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N-body simulations of collective effects in spiral and barred galaxies

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ABSTRACT

We present gravitational N-body simulations of the secular morphological evolution of disk galaxies induced by density wave modes. In particular, we address the demands collective effects place on the choice of simulation parameters, and show that the common practice of the use of a large gravity softening parameter was responsible for the failure of past simulations to correctly model the secular evolution process in galaxies, even for those simulations where the choice of basic state allows an unstable mode to emerge, a prerequisite for obtaining the coordinated radial mass flow pattern needed for secular evolution of galaxies along the Hubble sequence. We also demonstrate that the secular evolution rates measured in our improved simulations agree to an impressive degree with the corresponding rates predicted by the recently-advanced theories of dynamically-driven secular evolution of galaxies. The results of the current work, besides having direct implications on the cosmological evolution of galaxies, also shed light on the general question of how irreversibility emerges from a nominally reversible physical system.

1. Introduction

1.1. Self-organization in nonequilibrium systems

Understanding the self-organization behavior of nonlinear, far from equilibrium systems is among the most challenging of problems of contemporary research. This multi-disciplinary study is relevant to answering many key questions in condensed matter physics, biological and life sciences, social sciences, as well as the processes of structure formation in the universe.

Several leading scientists of the 20th century considered the exploration of collective behaviors, or the processes of morphogenesis, to be of central importance to the future advancement of science. More than half a century ago, Richard Feynman closed volume II of "The Feynman Lectures on Physics" by declaring: "The next great era of awakening of human intellect may well produce a method of understanding the qualitative content of equations. Today we cannot. Today we cannot see that the water flow equations contain such things as the barber pole structure of turbulence that one sees between rotating cylinders. Today we cannot see whether Schrödinger's equation contains frogs, musical composers, or morality—or whether it does not" (Feynman et al., 1964). P.W. Anderson, a noted condensed matter physicist, penned an influential article for *Science* titled "More is different" (Anderson, 1972), in which he called attention to the hierarchical organization of physical systems, and the ability of many-degrees-of-freedom systems to form emergent structures and dynamics, which break the symmetries of equations describing the underlying micro-dynamics. Among the studies on morphogenesis, one of the most prophetic is that of Ilya Prigogine. In his theory of "dissipative structures", Prigogine emphasized the entropy-production-enhancing function of self-organized global patterns in far-from-equilibrium systems, as well as the constructive role of dissipation in maintaining these patterns (Prigogine, 1980). To paraphrase this theory, most of the self-organized structures in nature come in roughly two types: (1) equilibrium structures, which are formed through equilibrium phase transitions. The examples of equilibrium structure formation include the phase transition of water to form ice when the temperature is lowered to zero degree Celsius, as well as the formation of minerals of a specific crystal structure when the environmental temperature and pressure satisfy a range of conditions (i.e. the formation of diamond crystal from carbon in a high pressure environment). (2) Nonequilibrium structures, which are formed in systems far from equilibrium, and which (in addition to sharing some common features with structures formed in equilibrium phase transitions) have the added feature that these self-organized structures are generally in a dynamical equilibrium state, meaning they are sustained through the competition of growth and decay tendencies (as highlighted by the well-known fluctuation–dissipation theorem, proved mostly at close-to-equilibrium regimes but is also valid at far-from-equilibrium situations for self-organized dissipative structures). There is in general also a continuous flux of energy

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and entropy through the system to maintain the nonequilibrium fluctuation. The formation of self-organized dissipative structures in nonequilibrium systems often serves the important function of greatly accelerating the speed of entropy evolution of the parent systems (Prigogine, 1980).[1]

The hierarchy of self-organization processes in a nonequilibrium system often leads to a series of effective singularities in the dynamics, which allow *emergent* new dynamics to form that cannot be *deductively* derived from the differential formulation one starts the analysis with. A synthetic approach uniting the various local aspects to achieve global self-consistency will need to be adopted. The correlations among the fluctuations of the individual degrees of freedom of the many-body system are shown to play a crucial constructive role at the juncture of nonequilibrium phase transitions.

Although the mechanism for the generation of new dynamics through so-called "spontaneous breaking of gauge symmetry" had been routinely proposed in high energy physics, it was mostly used in a model context, rather than derived from first principles in a self-consistent fashion. Quoting once again condensed matter physicist P.W. Anderson: "... the concept of broken symmetry has been borrowed by the elementary particle physicists, but their use of the term is strictly an analogy, whether a deep or a specious one remaining to be understood" (Anderson, 1972). On the other hand, the fact that, as of now, there have been very few examples of self-organized dissipative systems being analyzed from first principles (in Prigogine's work, chemical clock was used as one prominent example) is partly due to the intrinsic complexities of such problems, i.e., the many degrees of freedom of the components, and the correlations among the components, which invalidate many basic assumptions underlying the usual kinetic theory approach for treating many-particle systems. One of the most important assumptions used in the derivation of the Boltzmann kinetic equation is the so-called "molecular chaos" assumption (see, e.g., Kreuzer (1981) for a detailed description of the BBGKY procedure for the derivation of the collisional Boltzmann equation), or the assumption that particle collisions are uncorrelated. This assumption is crucial to Boltzmann's arriving at his famous H-theorem, or that entropy never decreases in nonequilibrium processes. The inter-particle correlations, however, are the necessary ingredient for obtaining self-organized behavior, and their re-introduction into the study of nonequilibrium dynamics allows local-entropy-decreasing processes to be admitted into the analyses.

N-body simulations of self-gravitating systems, in our case the simulation of disk galaxies containing self-organized density wave patterns, offer a rare chance to observe at close range the modification of differential dynamics to arrive at new (i.e. emergent) meta-laws, thus offer clues to the common features of spontaneous symmetry breaking processes in many-degrees-of-freedom dynamics. In this case, an added advantage is that a parallel theoretical development has also been accomplished in the past few decades, which can serve as standards of comparison with the simulation results.

1.2. Secular evolution of galaxies in the context of nonequilibrium phase transition

The striking coherence of spiral and bar patterns in disk galaxies has long captured our awe and fascination, but it was only since the advent of density wave theory (Lindblad, 1963; Lin and Shu, 1964; Kalnajs, 1965) that these patterns were understood as propagating waves of over-density in differentially rotating galaxy disks.[2]

As the study of density waves in galaxies progressed over the past few decades, the propagating wave picture of the initial studies further evolved into a *modal* view, in which the oppositely-propagating trains of density wave in the radial direction superpose to form growing density wave *modes* (Lin and Lau, 1979 and the references therein; Bertin et al., 1989a,b). In this formulation the so-called "grand-design" spirals and bars observed in nearby galaxies were regarded as spontaneously growing modes in a galactic resonant cavity whose properties are characterized by the axisymmetric distributions of disk-mass surface density, stellar and gaseous velocity dispersions, as well as the overall gravitational potential field (which include contributions not only from the disk mass, but also from the more spherically distributed luminous and dark halos, as well as the galactic bulge), which together form the so-called "basic state" of the galactic disk, upon which the wave modes grow as unstable harmonic perturbations.[3]

During the early decades of density wave study, the basic state of the galactic disk was treated as a stationary background from which the unstable trains and modes of density waves were calculated to varying orders of approximation (according to the orderings of either the degree of non-linearity, or else the degree of locality in the successive WKBJ approximations). The prospect of the secular evolution of the mass distribution of the basic state itself was never seriously considered, apart from phenomenological inferences of the possible role of gas accretion (Kormendy, 1979). As we know, gaseous mass in galaxies forms only a small percentage of the total disk mass, and the disk mass in most intermediate- and early-type galaxies was dominated by stellar mass. Therefore, a significant transformation of the Hubble type of a galaxy during its lifetime will necessarily involve the secular redistribution of the *stellar* mass, in conjunction with the redistribution of the gas mass.

The long-held view that the stellar disks of galaxies remain mostly unchanged throughout a galaxy's lifetime is partly a result of the belief that stars behave "adiabatically" during their orbital motion, and do not dissipate their orbital energy when interacting with a stationary density wave except at the wave/particle resonances (Lynden-Bell and Kalnajs, 1972)—a behavior summarized by the well-known "conservation of the Jacobi integral" of a single star's orbit in the rotating frame of a stationary wave perturbation (Binney and Tremaine, 2008). Another often-used phrase to describe this quasi-stability of the stellar orbit is the so-called "angular momentum barrier" to secular redistribution of stellar mass in a disk galaxy.

Observationally, there is growing evidence that galaxy morphology does evolve significantly throughout the cosmic history, in general following the trend from a disk-dominated late-Hubble-type to a bulge-dominated earlier-Hubble-type (Zhang, 2003; Kormendy and Kennicutt, 2004, as well as the references therein).

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[1] The transportation of entropy to its environment is the chief means a dissipative structure can maintain a low or constant entropy state despite it being a very efficient engine at the local production of entropy. This aspect also resolves the paradox of how nature can generate complex biological entities such as human being as a result of nonequilibrium evolution, despite being governed by the second law of thermodynamics universally. The study of nonequilibrium dissipative structures tells us that entropy increasing evolution does not always mean the rush towards homogeneity everywhere, at least not for open, many degree-of-freedom, far-from-equilibrium systems.

[2] The publication of the first round of density wave papers followed shortly after the appearance of the first volume of "The Feynman Lectures on Physics" in which Feynman suggested to the freshman and sophomore physics students in his class: "Incidentally, if you are looking for a good problem, the exact details of how the arms are formed and what determines the shapes of these galaxies has not been worked out" (Feynman et al., 1963).

[3] The "basic state" of the galactic disk is formally equivalent to the so-called "boundary condition" in an electromagnetic resonant cavity.