here is related to kinematics:

tightly wound central spirals↔isovelocity curves bent inward along spiral arms
open spirals↔isovelocity curves bent outward along spiral arms

That test can be achieved by the high resolution observations of molecular lines by using mm and sub-mm interferometry.

1.3 The Observations

We took a list of nearby galaxies provided to us by Dr. Luis Ho (private communication), supplemented with BIMA SONG galaxies. The majority of them do not have the corresponding HST data and rotation curves simultaneously. About 40 galaxies do have both. Then some of them have serious discrepancy in observed rotation curves from different sources; some of them are almost edge-on; some of them are marked with chaotic central structure. After eliminating them, about a half of them can be studied.

Among them, we present the results of our *atrous* wavelet analysis of the HST data of 10 nearby non-major-bar galaxies. We divide them in two groups: one with rapidly rising rotation curves and the other with slowly rising rotation curves. There are 7 for the former and 3 for the latter. Rotation curves are taken from Rubin et al (1999), Sakamoto et al (1995), Helfer and Blitz (1995), Courteau (1997), Sofue et al (1999), and Jogee et al (2002).

It is hard to draw a line between a rapidly rising rotation curve and a slowly rising one.

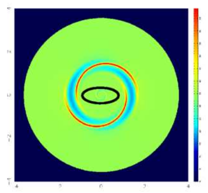
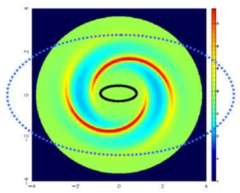
OLR	ILR
	

Fig. 1.1. The spirals excited by a fast bar and a slow bar at OLR and ILR respectively at $r = 1.5\ kpc$. The fast bar is necessarily a nuclear or central bar. The slow bar can be a nuclear or central bar, or a major bar of the galaxy, as long as it provides a doubly periodic forcing at ILR.

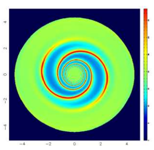
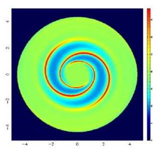
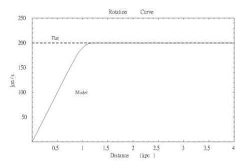
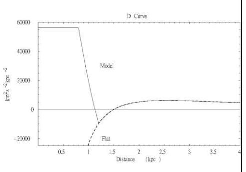
ILR-flat	ILR-model	Rotation curve	D curve
			

Fig. 1.2. Spirals excited at ILR propagate towards the center. The two examples shown above have the same viscosity and both are excited at $r = 1.5\ kpc$. The left one has a flat rotation curve and the right has flat rotation curve from $r = 1\ kpc$ outward and connected to a rigid-body rotation curve from $r = 0.8\ kpc$ to the center. On the left the waves go all the way to the center and on the right, waves are stopped immediately at the rigid-body region, which defines a wave forbidden region. It happens when $D = \kappa^2 - 4(\Omega - \Omega_p)^2 > 0$, where κ is the epicyclic frequency, Ω, the angular speed of the disk, and Ω_p, the rotating speed of the bar. The rotation curves and the $D - r$ are shown on the right.

In general, rotation curves rising above 200 km/s within 1 kpc are considered rapidly rising, and those below 120 km/s, slowly rising. In between, we usually group those not rising above 150 km/s over 2-3 kpc to be slowly rising. The results are shown in Figure 1.4 and Figure 1.5.

1.4 Concluding Remarks

Among the galaxies we study, seven have fast rising rotation curves, and they all have either tightly wound central spirals or spiral-bar structures. These spirals are waves excited by a fast rotating bar at the OLR. The nuclear bar can all be identified in these cases. The ring lies exterior to the spirals. And the high density accumulated in the ring will give rise to the starburst ring activities.

Three galaxies are grouped in the group with slowly rising rotation curves. They all have relatively open central spirals and for some of them we can follow the spirals all the way to the center, such as NGC5248. These spirals are excited at ILR by a slowly rotating nuclear bar. Whether they form a ring interior to the open spirals depends on the viscosity of the gas

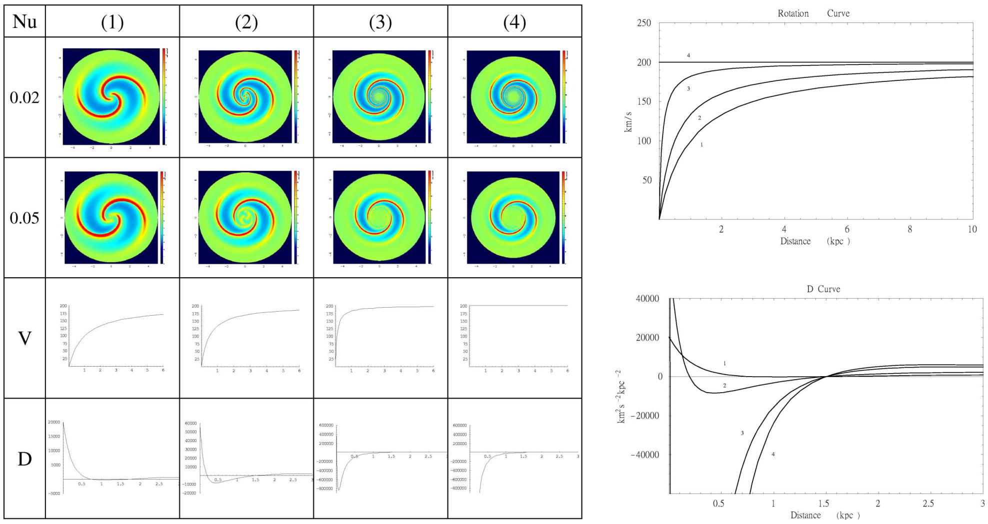


Fig. 1.3. The spiral patterns excited at ILR are sensitively dependent on the rotation curves. We make the ILR's all at $r = 1.5\ kpc$. The results vary considerably as how far the rotation curve rises. The slower the rotation curve rises, the more open the spirals become. We plot the results in the above. Two values of kinematic viscosity (ν, or Nu) are used for each spiral patterns, to demonstrate the effect of viscosity. The rotation curves and the D-curves are also shown for comparison. Please note the leading spirals at the center are waves excited at the inner inner Lindblad resonance (IILR).

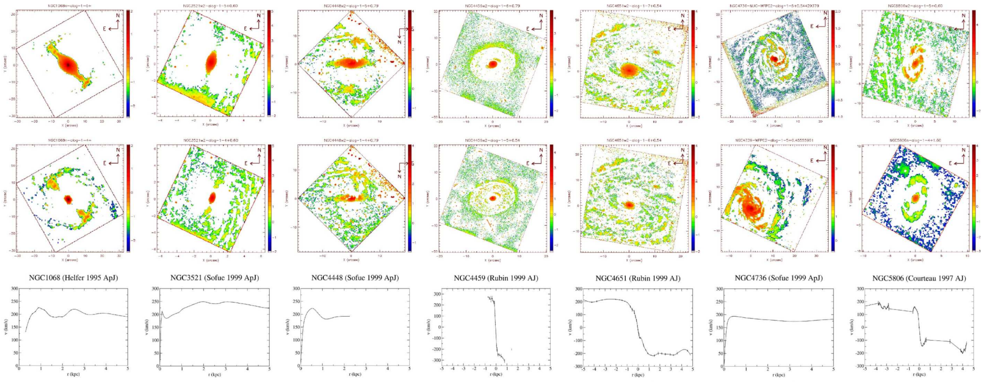


Fig. 1.4. Central spiral structure and rotation curves of 7 nearby galaxies. The rotation curves are all rapidly rising from the center. Spirals are believed to be excited by a fast nuclear bar at OLR. The top two rows are wavelet analysis results and the bottom row shows the rotation curves, taken from various sources. See text.

disk. If viscosity is small, as in the case of NGC5248, the waves can go all the way to the center and the disk mass will fall into the center to fuel the AGN. If viscosity is large, a ring interior to the spirals will form and it will be the site for starburst ring activities.

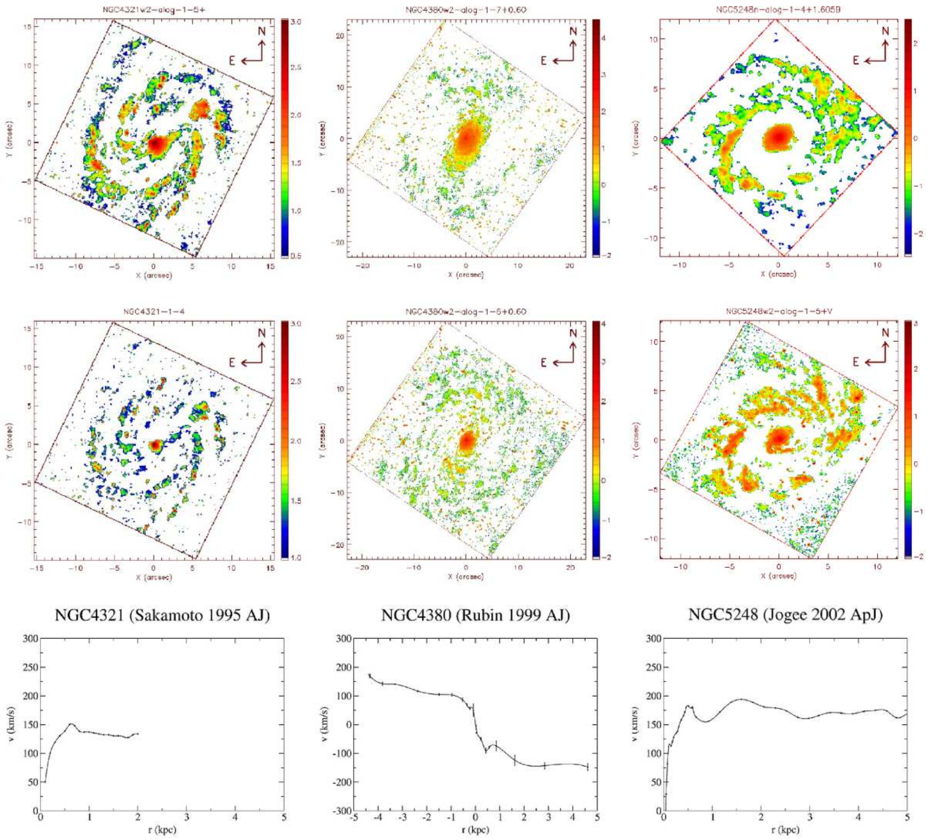


Fig. 1.5. Central spirals and rotation curves of 3 nearby galaxies. Their rotation curves are slowly rising from the center. The central spirals are all relatively open. Some of them can be traced all the way to the center. They are believed to be excited at ILR either by a slowly rotating nuclear bar. Wavelet results of the central region are shown in the first two rows. The rotation curves are depicted in the bottom row.

The comparison carried out here supports our theory. We hope to build up a stronger case in the future when more quality data in image and kinematics become available.

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