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Density-wave induced morphological transformation of galaxies along the Hubble sequence

Xiaolei Zhang[1*], Ronald J. Buta[2†]

[1] *Department of Physics and Astronomy, George Mason University, Fairfax, VA 22030, USA*
[2] *Department of Physics and Astronomy, University of Alabama, 514 University Blvd E, Box 870324, Tuscaloosa, AL 35401, USA*

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In the past two decades, secular evolution has emerged as an important new paradigm for the formation and evolution of the Hubble sequence of galaxies. A new dynamical mechanism was identified through which density waves in galaxies, in the forms of nonlinear and global spiral and bar *modes*, induce important collective dissipation effects previously unknown in traditional studies. These effects lead to the evolution of the *basic state* of the galactic disk, consistent with the gradual transformation of a typical galaxy's morphological type from a late to an early Hubble type. In this paper, we review the theoretical framework and highlight our recent result which showed that there are significant qualitative and quantitative differences between the secular evolution rates predicted by the new theory compared with those predicted by the classical approach of Lynden-Bell and Kalnajs. These differences are the outward manifestation of the dominant role played by collisionless shocks in disk galaxies hosting quasi-stationary, extremely non-linear density-wave modes.

Keywords: Galaxy structure; Galaxy evolution; Density wave theory; Collective effects

1 Introduction

The possibility that galaxy morphologies can transform significantly over their lifetime, not only through violent episodes such as merger or satellite accretion, but also through slow but steady internal secular dynamical processes, is a notion that has been gaining acceptance in recent decades. In the past, the work on secular evolution has been focused on gas accretion in barred galaxies and the growth of pseudo bulges ([1] and the references therein). This is partly due to the long-held notion that gas is the only mass component capable of dissipation, and the stellar component is adiabatic and generally does not lose or gain energy and angular momentum as they orbit around the center of a galaxy.

*Email: xzhang5@gmu.edu
†Email: buta@sarah.astr.ua.edu

The first indication that there is the possibility for significant *stellar mass redistribution* in galaxies originates from the seminal work of Lynden-Bell and Kalnajs ([2], hereafter LBK), who showed that a trailing spiral density wave possesses a gravitational torque that over time can transport angular momentum outward. LBK were interested in the angular momentum transport phenomenon because they were seeking a generating mechanism for the spiral density waves, thought to be short-lived wave trains constantly being amplified out of noise and subsequently absorbed at the inner Lindblad resonance. Since the density wave is considered to possess negative energy and angular momentum inside corotation relative to the basic state (i.e. the axisymmetric disk), an outward angular momentum transport would encourage the spontaneous growth of the wave trains. LBK at that time was not interested in the secular morphological evolution of the basic state of the disks. In fact, in the same paper, they showed that for WKBJ (tightly wrapped) waves, the long-term energy and angular momentum exchange between the wave and the basic state is zero away from the wave-particle resonances. This is possible in the presence of the outward angular momentum transport by gravitational torque couple because they showed that there is a second type of torque couple, the so-called advective torque couple (due to lorry transport), that opposes the gravitational torque couple, and the sum of the two types of torque couples is a constant independent of the galactic radii. The total torque couple, which is equal to the rate of total radial angular momentum flux, is thus a constant during the outward angular momentum transport, and there is no interaction of the wave and basic state except at the wave-particle resonances (i.e., they thought the wave picks up angular momentum from the basic state at the inner Lindblad resonance and dumps it at the outer Lindblad resonance, and en route of this radial transport the total angular momentum flux remains constant).

Zhang [3] showed that the classical theory of LBK ignored an important collective dissipation process present in the gravitational N-body disks possessing *self-organized, or spontaneously-formed, density wave modes*. This process is mediated by collisionless shocks at the density wave crest, which breaks the adiabaticity or the conservation of the Jacobi integral condition – a condition which is shown to be valid only for a *passive* orbit under an *applied* spiral or bar potential, and is now shown not to be obeyed by orbits undergoing collective dissipation. The overall manifestation of the collective dissipation process is an azimuthal phase shift between the potential and the density distribution of the density wave pattern, and for a self-sustained mode this phase shift is positive inside corotation, and negative outside. The presence of the phase shift means that for every annulus of the galaxy, there is a secular torque applied by the density wave on the disk matter in the annulus, and the associated energy and angular momentum exchange between the wave and the basic state of the disk. As a result the disk matter inside corotation (both stars and gas) loses energy and angular momentum to the wave, and spirals inward, and the disk matter outside corotation gains energy and angular momentum from the wave and spirals outward. This energy and angular momentum exchange between the wave and the basic state of the disk thus becomes the ultimate driving mechanism for the secular evolution of the mass distribution of the basic state of galaxy disks. The energy and angular momentum received by the wave from the basic state, incidentally, serve as a damping mechanism for the spontaneously growing unstable mode, allowing it to achieve quasi-steady state at sufficiently nonlinear amplitude.

In [4], a set of analytical expressions for the secular mass accretion/excretion rate was derived, and was confirmed quantitatively in the N-body simulations presented in the same paper. However, due to the 2D nature of these simulations, where the bulge and halo were assumed to be spherical and inert, the simulated wave has an average density contrast of 20% and potential contrast of 5%, both much lower than the average observed density wave contrast in physical galaxies, so the simulated disk did not evolve a lot [5], despite the fact that these low evolution rates conform exactly to the analytical formula's prediction for the corresponding wave amplitude [4].

Zhang & Buta [6] and Buta & Zhang [7] used near-infrared images of observed galaxies to derive the radial distribution of the azimuthal potential-density phase shifts, and to use the positive-to-negative zero crossings of the phase shift curve to determine the corotation radii (CRs) for galaxies possessing spontaneously-formed density wave modes. This approach works because the alternating positive and negative humps of phase shift distribution lead to the correct sense of energy and angular momentum exchange between the wave mode and the disk matter to encourage the spontaneous emergence of the mode. In [6] and [7], we have found good correspondence between the predicted CRs using the potential-density phase shift approach with the resonance features present in galaxy images, and also with results from other reliable CR determination methods within the range of validity of these methods. Beside CR determination, an initial test case for mass flow rate calculation, for galaxy NGC 1530, was also carried out in [6] using the same volume-torque-integration/potential-density phase shift approach, and there we found that since this galaxy has exceptionally large surface density and density-wave arm-to-interarm contrast, a mass flow rate of more than 100 solar masses per year was obtained across much of the galactic radii for this galaxy. This level of mass flow rate is more than sufficient to transform the Hubble type of a late type galaxy to an early type within a Hubble time. Other galaxies we have tested have significantly lower mass flow rates but still are sufficient to lead to significant mass redistribution over a Hubble time.

Recently, we have applied the potential-density phase shift/volume-torque method to a larger sample of galaxies in order to estimate their mass flow rates. In related earlier works, Gnedin et al. [8] and Foyle et al. [9] have applied an LBK type gravitational torque integral to the calculation of the angular momentum redistribution rate in a number of galaxies. In our own studies, we found that such earlier work using the gravitational torque couple alone had significantly under-estimated the (implied) total mass flow rates in these galaxies. As it turns out, the advective torque couple, which opposes the gravitational torque couple in the LBK classical theory, becomes to have the same sense of angular momentum transport direction for spontaneous-formed density wave modes in the nonlinear regime. Furthermore, at the extremely non-linear wave amplitudes usually found for observed galaxies, the contribution of advective torques due to the collisionless shocks far exceeds the contribution from gravitational torques, and becomes the dominant driver for the secular evolution of galaxy mass redistribution. The sum of both types of (surface) torque couples turns out to be equal to the (integral of the) volume-type torque we used in this work, which is first proved in [4, 5]. The past calculations of gas mass accretion near the central region of galaxies (e.g. [10]) are likely to have significantly underestimated the gas mass flow rate for the same reason.

Our current work also has other important implications for the fundamental

questions of galactic dynamics. For example, on the modal versus transient nature of the density wave patterns in galaxies (see, e.g. [11] and the references therein). The bell-shaped total angular momentum flux or torque coupling integral, which is equivalent to the two-humped phase shift or volume torque distribution, that we have found to be overwhelmingly present in observed galaxies, has no explanation in the classical LBK theory of transient waves, which predicts constant total angular momentum flux for a wave train between the inner and outer Lindblad resonances (LBK; [12]), but is a natural consequence of the spontaneously-formed intrinsic modes of disk galaxies, as first demonstrated in [4]. Also, the result of CR determination for the majority of the more than 150 galaxies analyzed in [7] using the potential-density phase shift method also supports the modal view, since for transient waves one should not be able to use the Poisson equation alone to predict a partially-kinematic quantity such as the corotation radius. For the successful application of the potential-density phase shift method, the Poisson equation and the equations of motion must have achieved a good degree of mutual consistency to allow a quasi-steady state to form, a condition naturally met by self-sustained modes, and in general not expected to hold for transient waves.

2 Theoretical basis for applying the potential-density phase shift approach to the mass flow rate calculation

The detailed discussion on the new dynamical mechanism responsible for the secular mass redistribution in galaxies (both stellar and gaseous) is described in [3–5]. We now briefly summarize the derivations relevant to the calculation of the mass flow rate in galaxies.

The (inward) radial mass accretion rate at a galactic radius R can be written as

$$\frac{dM}{dt} = -\frac{dR}{dt} 2\pi R \Sigma_0(R) \tag{1}$$

where $\Sigma_0(R)$ is the mean surface density of the basic state of the disk at radius R, and $-dR/dt$ is the mean orbital delay rate of an average star.

We also know that the mean orbital decay rate of a single star is related to its angular momentum loss rate dL^*/dt through

$$\frac{dL^*}{dt} = -V_c M_* \frac{dR}{dt} \tag{2}$$

where V_c is the mean circular velocity at radius R, and M_* the mass of the relevant star.

Now we have also

$$\frac{dL^*}{dt} = \frac{d\bar{L}}{dt} \frac{M_*}{\Sigma_0} \tag{3}$$

where $\dfrac{d\bar{L}}{dt}$ is the angular momentum loss rate of the basic state disk matter per unit area at radius R.

Since

$$\frac{d\bar{L}}{dt} = \frac{1}{2\pi}\int_0^{2\pi} \Sigma_1 \frac{\partial \mathcal{V}_1}{\partial \phi} d\phi \tag{4}$$

[3], we have finally

$$\frac{dM}{dt} = \frac{R}{V_c}\int_0^{2\pi} \Sigma_1 \frac{\partial \mathcal{V}_1}{\partial \phi} d\phi \tag{5}$$

where the subscript 1 denotes the perturbation quantities.

In the above derivation we have used a volume-type of torque $T_1(R)$,

$$T_1(R) \equiv R\int_0^{2\pi} \Sigma_1 \frac{\partial \mathcal{V}_1}{\partial \phi} d\phi, \tag{6}$$

which was first introduced in the context of the self-torquing of the disk matter by its associated spontaneously-formed density wave modes in [3, 4]. The volume torque is equal to the time rate of angular momentum exchange between the density wave and the disk matter in a unit-width annulus located at galactic radius R, for wave modes in approximate quasi-steady state. In the past, two other types of torque-coupling integrals have also been used [2, 12]. These are the gravitational torque couple $C_g(R)$

$$C_g(R) = \frac{R}{4\pi G}\int_{-\infty}^{\infty}\int_0^{2\pi} \frac{\partial \mathcal{V}}{\partial \phi}\frac{\partial \mathcal{V}}{\partial R} d\phi dz, \tag{7}$$

and the advective torque couple $C_a(R)$

$$C_a(R) = R^2\int_0^{2\pi} \Sigma_0 V_R V_\phi d\phi, \tag{8}$$

where V_R and V_ϕ are the radial and azimuthal velocity perturbation relative to the circular velocity, respectively.

In the classical theory, the volume torque integral $T_1(R)$ can be shown to be equal to dC_g/R in the linear regime ([4], original derivation due to S. Tremaine, private communication). However, for spontaneously-formed density wave modes, when the wave amplitude is significantly nonlinear and the importance of collisionless shocks at the density wave crest begins to dominate, it can be shown that one of the crucial conditions in the proof of the $T_1(R) = dC_g/dR$ relation, that of the validity of the differential form of the Poisson equation, is no longer valid [4]. At the quasi-steady state (QSS) of the wave mode, it can be shown that in fact $T_1(R) = d(C_a + C_g)/dR \equiv dC/dR$ [5]! An intuitive derivation of this equality can be given as follows: $d(C_a + C_g)/dR \equiv dC/dR$ is the wave angular momentum flux gradient in the Eulerian picture, and $T_1(R)$ is the rate of angular momentum loss for the disk matter in a unit-width annulus located at R in the Lagrangian picture. At the quasi-steady state of the wave mode, these two need to balance each other so the wave amplitude does not continue to grow (i.e., all the negative angular momentum deposited by the wave goes to the basic state of the disk matter and none goes to the wave itself, so that the wave amplitude does not continue to grow, as required by the condition for the quasi-steady state of the wave mode).

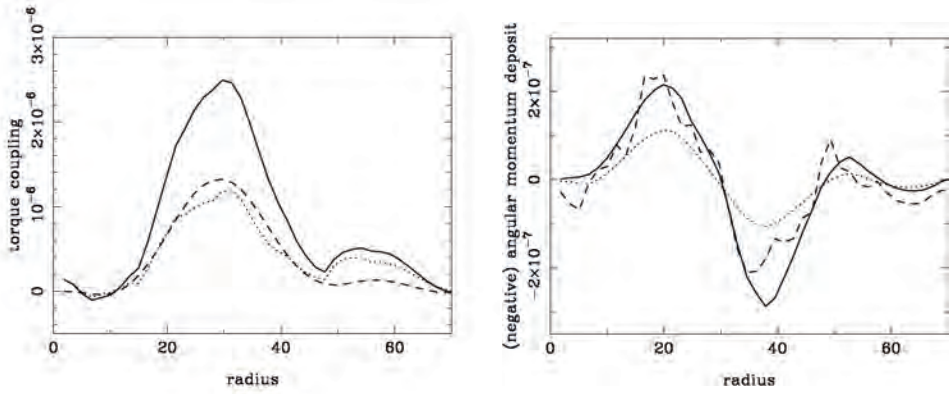


Figure 1 *Left*: Gravitational (dotted), advective (dashed), and total (solid) torque couples from the N-body simulations of Zhang [3, 4]. *Right*: Gradient of gravitational (dotted) and total (dashed) torque couples, and the volume torque T_1 (solid), from the same N-body simulations (previously unpublished).

The past calculations of the secular angular momentum redistribution rate (i.e. [8, 9]) considered only the contribution from gravitational torque couple and ignored the contribution of the advective torque couple (which cannot be directly estimated using the observation data, except through our round-about way of estimating the total torque using the volume-type of torque integral $T_1(R)$). In the following, we will show that the advective contribution to the total torque in fact is several times larger than the contribution of the gravitational torques in the extreme nonlinear regime usually encountered in observed galaxies, and is of the same sense of angular momentum transport as the gravitational torque couple – another characteristic unique to the nonlinear modal case. Furthermore, the two-humped shape of the volume torque distribution (with zero crossing at CR), which is equivalent to the two-humped distribution of the phase shift, is consistent with the bell-shaped torque couplings previously found in both N-body simulations [4] and in observed galaxies ([8]; for the gravitational torque coupling contribution only). This characteristic distribution is another important piece of evidence that the density waves present in disk galaxies are in fact spontaneous unstable modes in the underlying basic state of the disks.

In Fig. 1, left, we show the result of N-body calculated gravitational and advective torque couplings obtained in [3, 4], which shows obviously the bell-shaped curves for both type of couples, and with the peak near the CR of the dominant spiral mode at $r = 30$. In Fig. 1, right, we show the gradient of the gravitational and total torque couples, and compare them with $T_1(R)$. It is clear that $T_1(R) \neq dC_g/dR$, and rather is closer to dC/dR, though the equality is not yet exact because this particular simulated N-body mode never achieved true steady state. The second hump in the left plot is due to a spurious edge mode. In physical galaxies, as our examples below will show, the difference between $T_1(R)$ and dC_g/dR becomes even more pronounced than in these N-body simulations because of the higher degree of nonlinearity of the wave modes in physical galaxies.

3 Examples of phase-shift, volume torque, and mass-flow analysis for individual galaxies

3.1 NGC 4321 (M100)

In Fig. 2 we plot the phase shift vs galactic radii for late-type barred galaxy NGC 4321 (M100), as well as the CRs determined by the major positive-to-negative (P/N) crossings and overlaid on the galaxy image (Spitzer 3.6 μm SINGS survey, [13]) used for carrying out this analysis. We find four well-resolved corotation radii for this galaxy [6].

In [6], we have used the SINGS image to perform a bar-spiral separation using the methods described by [14], the results of which are shown with our four CR circles superposed in the top two panels of Fig. 3. The lower two frames of Fig. 3 present the original image (without bar-spiral separation) zoomed-in by a linear factor of 2 and 4, respectively, compared to the top two frames. Here we see clearly that the innermost corotation circle (CR_1) encloses the strong secondary bar. Between the next two CRs (CR_2 and CR_3) there appear to be faint spiral structures.

In Fig. 4, we plot the calculated gravitational torque couple for NGC 4321 using the SINGS 3.6 μm image. This torque calculation result is very similar in shape to the one calculated for the same galaxy by Gnedin et al. [8], though the scale factor is more than a factor of 10 smaller than obtained in their paper. We have tried to switch to use an R-band image as in [8], and rescaled the galaxy parameters to be in agreement with what they used, still the resulting scale is smaller by a factor of 5

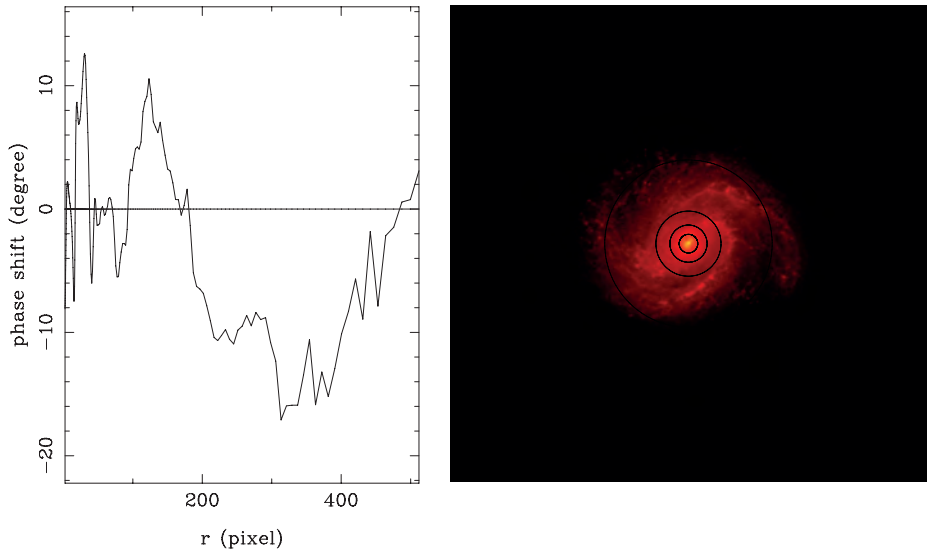


Figure 2 *Left*: Calculated phase shift versus galaxy radii for NGC 4321. Two corotation radii are indicated, as is the location of the ends of the bar. *Right*: Deprojected mid-infrared 3.6 μm SINGS image of NGC 4321 in log scale, with the corotations determined by the phase shift method superimposed as circles. From [6].

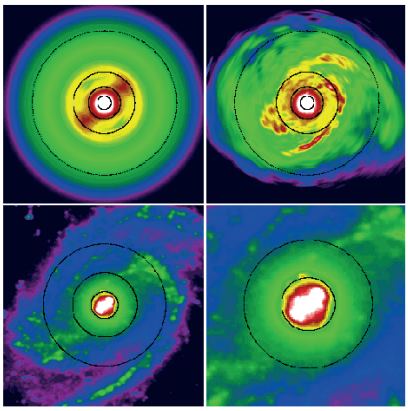


Figure 3 *Top left:* Bar-separated SINGS image of the bright inner region of NGC 4321 superimposed with the 4 corotation circles determined using the phase shift method. The box size of the image is 6′.4 by 6′.4. *Top right:* Spiral-separated SINGS image of NGC 4321 of the same region as at left superimposed with the 4 corotation circles determined using the phase shift method. The box size of this image is also 6′.4 by 6′.4. *Bottom left:* SINGS image (without bar-spiral separation) of NGC 4321 with a factor of 2 linear zoom compared to the top panels (box size 3′.2 by 3′.2), superimposed with the central 3 corotation circles determined using the phase shift method. *Bottom right:* SINGS image (without bar-spiral separation) of NGC 4321 with a factor of 4 linear zoom compared to the top panels (box size 1′.6 by 1′.6), superimposed with the central 2 corotation circles determined using the phase shift method. From [6].

from that in [8]. This same amount of scaling difference is recently found by Foyle et al. [9] as well, when they try to reproduce the Gnedin et al. result. Therefore it is possible that the Gnedin et al. calculation suffered an internal error somewhere, since our result and the Foyle et al. result were obtained entirely independently and using data from different passbands.

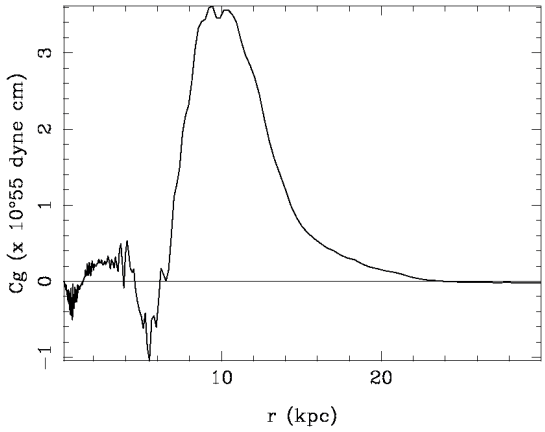


Figure 4 Calculated gravitational torque coupling versus radius for galaxy NGC 4321.

In Fig. 5, we show the calculated mass flow rates and radial gradient of gravitational torque coupling integral $C_g(R)$ as compared to the volume torque integral $T_1(R)$. There is about a factor of 4 difference between the volume torque integral and the gradient of the gravitational torque integral, indicating that the remainder, which is contributed by the advective torque coupling, is in the same sense, but much greater in value, than the gravitational torque coupling integral. Note that this difference between the volume torque integral and the gradient of the (surface) gravitational torque couple is only expected in the new theory: in the traditional theory of LBK these two are supposed to be equal to each other. Furthermore, if the LBK theory is used literally, one should not expect any mass flow rate at all expect at isolated resonance locations (since the total angular momentum flux is expected to be constant). The existence of a mass flux across the entire galactic disk is also contrary to the LBK's original expectations.

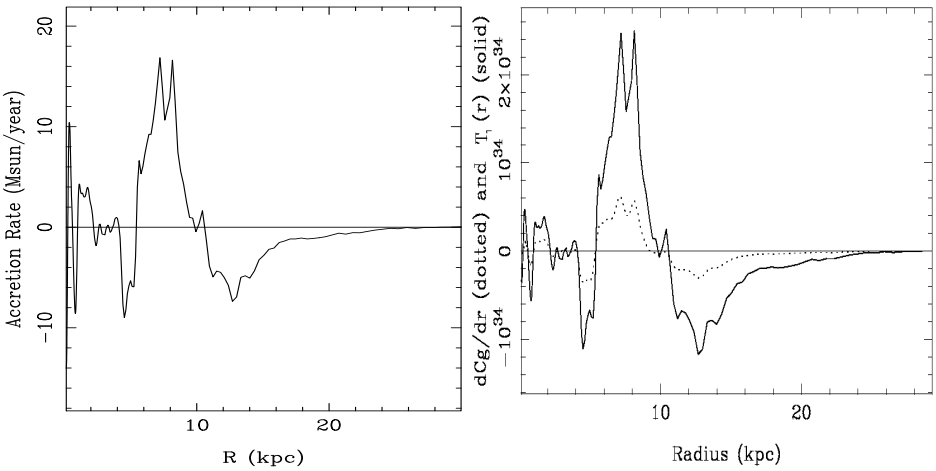


Figure 5 *Left*: Calculated stellar mass flow rate radius for galaxy NGC 4321. *Right*: Calculated radial gradient of gravitational torque coupling integral compared with the volume torque integral for galaxy NGC 4321 (unit: dyne).

3.2 NGC 5194 (M51)

We have also used the potential-density phase shift method on the interacting galaxy NGC 5194 (M51) (Figure 6). By focusing on the area that just excludes the small companion NGC 5195, which is likely to lie outside of the M51 galactic plane and thus have minor influence on the internal dynamics of M51 at the epoch of observation (a conjecture which is confirmed by our analysis), the phase shift analysis gives two major CR radii (P/N crossings on the phase shift plot, represented by red circles on the overlay image) followed by two negative-to-positive (N/P) crossing radii, represented by the green circles on the image; the latter are believed to be where the inner mode decouples from the outer mode. These radii match very well the galaxy morphological features (i.e., the inner CR circle lies near the end of the bar, and the first N/P

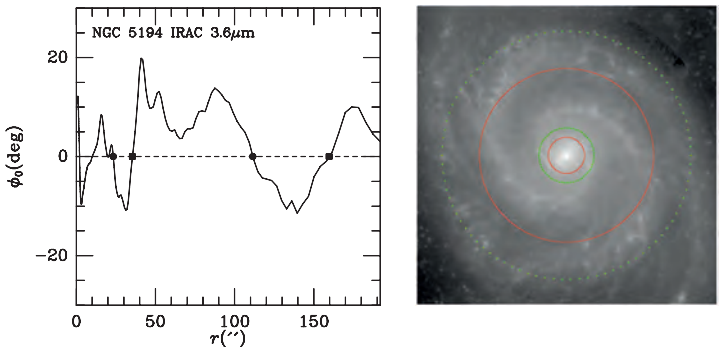


Figure 6 *Left*: Calculated phase shift vs galaxy radii for NGC 5194 (M51). Two corotation radii are indicated, as well as the mode decoupling points. *Right*: Deprojected mid-infrared 3.6 μm SINGS image of NGC 5194 (M51), with the CRs determined by the phase shift method superimposed as solid red circles, and mode decoupling radii as dashed green circles.

crossing circle is where the two modes are seen to decouple). For the outer mode, the CR circle seems to just bisect the regions where the star-formation clumps are either concentrated on the inner edge of the arm, or on the outer edge of the arm – a strong indication that this second CR is located right near where the pattern speed of the wave and the angular speed of the stars match each other. This supports the hypothesis that the spiral patterns in this galaxy are intrinsic modes rather than tidal transients, and that tidal perturbation serves to enhance the prominence of the intrinsic mode, but does not alter its modal shape.

In Fig. 7, we plot the calculated mass flow rates and the comparison of the gradient of gravitational torque couple $C_g(R)$ and volume torque $T_1(R)$ for NGC 5194. Once again we see that for this galaxy, as for NGC 4321, the advective torque couple is in the same sense as the gravitational torque couple, and dominates the value of the total torque coupling. Similar results were found for other galaxies we have analyzed so far as well.

4 Conclusions

The correct treatment of gravitational many-body systems containing self-organized global patterns, such as density wave modes in disk galaxies, requires a re-examination of classical dynamical approaches and assumptions. Our experience so far has shown that entirely new qualitative and quantitative results can emerge from the collective interactions of the many particles in a complex dynamical system. Formerly sacred laws (such as the differential form of the Poisson equation) can break down at the crest of collisionless shocks, and new meta-laws (such as the equality of the volume torque integral with the derivative of the sum of gravitational and advective surface torque coupling integrals) appear as emergent laws. Such emergent behavior is the low-energy Newtonian dynamical analogy of high energy physics' spontaneous breaking

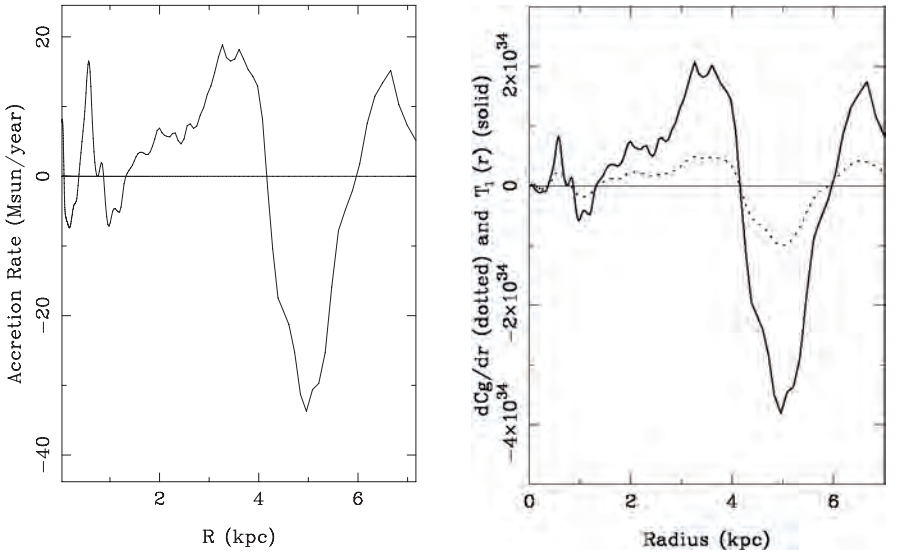


Figure 7 *Left*: Calculated stellar mass flow rate vs radius, and *Right*: Calculated radial gradient of torque coupling integral compared with the volume torque integral, for galaxy NGC 5194 (unit: dyne).

of gauge symmetry, a well known pathway for forming new meta laws when traversing the hierarchy of organizations.

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