Density Wave-Induced Morphological Transformations of Galaxies Along the Hubble Sequence

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Goals of this Presentation

- A full-fledged theory of secular evolution that can explain a variety of effects cannot be based on gaseous flows alone (Kormendy & Kennicutt 2004 and the references therein). The buildup of bulges likely depends on radial flows of stellar mass also (Pfenniger 1999).

- In Zhang (1996, 1998, 1999) a new dynamical mechanism for the radial redistribution of both the stellar mass and gaseous mass was discovered, through the consideration of collective effects associated with spontaneously formed density wave modes.

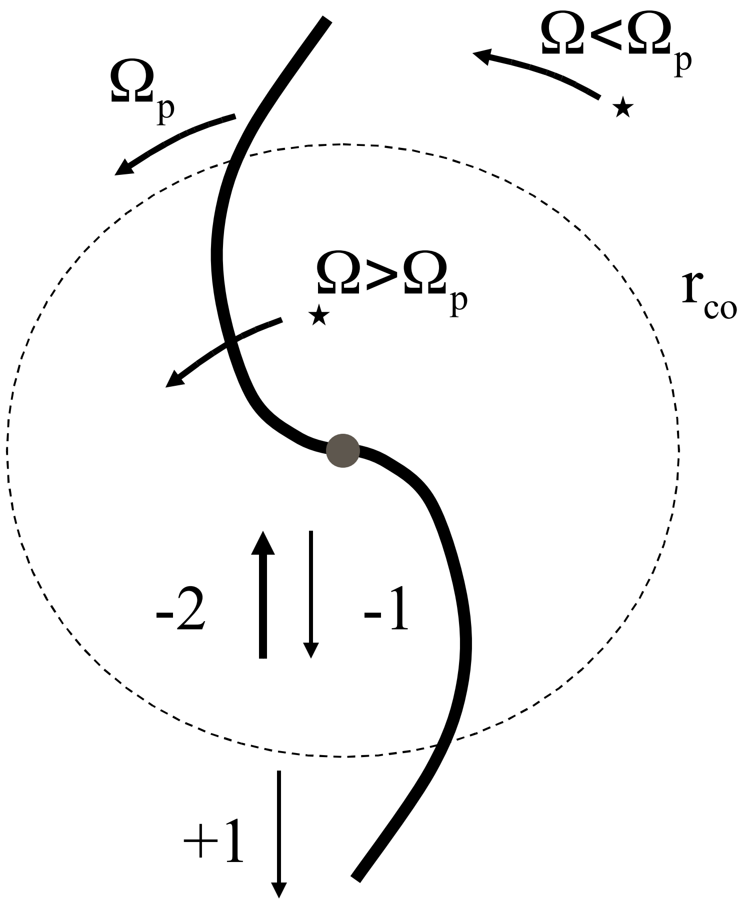
- In these studies, the significance of a potential-density phase shift became clear, and the major inferences from the theory invalidated earlier conclusions of Lynden-Bell and Kalnajs 1972 (LBK72).

- The implications of the new secular evolution mechanism are far-reaching and need to be further explored. In this presentation, we will describe recent developments in examining the applicability of the theory to real galaxies (Zhang & Buta 2007; Buta & Zhang 2009).

Self-Organization and Collective Dissipation in Complex Natural Systems

- Ilya Prigogine's theory of "dissipative structures" in open, far-from-equilibrium, complex physical and biological systems.
- Other related terminologies: symmetry-breaking; morphogenesis; emergence of simplicity from complexity, synergetics.
- Existence of pattern not merely as veneer: The role of dissipative structures in accelerating the speed of entropy evolution in the parent systems. Entropy evolution of self-gravitating systems.
- Density wave patterns as self-organized global instabilities in differentially rotating galaxy disks (N-body simulations).
- Fluctuation-dissipation theorem.

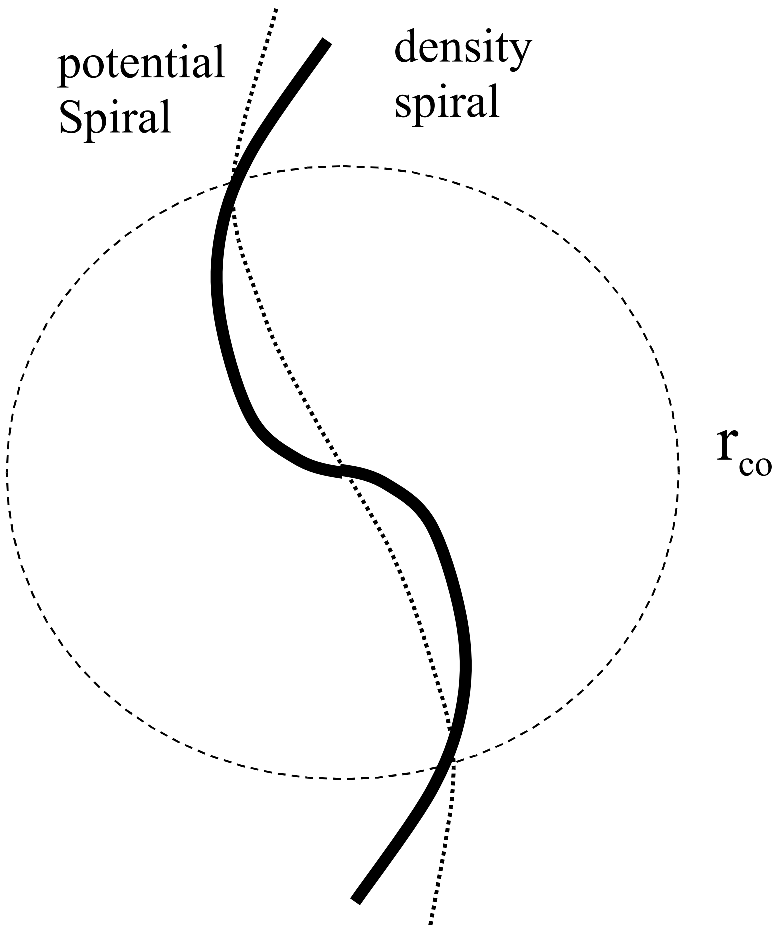
Formation of Spontaneously-Growing Spiral Modes Due to Galactic Resonant Cavity Feedback Loop and Over-Reflection at the Corotation Circle



Main Results of Classical Density Wave Theories

- Mechanisms for the maintenance and amplification of the density wave modes were found through self-consistent solution of Poisson equation and equations of motion (Lin & Shu 64, 66; Toomre 69,81; Mark 74).
- Locally self-consistent nonlinear solutions for spiral modes obtained using WKBJ approximation (Shu, Yuan, & Lissauer 1985). No dissipation incorporated.
- Globally self-consistent solutions found to linear order, but produced infinitely growing modes. Nonlinear damping mechanisms being sought through dissipation in the gas, as well as stellar heating (Kalnajs 72; Roberts & Shu 72; Bertin et al. 89).
- Outward angular momentum transport by trailing spiral density wave, but no wave/basic-state interaction except at wave-particle resonances (due to conservation of the Jacobi integral for passive orbits under spiral potential). No secular basic-state evolution. Angular momentum flux across the galactic disk is a **constant** (Lynden-Bell & Kalnajs 72) -- true only for wave trains not for spontaneously-formed density wave modes.

Phase Shift, Torque, and the Angular Momentum Exchange between the Wave and the Basic State



The torque applied by the spiral potential on the disk density in an annulus at r is:

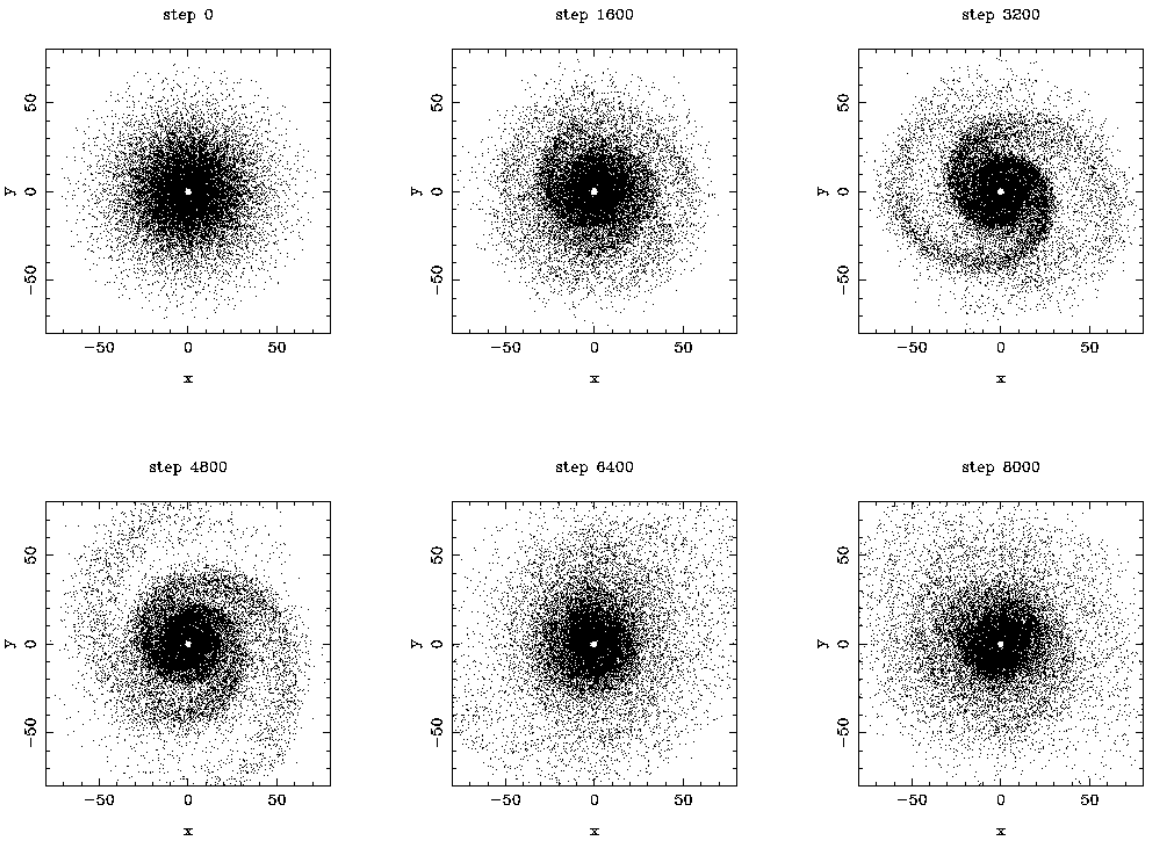
$$T(r) = \frac{dL}{dt} = r \int_0^{2\pi} - \Sigma(\vec{r} \times \nabla V)_z \, d\varphi$$

$$= - m\pi \, r \Sigma_1(r) V_1(r) \sin(m\varphi_0(r))$$

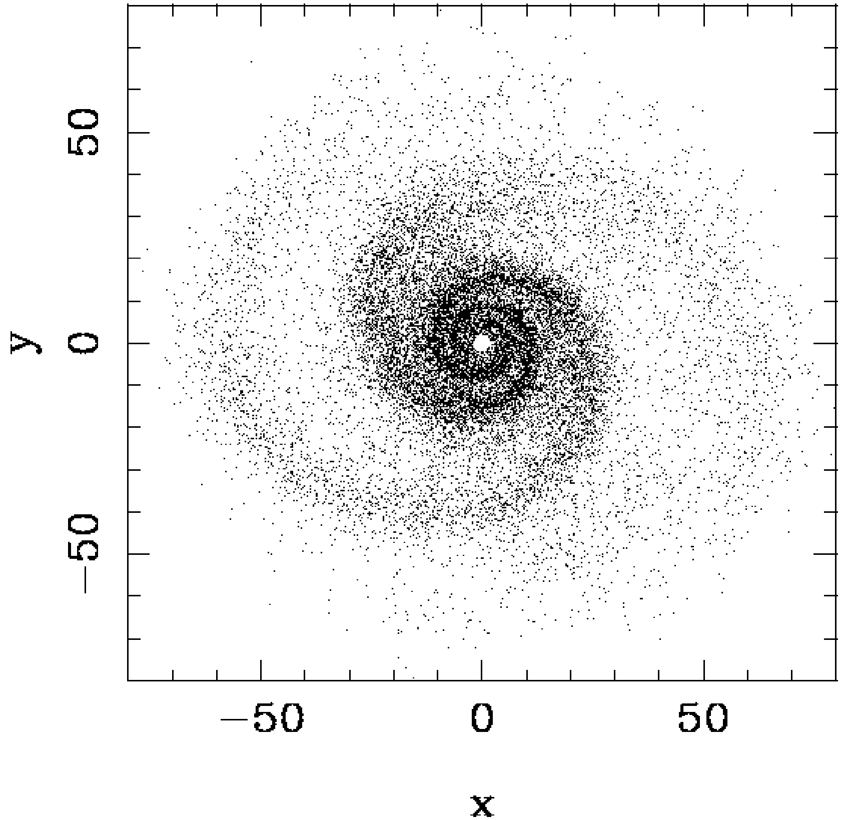
where: Σ is the disk surface density, V is the disk potential, m is the number of arms, Σ_1 is spiral density perturbation amplitude, V_1 is spiral potential perturbation amplitude, L is the angular momentum in the annulus, φ is the potential/density phase-shift.

Question: What then is the dissipative mechanism which leads to the wave/basic-state energy and angular momentum exchange? Answer: Collisionless shocks in spiral arms.

N-Body Simulations of Spontaneously-Formed Spiral Patterns (Zhang 1996, 1998, 1999)

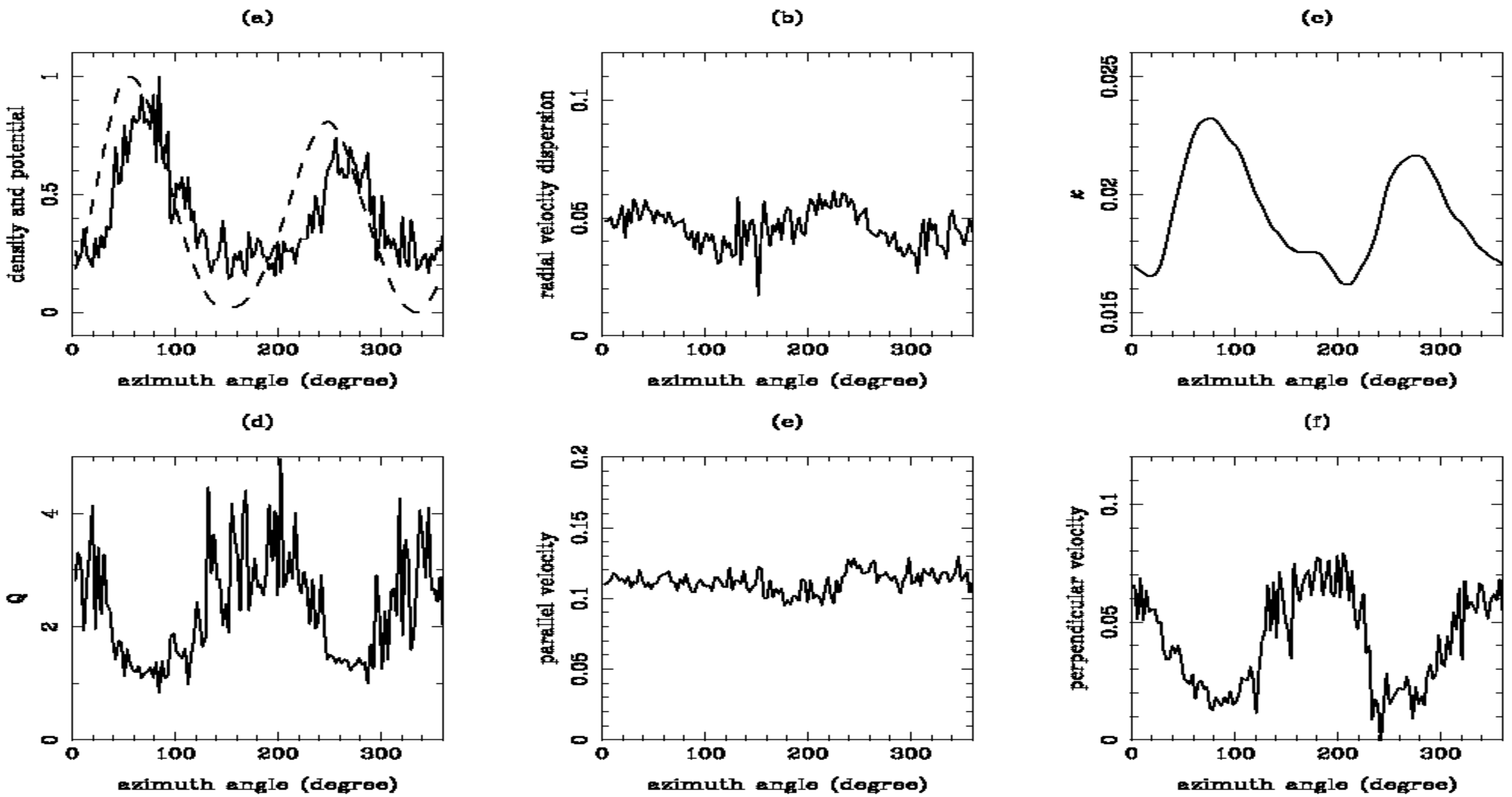


Close-up Image of an N-Body Spiral Mode

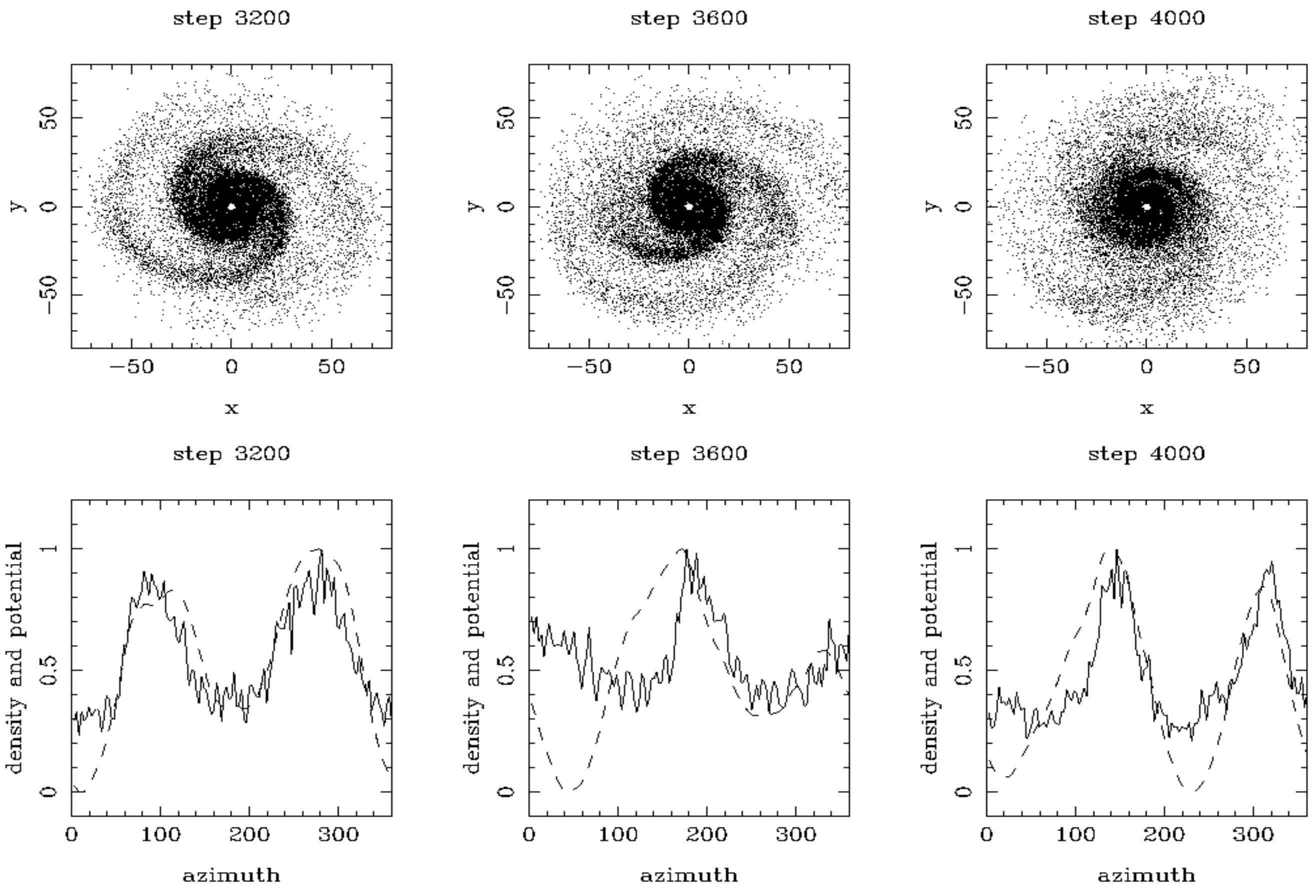


From Zhang 1996, ApJ, 457, 125

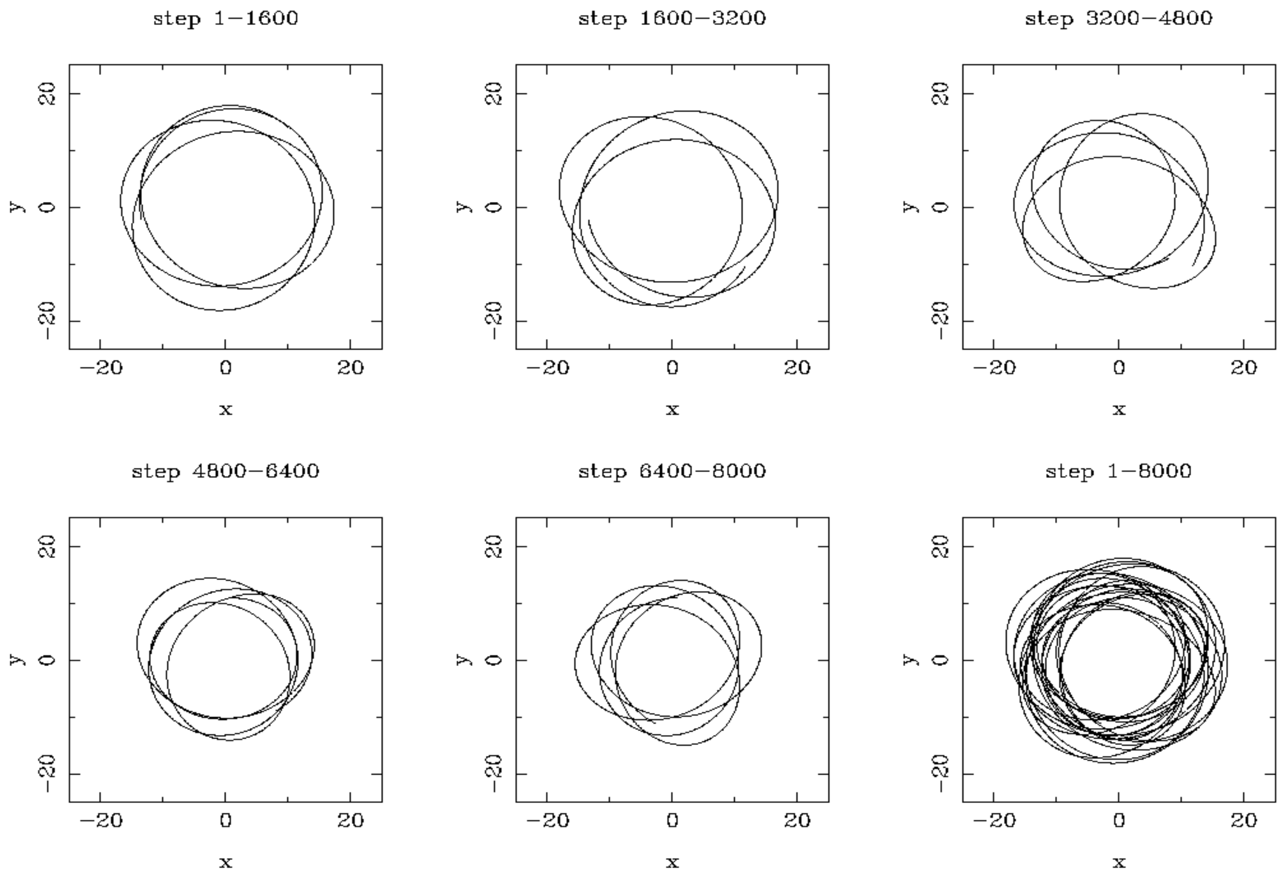
Variation of Disk Characteristics Across Azimuth for a Radial Location Inside Corotation



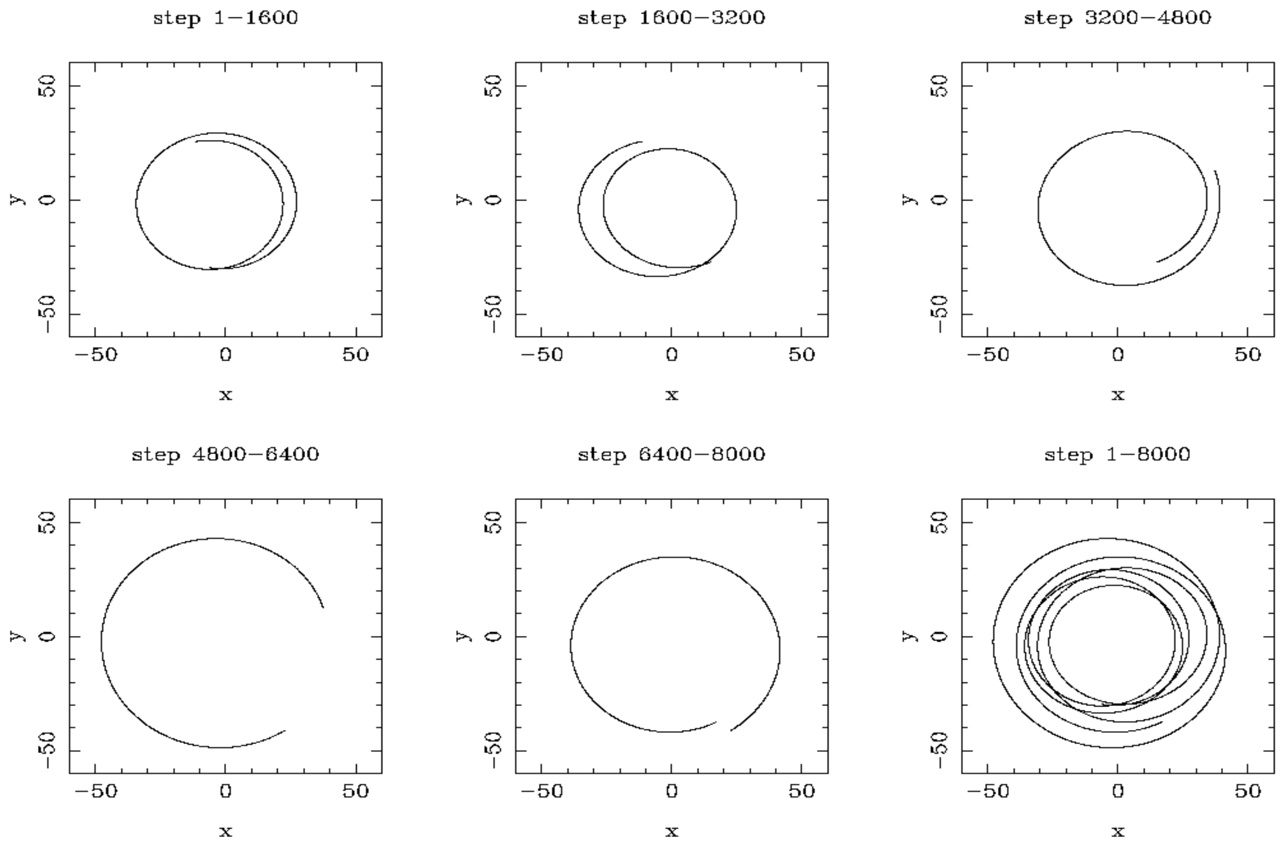
Profiles of the Spiral Collisionless Shock and its relation to potential-density phase-shift



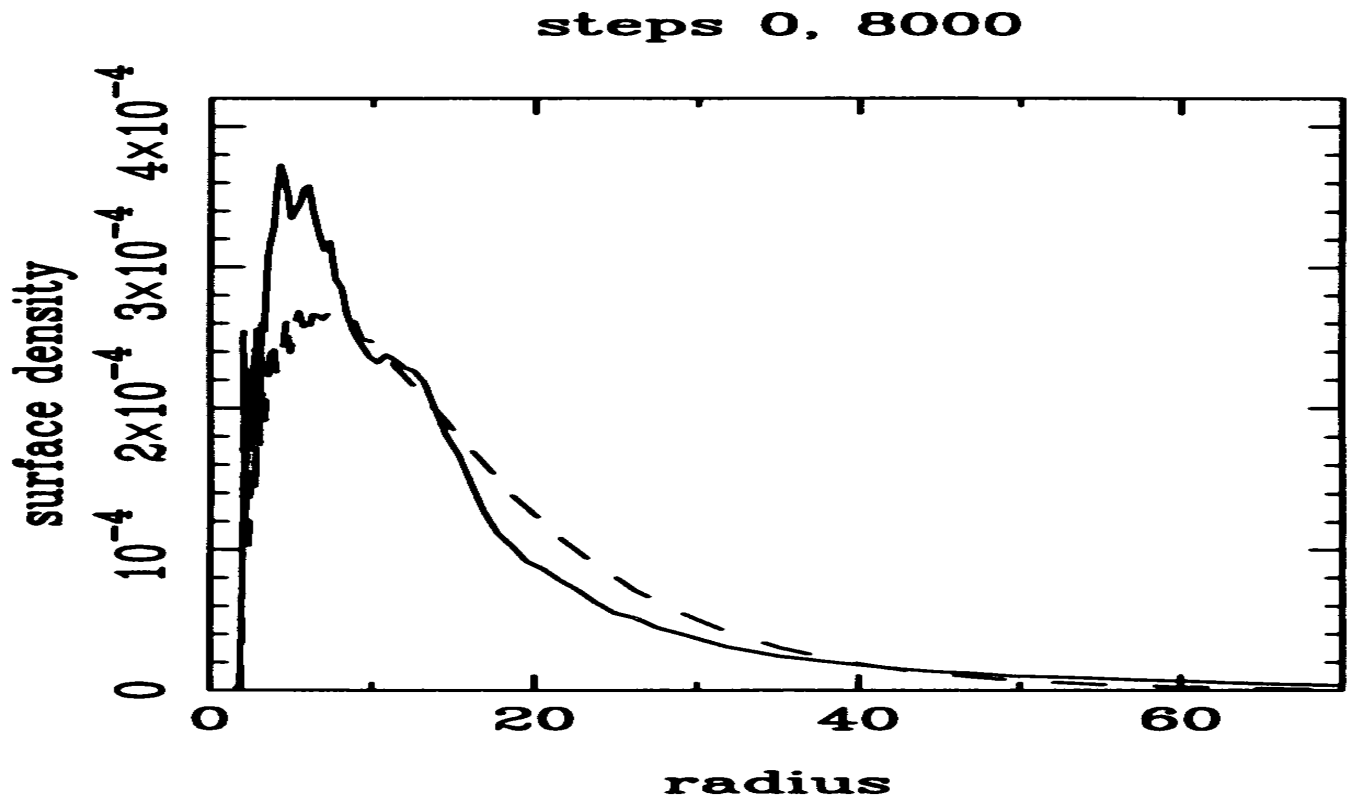
Evolution of a Typical Stellar Orbit Inside Corotation



Evolution of a Typical Stellar Orbit Outside Corotation



Simulated Disk Surface Densities at Time Step 0 (Solid Line) and 8000 (Dashed Line)



Radial Mass Accretion

Orbital decay rate and radial mass accretion rate derived from the secular evolution theory (numerical values refer to that of the Milky Way Galaxy):

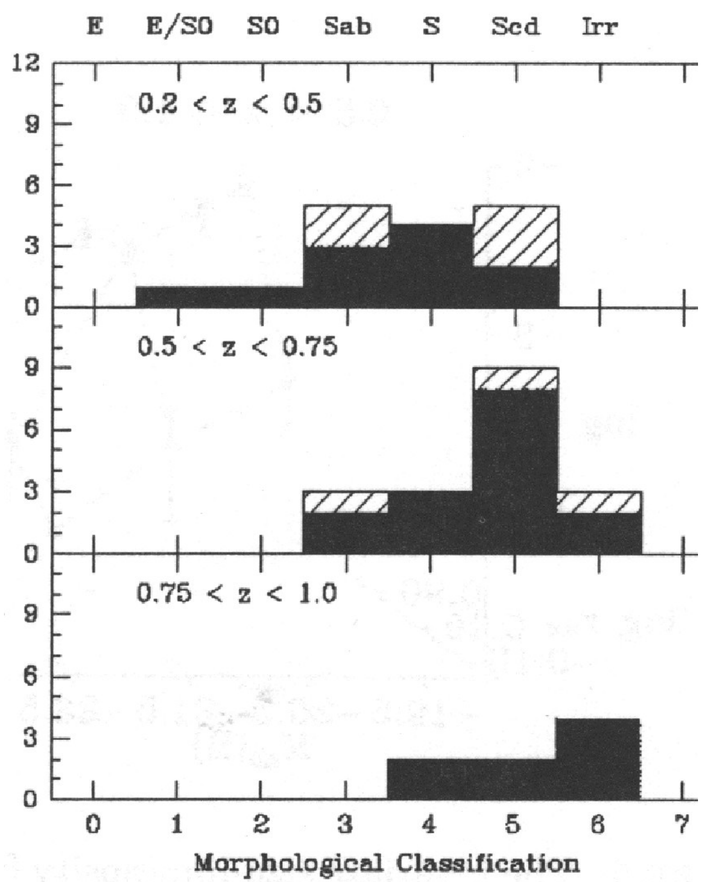
$$\frac{\mathrm{d}r_*}{\mathrm{d}t} = -\frac{1}{2} F^2 v_c \tan(i) \sin(2\varphi_0) = \frac{2kpc}{10^{10}\, yr}$$

$$\frac{dM}{dt} = 2 r \Sigma \pi \frac{dr_*}{dt} = 0.6 \times 10^{10} M_{sun} / (10^{10}\, yr)$$

where F is the fractional wave amplitude, v_c is the circular velocity in the disk, S is the surface density, i is the spiral pitch angle, and f_0 is the potential-density phase shift. For pitch angles not too large f_0 is approximately proportional to i. So the effective evolution rate is approximately proportional to wave amplitude squared and pattern pitch angle squared.

These analytical rate equations are quantitatively confirmed in N-body simulations (Zhang 1998).

Morphological Transformation of Large Disk Galaxies in the Fields



Data from Lilly et al. (1998). Large disk galaxies in the fields are one of the groups which show the slowest morphological transformation with redshifts.

Cluster galaxies show much more pronounced transformation (the so-called morphological Butcher-Oemler effect).

In secular evolution scenario this difference in evolution speed is due to the dependence of evolution rate on the spiral amplitude squared and spiral pitch angle squared.

The Differing Evolution Rates for Cluster and Field Galaxies

- Cluster galaxies show pronounced evolution (late-type disks to S0s and ellipticals) between the intermediate redshift and the present (Butcher & Oemler 1978; Dressler et al. 1994, Couch et al. 1994).

- Large field galaxies show slow but still discernible evolution from late to early types (Lilly et al. 1998). The faint blue population rapidly disappears between intermediate redshift and the local universe (Koo & Kron 1992; Ellis 1997).

- In the secular evolution scenario, since the effective evolution rate is proportional to the density wave amplitude squared, and wave pattern pitch angle squared, the above difference in evolution rates is easily explained by the large-amplitude, open spiral and bar patterns excited through the tidal interactions in clusters (Byrd & Valtonen 1990, Aragon-Salamanca et al. 2002; Zhang 2008). Galaxy evolution is through both nature (internal mechanism) and nurture (environmental influence).

Secular Heating of Disk Stars

$$\frac{dE_{basic-state}}{dt} = \Omega \frac{dL_{basic-state}}{dt}$$

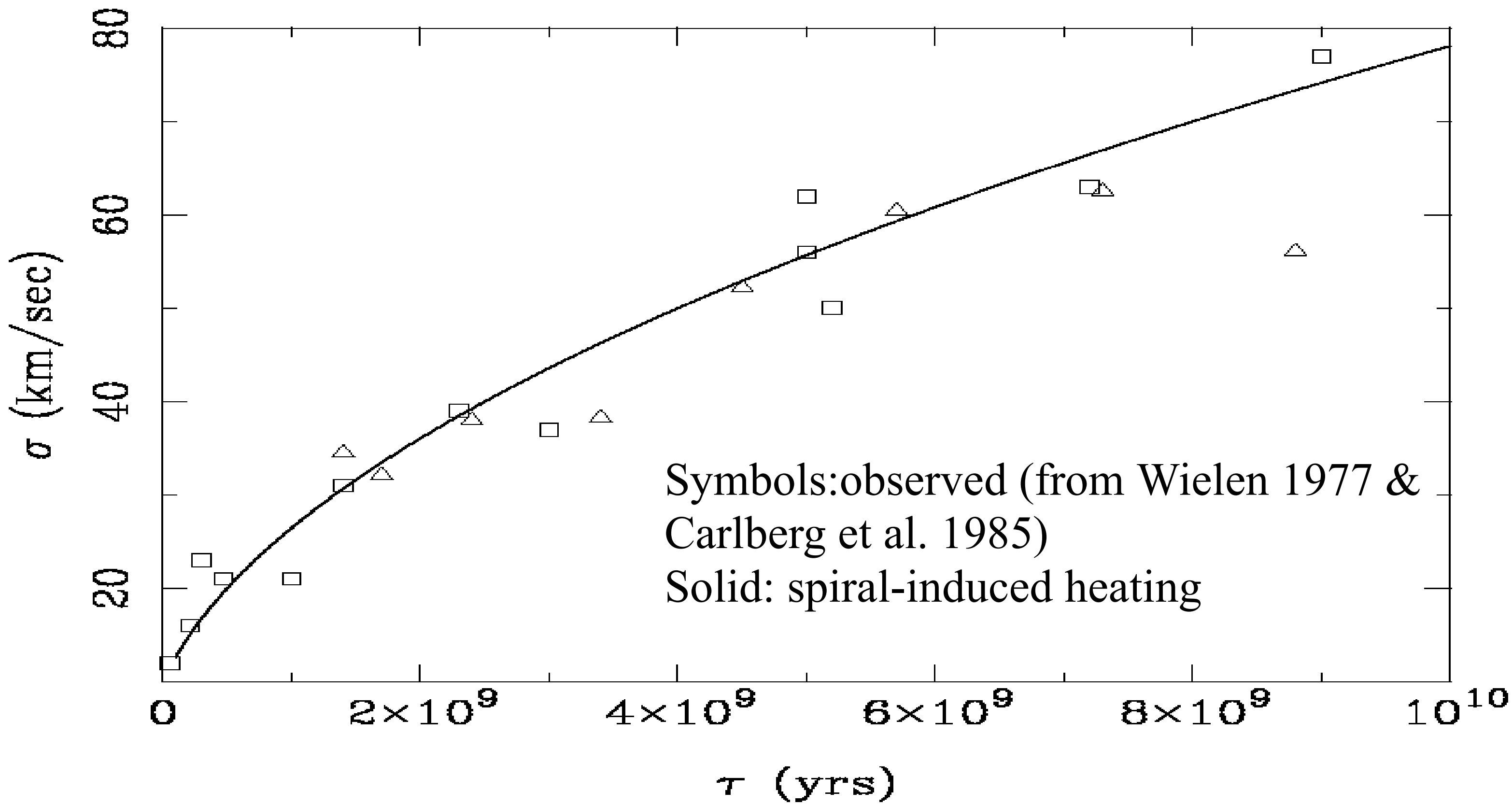
$$\frac{dE_{wave}}{dt} = \Omega_p \frac{dL_{wave}}{dt}$$

$$\frac{d\Delta E}{dt} = \frac{1}{2}(\Omega - \Omega_p) F^2 v_c^2 \tan(i) \sin(m\varphi_0) \Sigma_0$$

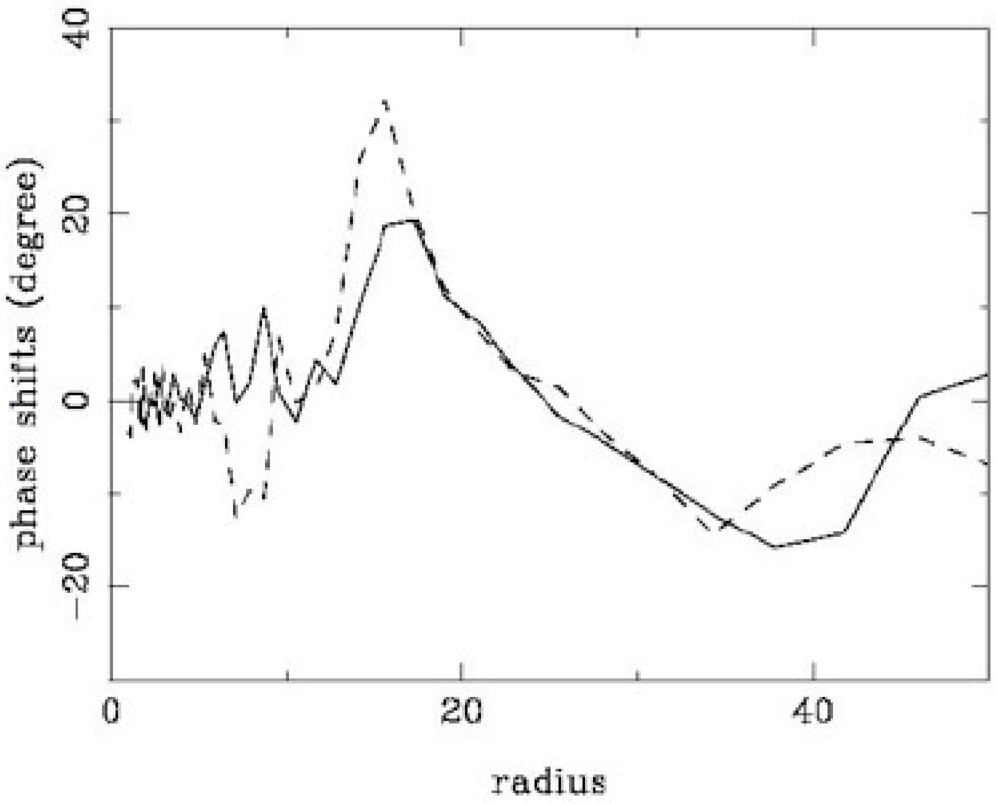
$$\frac{d\sigma^2}{dt} \equiv D^{3d} = (\Omega - \Omega_p) F^2 v_c^2 \tan(i) \sin(m\varphi_0)$$

where D^{3d} is the diffusion constant of the space velocity of a single star. Using parameters of solar neighborhood stars, we get $D^{3d} = 6 \times 10^{-7} (km/\sec)^2 yr^{-1}$.

Age-Velocity Dispersion Relation of Solar Neighborhood Stars



Phase Shifts between the Stellar Density and Potential (Solid) and Gaseous Density and Potential (Dash)



Conclusion: gas phase shift is only somewhat larger than stellar phase shift with repsect to their common potential. But stellar component is much more massive.

Confirmation of Theoretical Predictions Using Observed NIR and MIR Images of Galaxies

- The need for observational confirmation: Simulation of whole galaxies mostly 2D. Unrealistically small density wave strength due to the enforcement of rigid bulge/halo. Current 3D simulation also not used entirely realistic parameters. Failed to produce the high arm/interarm contrast in real galaxies.

- Near-Infrared (NIR) light of galaxies traces the underlying disk mass and suffers little from dust obscuration.

- Zhang and Buta (2007) and Buta & Zhang (2009) used 1.65 um (Ohio State Bright Galaxies Survey, or OSUBGS, Eskridge et al. 2002) and 3.6 um (Spitzer Survey of Stellar Structure in Galaxies, or S4G, Sheth et al. 2010) images of nearby spiral galaxies, de-projected to face-on orientation, and an empirically obtained M/L ratio to obtain surface density maps, which are then used to calculate the potential maps and potential-density phase shifts across radius to determine corotation radii and pattern speeds, as well as mass accretion rates together with the use of a rotation curve.

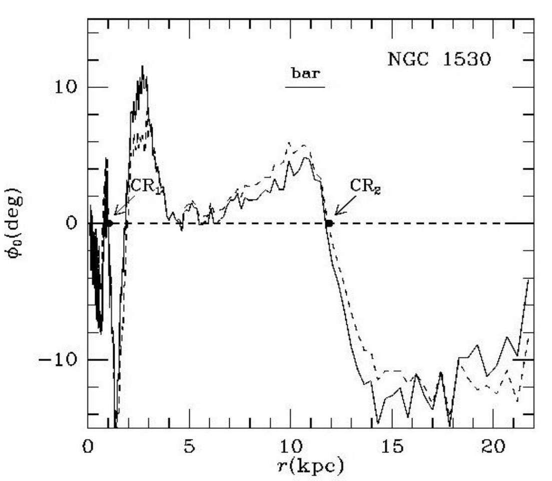
Physical Basis for Using the Potential-Density Phase Shift Positive-to-Negative Crossing to Locate Corotation

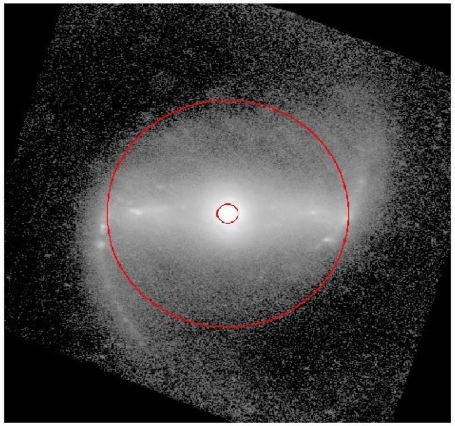
- Due to the long-range nature of gravitational interaction, potential as the weighted integral of density in principle does not have to look like density.

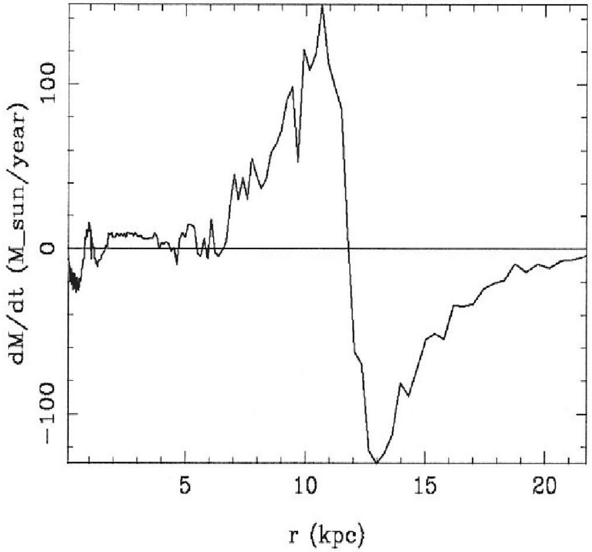
- In the case of spontaneously formed spiral or bar modes, it can be shown that the potential is systematically phase shifted from the density in azimuth, and the radial distribution of this phase shift is such that the phase shift is positive inside corotation, and negative outside corotation. The location of CR is thus at the P/N crossing of phase shift versus r distribution.

- This result is most robust for a spontaneously formed mode at its quasi-steady state, and is approximately correct in other cases, from the sign of wave angular momentum density argument.

Phase Shift and Mass Flow Rate for N1530 (Rapid Evolution Towards Early Types through a Strong Bar)





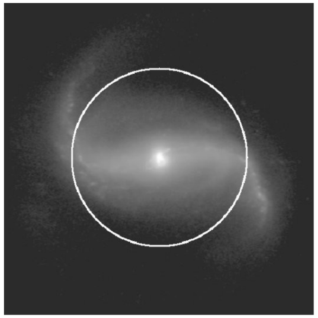


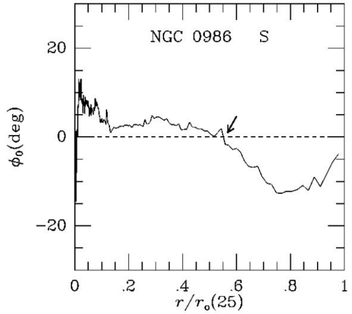
Phase shift zero crossing positions do not sensitively depend on M/L correction.

Other galaxies tested in our sample show between tens to few tenths of solar-mass/year mass flow rate (some field spirals will remain spirals for a long time to come).

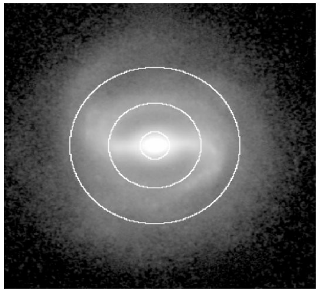
Several Different Pattern Categories from Phase Shift Analysis

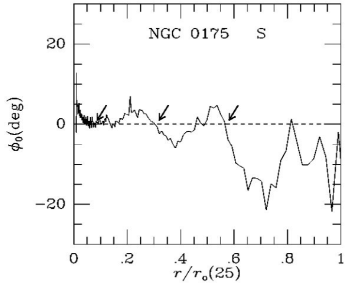
NGC 0986: Bar-driven spiral (bar ends at its CR), inner pattern in the process of decoupling



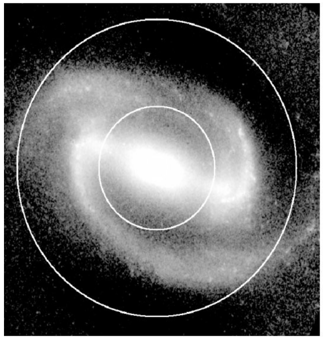


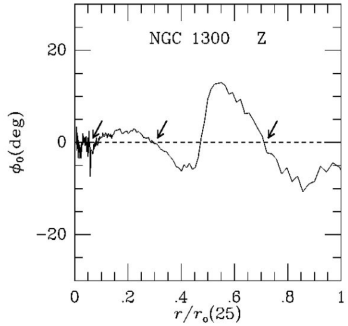
NGC 0175: Decoupled inner and outer spiral, bar ends at its CR





NGC 1300: Bar extending beyond its CR,contradicting passive orbit analysis.
Support for it: SWING mechanism (Toomre 1981). Also N-body simulation of Sparke and Sellwood (1987)

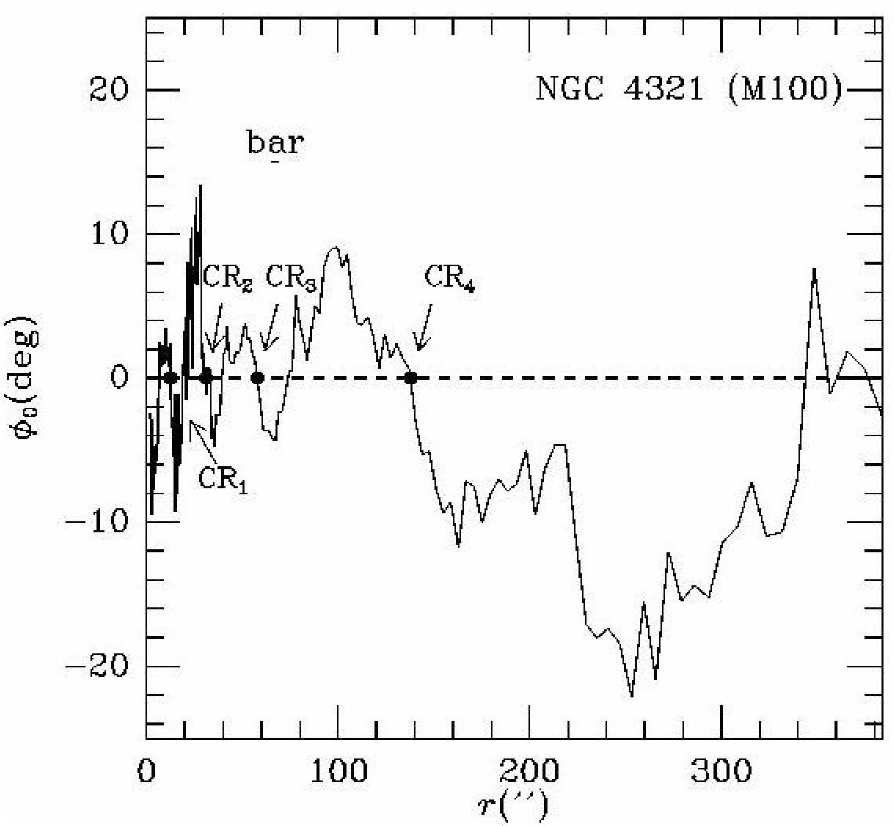


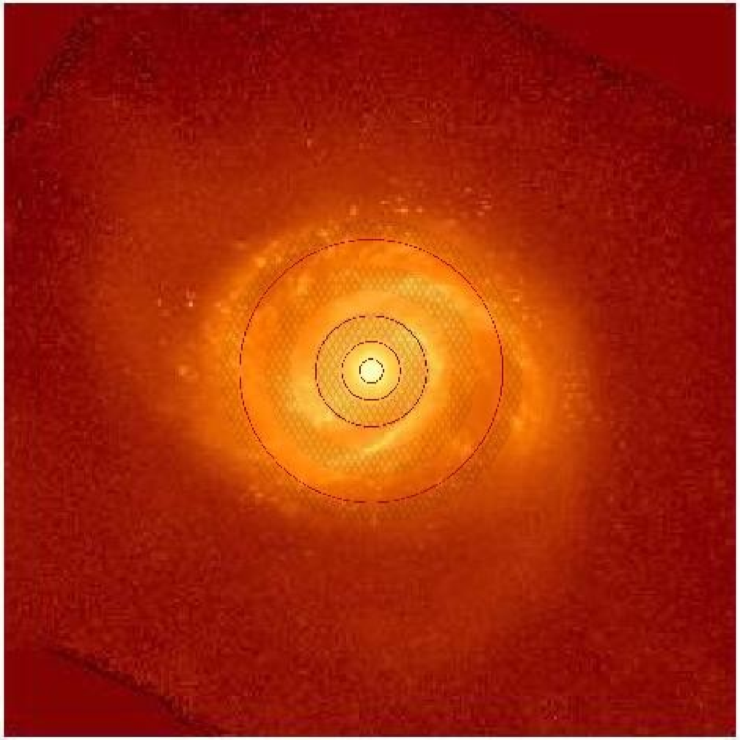


Why the Passive Orbit Analysis is Expected to Fail When Dealing with Self-Organized Structures

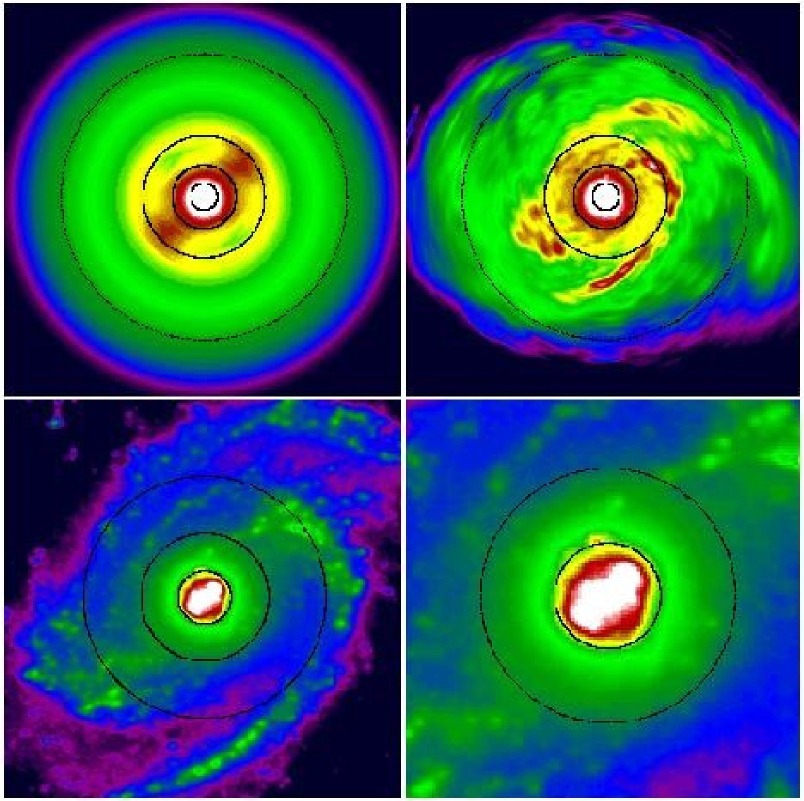
- The most crude example: A living organism cannot be constructed by piling up a large assembly of cells – even if these are exactly the same cells that make up the organism and are arranged in the same order.
- The missing factor is a history of interaction of constituting elements, both among one another and with the environment. Interaction establishes a complex web of correlations, and the process of formation is irreversible.
- Passive orbit analysis (i.e., analyzing orbit behavior under applied, rigid potential) can reproduce appearance, but is bound to miss the “life force” that holds the living entity together (i.e. it is missing the “co-evol” feature of a “live” system, which makes the “whole” more than the sum total of “parts”).
- Passive orbit analysis in the past not only predicted bar not extending beyond CR (Contopoulos 1980), but also (symmetric) spiral not extending beyond inner 4:1 resonance, which lies inside CR (Contopoulos & Grosbol 1986), which is contradicted by observations (Zhang & Buta 2007; Gonzalez-Lopezlira et al. 2010, this conference). It also predicted no secular decay or increase of stellar orbit size for quasi-stationary density waves, which is contradicted by N-body simulation (Donner & Thomasson 2004; Zhang 1996).

NGC 4321, Phase Shift vs. Galaxy Radii (left) and Spitzer Space Telescope Image with Overlaid Corotation Circles (right)



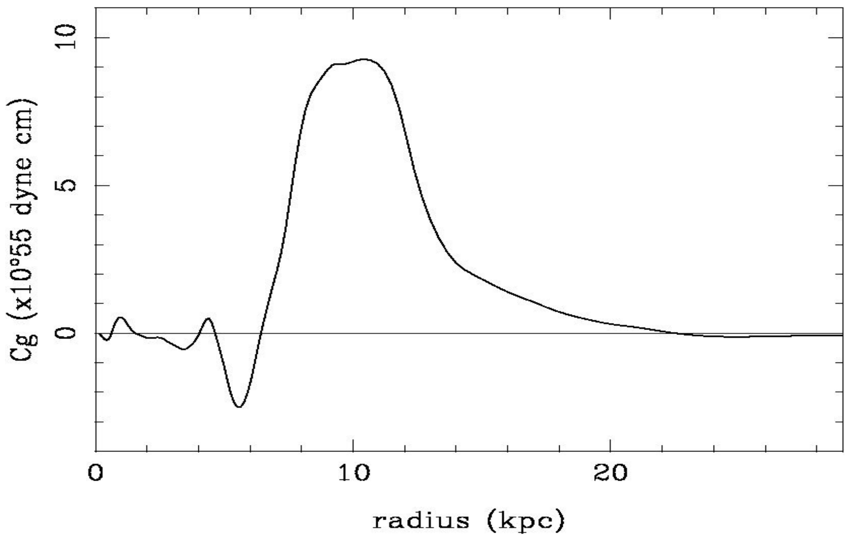


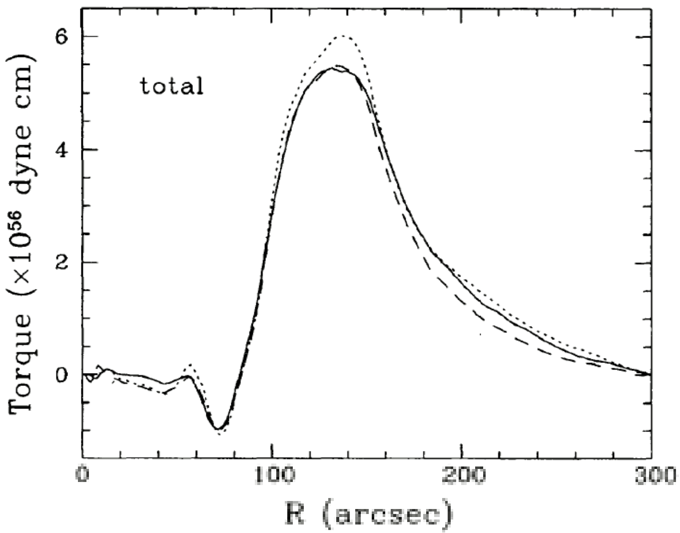
Processed Spitzer 3.6 um Image of NGC 4321 (Bars within Spirals and Vice Versa)



Bars and spirals cannot be assigned to different kinds of basic state, where for bars it allows unstable mode, for spirals it only admits fast transient (Sellwood 2008 and references therein).

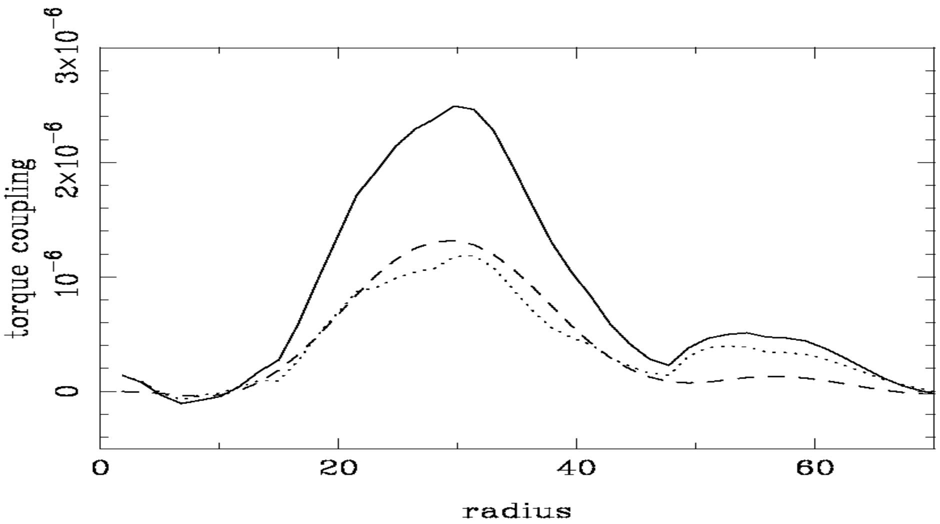
Gravitational Torque Coupling for NGC 4321 (M100)





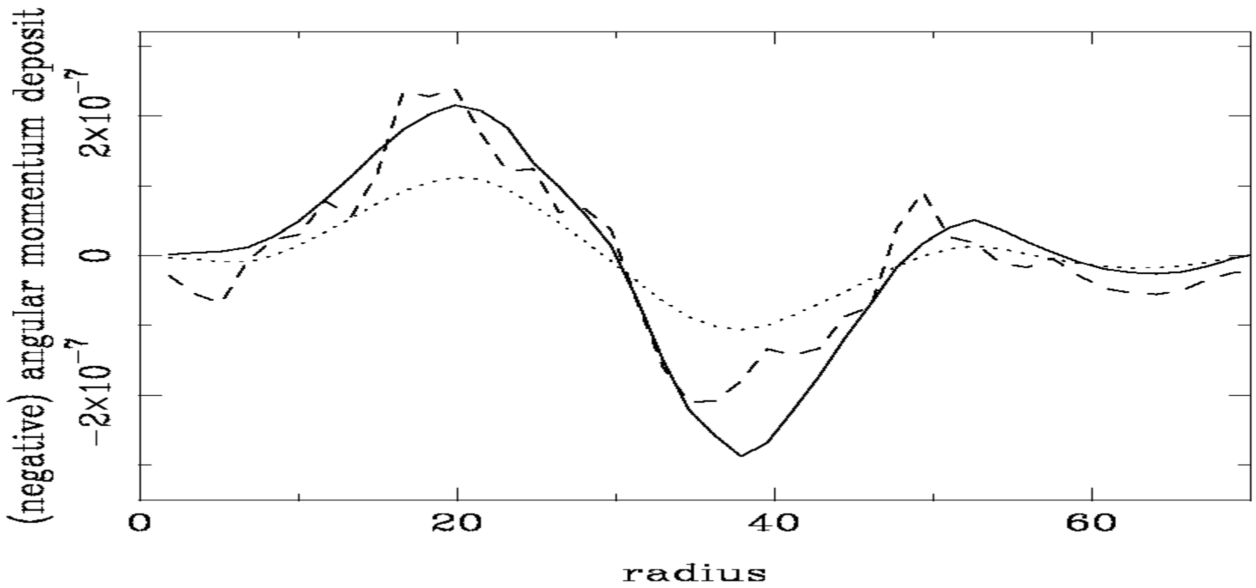
Left frame: This work. Right frame: Gnedin et al. 1995. We found, as also found by Foyle et al. (2009) that the Gnedin et al. calculation appears to have a factor of 5 error in magnitude. Furthermore, so far all calculations of SE rate considered only gravitational torque coupling. Advective torque coupling cannot be directly calculated from observational data. However, Zhang (1998, 1999) proved that at the QSS of wave mode the gradient of the **sum** of the gravitational and advective torque couplings is contained in our T(r), which is a volume-type torque integral closely-connected with phase shift.

Gravitational Torque Coupling (Cg) and Advective Torque Coupling (Ca) from N-body Simulations



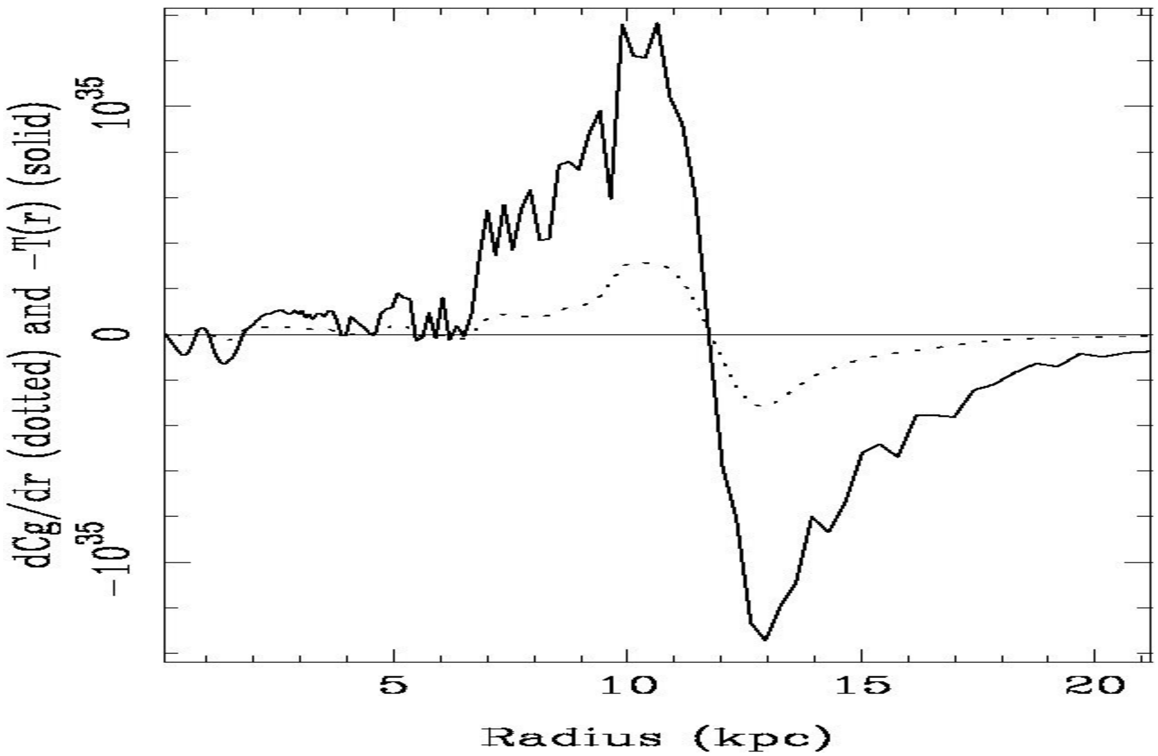
LBK72 predicted that the sum of gravitational and advective torque couplings are a constant independent of radius, whereas in both N-body simulations and in real galaxies it is found the total torque couple is a bell centered on CR.

dCg/dr (dotted), d(Ca+Cg)/dr (dashed), and -T(r) (solid) (from the same set of N-body simulations)



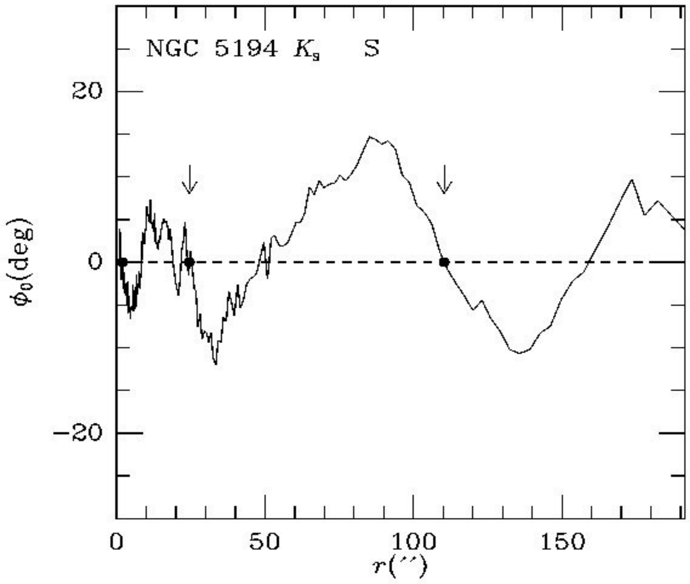
Classical theory predicts that dCg/dr = -T(r), whereas at QSS the new theory predicts d(Ca+Cg)/dr = -T(r) (Zhang 1998, 1999)

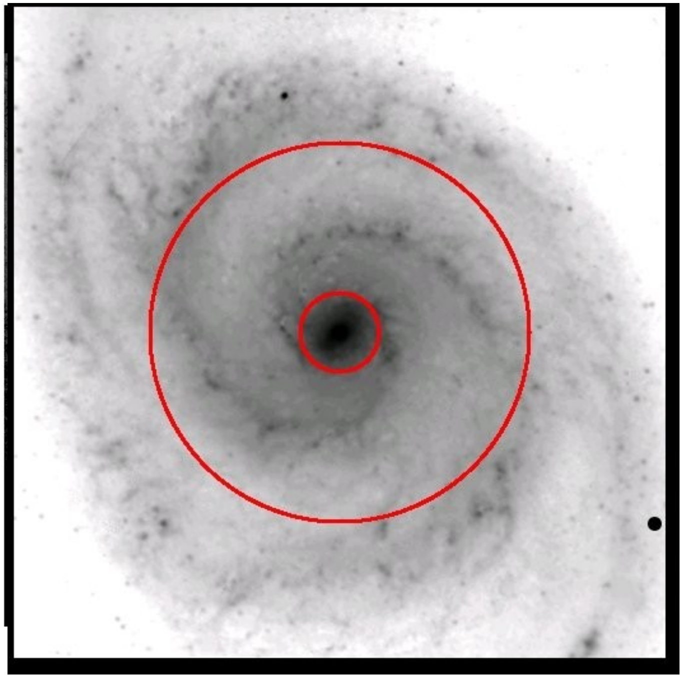
dCg/dr and -T(r) for N1530



Other galaxies in our sample that have been checked so far all show significant difference in value between dCg/dr and -T(r) – indicating the significance of collisionless shocks. The two are however always similar in shape – indicating Ca tracks Cg in trend.

M51 Phase Shift and Overlay Image (Spiral Modes in Interacting Galaxies)





Inner CR encloses the inner bar, outer CR lies where the dust lane transits from the inner edge of the spiral to the outer edge of the spiral. Companion has minimal in-plane gravitational effect at the epoch of observation.

Reasons Classical Density Wave Theory Missed this Important Physical Mechanism for Secular Evolution of the Galactic Disk

- The study of self-organized patterns in complex systems is still in its infancy. The far-from-equilibrium condition created by long-range gravitational force further creates a unique environment for the self-organization process in self-gravitating systems, which is not shared by other self-organized systems (such as chemical clocks, convection flow in the atmosphere, and lasers, which are all driven by potential gradient established externally, and not by an internal long-range force such as gravity). Other self-organized systems also do not need to consider "basic state" secular evolution as boundary condition is fixed by the outside agent.

- The dissipation effect encountered in galaxy disks has analogy in plasma collisionless shocks, yet the amount of shock dissipation in galaxies is determined ultimately by the global characteristics of the galaxy (i.e., by its basic state and the resulting modal characteristics), not by local physics. The requirement for global self-consistency and for the maintenance of the quasi-stationary spiral modes ultimately resulted in the invalidation of the differential form of the Poisson equation, and in the closure relation between Ca, Cg, and T(r).

- Intuitive reasoning that at the QSS $dCg/dr + dCa/dr = - T(r)$: LHS is wave angular momentum flux gradient (Eulerian), and RHS is the basic state angular momentum loss (Lagrangian), at QSS the two need to balance so the wave amplitude doesn't continue to grow (i.e. all angular momentum deposit goes to basic state, none goes to wave). (Zhang 1998).

Why the “Broadening of Resonances” Approach Cannot be Used to Explain the Results of the Current Theory

- In the resonance-broadening scenario, even though the mass flow directions predicted near the ILR and OLR are consistent with what we found using the phase shift method, these same mass flow directions at the ILR and OLR were found (Carlberg & Sellwood 1985, CS85, p. 88) to be ``independent of the winding sense of the spiral (see LBK)''. This result of CS85 or LBK is expected since resonant interaction is a local effect, so the winding sense of the pattern does not matter. In contrast, for the collective effect we are dealing with here, the sense of the phase-shift is critically dependent on whether the wave is leading or trailing, since the geometrical phase shift is determined by the Poisson equation, whereas the physical sense of whether the potential is torquing the density forward or backward depends on which direction the pattern is rotating. This fact alone tells us that the collective dissipation effect in spiral galaxies cannot be viewed as a broadening-of-resonance effect.

- In addition, the resonance-broadening effect is a kind of top-down-control effect – it is a single-orbit's response to the applied potential (CS85, p. 81, mentioned the equivalence of their current approach with LBK's single-orbit approach, even though one is Eulerian and the other is Lagrangian). In a self-organized instability it is the ``sideways'' interactions among stars themselves that leads to pattern coherence and collective dissipation. This latter effect cannot be modeled entirely as a top-down-control hierarchy due to an applied spiral or bar potential.

- An additional piece of evidence of the disparity of the two approaches is that, near the CR region, the sense of angular momentum exchange between the basic state and the wave, and thus the sense of mass flow predicted by the broadening-of-resonance approach (see Sellwood & Binney 2002, Figure 4) are exactly opposite to that predicted by the phase shift method (the latter being consistent with that needed to build up the Hubble sequence), and thus the behavior at CR of the resonance-broadening approach could not lead to the secular mass re-distribution needed to build up the Hubble sequence.

Other Astrophysical Implications and Observational Confirmations of the Theory

- Damping and stabilization of the growing mode to achieve quasi-stationary spiral modes (Zhang 1998).

- Energy injection into the ISM to fuel interstellar-medium turbulence, or to produce the Larson-Law (Zhang 1999; Zhang, Lee, Bolatto & Stark 2001).

- Accelerated evolution rate for rich cluster galaxies (Butcher-Oemler effect) due to interaction-enhanced density wave amplitude and open pitch angle (Zhang 2008).

- Fueling of nuclear mass accretion and active galactic nuclei through the build-up of successive nested density wave patterns (Zhang, Wright, Alexander 1993; Zhang & Buta 2007; Buta & Zhang 2009).

- Cosmological implications: Nearby galaxy results place constraints (Zhang 2008).

Conclusions

- The potential-density phase shift is an important concept underlying galactic secular evolution. The stellar mass accretion enabled by the collective dissipation process is likely to be even more important than gas inflow in bulge building, due to the larger stellar-mass reservoir compared to gas. Phase shifts follow naturally not only for a spiral, but also for skewed bars.

- The bell-shaped torque coupling, or equivalently, the double-humped phase shift distribution, as well as the good correspondence of the zero crossing of phase shift distribution with CR, indicate the modal origin of patterns. Transient features are also seen in both the phase shift and morphology plots, but most indicates modes in the process of stabilization. The LBK72 theory failed to predict the correct trends and values of angular momentum flux for secular evolution.

- Near and mid-IR imaging allows the possibility of direct measurements of phase shifts. With this, we can locate corotation radii with no direct kinematic knowledge and no measurement of pattern speed. Our recent work on more than 100 nearby galaxies brought our attention to multiple CRs, possible mode decouplings, and "super fast bars." Further independent observations of pattern speeds and CR radii will help confirm these results. Further simulations are also needed.

- We are in the process of conducting a systematic study of the galaxy morphological transformation rates using the approach outline in this talk. The new approach will allow us the opportunity to assess the role of secular evolution process in forming the Hubble sequence.