Locating Corotation Radii in Galaxies Using the Potential-Density Phase Shift Method

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ABSTRACT

The most important wave-particle resonance in disk galaxies is the corotation resonance (CR), where the pattern speed of the density wave equals the angular speed of the rotation of the stellar disk. CR is one of the parameters that characterize how a wave interacts with the basic state of a galactic disk, and determining its location is important to characterizing the dynamics and evolution of a given galaxy's disk. We have shown (Zhang & Buta 2007=ZB) that CR for a wave *mode* may be located using an azimuthal **potential-density phase shift** which is non-zero for a wave mode possessing a bell-shaped radial angular momentum flux, which is found to be the case for all spontaneously-formed density wave modes. The non-zero potential-density phase shift is predicted both by the Poisson's equation and by the equations of motion. Because these two approaches needs to give consistent predictions for the potential and density for a self-sustained density wave, we can use near-infrared images alone to locate phase shift zero-crossings, which we identify as the CR radii, assuming the light traces the mass. In this poster, we apply the ZB method to 153 galaxies in the Ohio State University Bright Galaxy Survey (OSUBGS, Eskridge et al. 2002). Full details are in Buta & Zhang (2009).

BACKGROUND

The ZB approach is based on the theory of Zhang (1996, 1998, 1999), who, in contrast to Lynden-Bell & Kalnajs (1972) showed that not only gas, but also stars must be involved in the secular evolutionary history of a galaxy, and furthermore should be a major contributor of the mass redistribution process which grows bulges and transforms galaxy morphologies. To enable the participation of stars requires the presence of spontaneously formed spiral and bar modes, because the azimuthal phase shift between the modal density distribution and the potential implied by that density leads to a collective dissipation process that redistributes angular momentum and slowly transforms a galaxy's morphology.

The ZB method has a number of advantages over other approaches to locating CR: (1) relatively insensitive to star formation, M/L variations, and vertical scale height assumptions; (2) can be applied to face-on galaxies; (3) can be applied effectively to all Hubble types, at least those with a disk shape; (4) multiple pattern speeds are simultaneously determined; (5) gives corotation radii directly; and (6) can use existing databases of images without the need for significant investments in new telescope time.

APPLICATION OF THE NEW APPROACH

For a self-sustained spiral or bar mode, the potential-density phase shift should change sign at the corotation radius. This sign change can be used to locate corotation radii (Zhang 1996).

NIR images can be used to measure the phase shifts because such images trace the stellar mass distribution better than do optical images, and may be used to calculate the gravitational potential. We have made such calculations for 153 OSUBGS galaxies, a statistically viable sample limited to $B_T < 12.0$ (Eskridge et al. 2002). A typical phase shift distribution is shown in Fig. 1. The basic assumptions are that the H-band mass-to-light ratio is constant, the vertical scale height is a type-dependent fraction of the radial scale length, and that galaxies can be deprojected using the shapes of outer isophotes. The deprojected images we use are due to Laurikainen et al. (2004).

The basic rule for identifying a CR radius using the ZB method is that a region of positive phase shift (P) must be followed by a region of negative phase shift (N). CR is identified as the positive-to-negative (P/N) crossing. This is not always clear-cut as multiple patterns may be in the process of decoupling. Fig. 2 shows a possible pattern decoupling sequence based on three OSUBGS galaxies. The rule has also brought attention to the possible existence of superfast bars, where the bar extends beyond its CR, possibly all the way to its outer Lindblad resonance. Figs. 2-5 summarize the main results from our study.

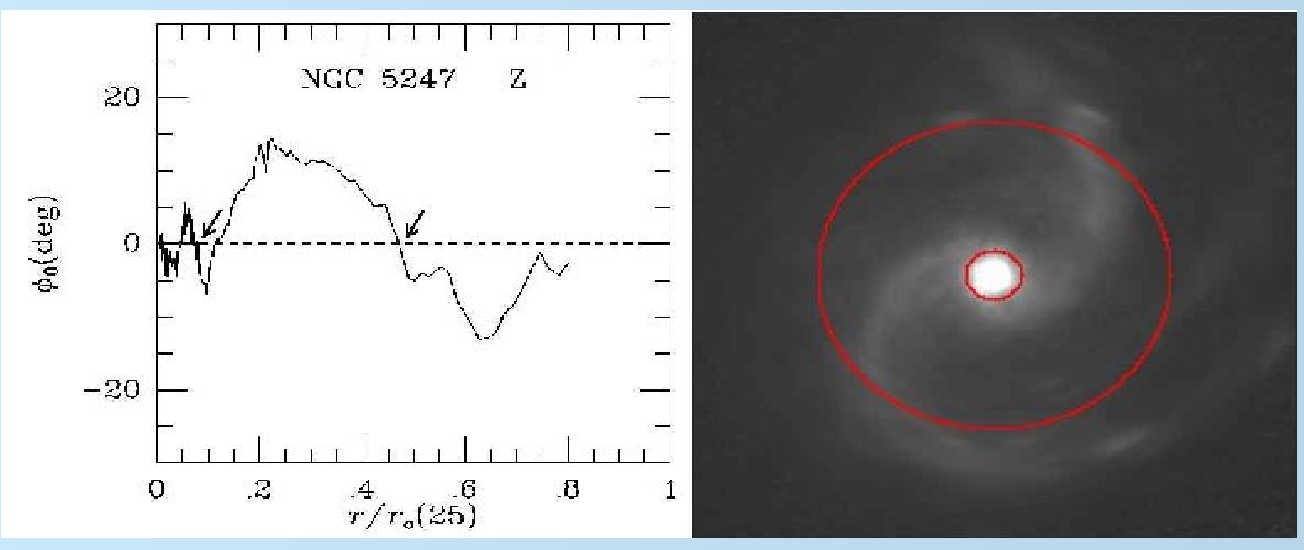

Fig. 1. Phase shift versus radius for the ordinary spiral NGC 5247, showing a major (positive to negative, or P/N) crossing at r/r_o=0.45, where r_o is the corrected (face-on) RC3 isophotal radius at a B-band surface brightness of 25.00 mag/arcsec^2. The red circle superposed on the OSUBGS H-band image at right shows that this CR lies in the middle of the bright spiral. Another CR lies near the center of the galaxy.

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Fig. 2. Schematics of a possible evolution scenario of the phase-shift distribution. In phase 1, the bar and the spiral share a single pattern speed and there is one major P/N crossing. In phase 2, there is a weak/shallow P/N crossing in the intermediate region of the bar/spiral, indicating decoupling of patterns. In phase 3, this decoupling has been largely completed, and there are now separate crossings for the bar and the spiral. The ``model'' for phase 1 is NGC 7479, that for phase 2 is NGC 613, and that for phase 3 is NGC 4593. In each case, the radii have been scaled to place the main CR (arrows) in the same relative position. Galaxy images with overlaid CRs for these three cases can be found in Buta & Zhang (2009).

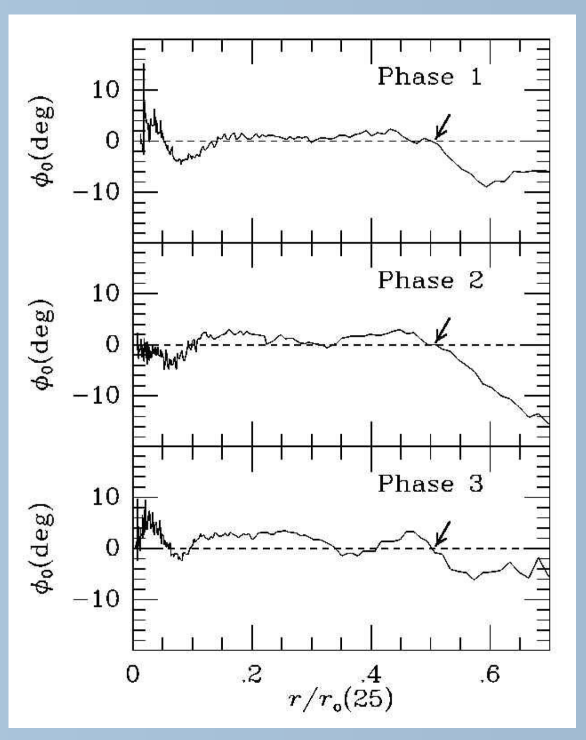
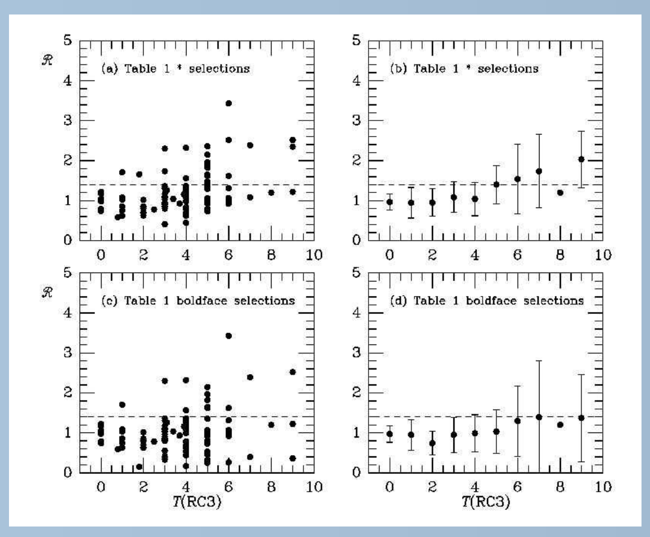


Fig. 3. The ratio of corotation to bar radius, ***R*** = r(CR)/r(bar), for the OSUBGS galaxies having a ``Fourier bar'' (Laurikainen et al. 2004), plotted versus numerical RC3 stage-index (a kind of modified Hubble type). Case (a),(b): Individual points and means with standard deviations based on the CR radii closest to or larger than the bar radius (* in paper Table 1). Case (c),(d): Same as (a),(b) but using CR radii inside the bar (boldfaced in paper Table 1) as alternative interpretations. The dashed horizontal line is set at the value 1.4, used to delineate a boundary between fast and slow bars (Debattista & Sellwood 2000).



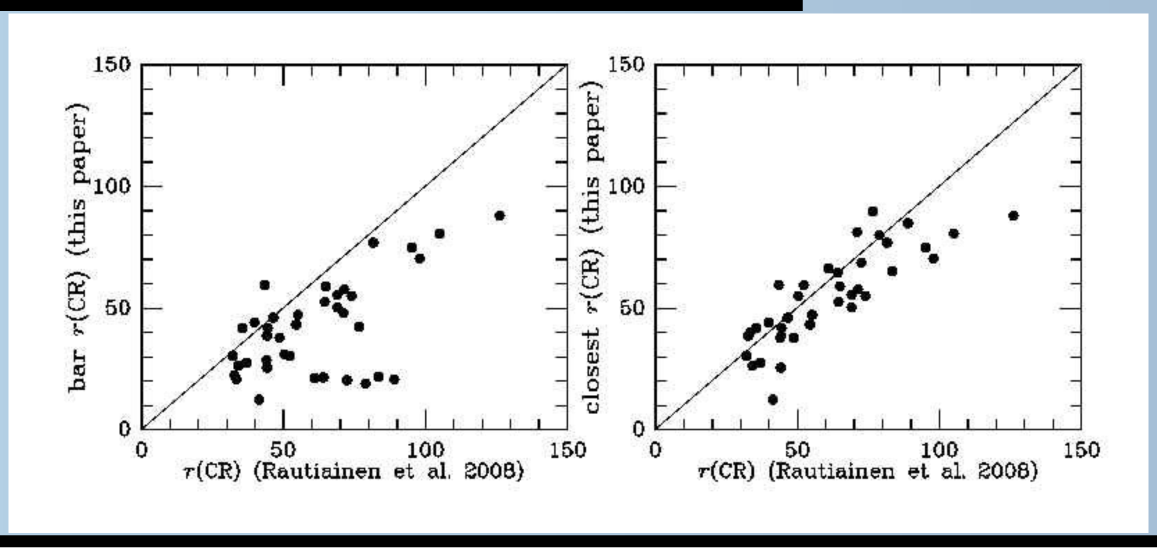


Fig. 4. Comparisons of phase-shift method radii (in arcseconds) with those estimated from numerical simulations by Rautiainen et al. (2005,2008). (left) Comparison between our selected bar CR radii and theirs. (right) Comparison between the phase shift CR radii closest in absolute value to theirs. Results indicate that Rautianinen et al.'s single pattern speed in simulations might be the speed of outer spiral rather than bar.

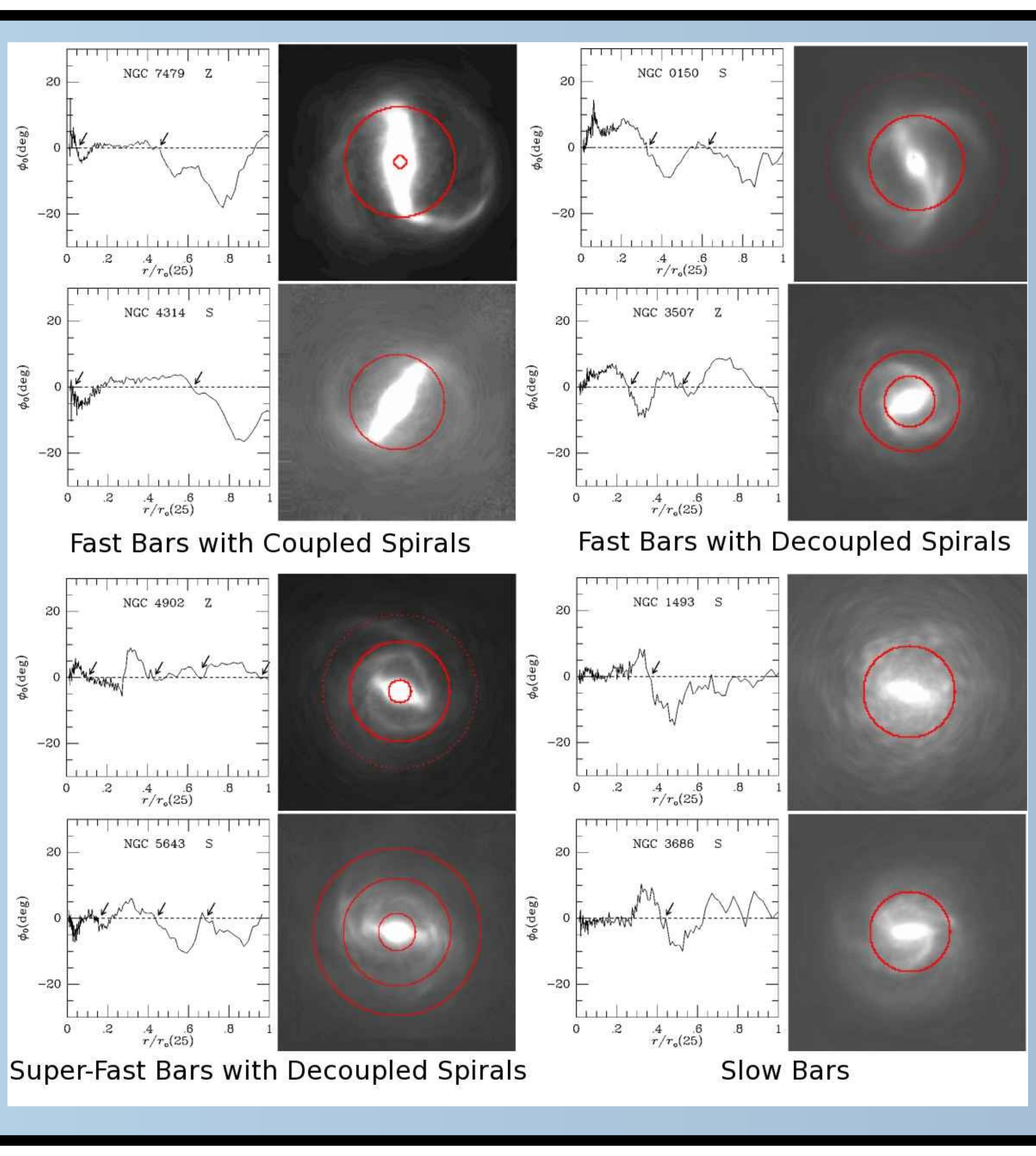


Fig. 5: Montage showing examples of bars in different categories. Fast bars with coupled spirals are cases where the bar and spiral probably have the same pattern speed. Fast bars with decoupled spirals are cases where the bars extend to near their CR radius, but the spiral has a different CR radius. Super-fast bars with decoupled spirals are very unusual cases where the CR of the bar is likely to be well inside the ends of the bar. Slow bars are cases where ***R*** > 1.4.

CONCLUSIONS

- most phase shift distributions correspond to real galaxy features, are not just noise
- multiple CRs are found in many galaxies, indicating nested resonance patterns with different pattern speeds
- some phase shift distributions show evidence of ongoing pattern decoupling
- for grand-design spirals, ZB method places CR in the middle of the spiral
- phase shift CR radii are generally smaller than numerical simulation CR radii, indicating these single-pattern-speed simulations tend to lock onto outer spiral speed
- a possible Hubble-type dependence in the CR-to-bar length ratio ***R*** is identified, with later types having larger values
- compelling evidence for normal fast (***R*** ~ 1) bars with either a coupled or decoupled spiral is found
- evidence is less compelling for slow bars (***R*** > 1.4).
- the existence of "superfast" bars ((***R*** < 1) strengthened by our analysis; if real, the type dependence in ***R*** is weakened.
- our finding of quasi-steady ***nested wave modes*** and their close correspondence with the phase shift distribution contradicts Lynden-Bell & Kalnajs (1972)'s conclusion of a constant angular momentum flux throughout the disk

We thank E. Laurikainen for the deprojected images we have used in this study. RB acknowledges the support of NSF grant AST 050-7140 to the University of Alabama. Funding for the Ohio State University Bright Galaxy Survey was provided by NSF Grants AST 92-17716 and AST 96-17006, with additional funding from the Ohio State University.