New Astronomy 30 (2014) 8–27

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Density wave formation in differentially rotating disk galaxies: Hydrodynamic simulation of the linear regime ☆

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HIGHLIGHTS

- The behavior of a galactic disk is examined numerically by a hydrodynamic code.
- The linear regime of density wave formation are explored.
- The simulation results are compared with the generalized "fluid"–wave theory.
- The disk evolution is fairly well described by the local approximation of the theory.

ARTICLE INFO

Article history:
Received 7 March 2013
Received in revised form 8 November 2013
Accepted 1 January 2014
Available online 8 January 2014
Communicated by G.F. Gilmore

Keywords:
Instabilities
Waves
Methods: numerical
Galaxies: spiral
Galaxies: kinematics and dynamics

ABSTRACT

Most rapidly and differentially rotating disk galaxies, in which the sound speed (thermal velocity dispersion) is smaller than the orbital velocity, display graceful spiral patterns. Yet, over almost 240 yr after their discovery in M51 by Charles Messier, we still do not fully understand how they originate. In this first paper of a series, the dynamical behavior of a rotating galactic disk is examined numerically by a high-order Godunov hydrodynamic code. The code is implemented to simulate a two-dimensional flow driven by an internal Jeans gravitational instability in a nonresonant wave–"fluid" interaction in an infinitesimally thin disk composed of stars or gas clouds. A goal of this work is to explore the local and linear regimes of density wave formation, employed by Lin, Shu, Yuan and many others in connection with the problem of spiral pattern of rotationally supported galaxies, by means of computer-generated models and to compare those numerical results with the generalized fluid-dynamical wave theory. The focus is on a statistical analysis of time-evolution of density wave structures seen in the simulations. The leading role of collective processes in the formation of both the circular and spiral density waves ("heavy sound") is emphasized. The main new result is that the disk evolution in the initial, quasilinear stage of the instability in our global simulations is fairly well described using the local approximation of the generalized wave theory. Certain applications of the simulation to actual gas-rich spiral galaxies are also explored.

1. Introduction

The dynamics of highly flattened, rapidly and differentially rotating self-gravitating systems, in which the sound speed (thermal velocity dispersion) is smaller than the orbital velocity, has now been studied quite thoroughly since the pioneering works by Toomre (1964) for collision-free stellar disks and Goldreich and Lynden-Bell (1965) for gas sheets. The research is aimed above all to explain the origin of circular and spiral structures in galaxies, the fragmentation of the rotationally flattened solar nebula, rapid lunar and planetary formation, structures in accretion disks around massive objects, fine-scale structures of Saturn's main rings and, finally, the enhanced angular momentum and mass redistribution in astrophysical disk configurations. One of the main trends has therefore been to analyze the perturbation dynamics in such systems, in both linear and nonlinear regimes. It has been shown that the evolution of all these systems are dominated by the internal instabilities of gravity perturbations (e.g. those produced by a spontaneous disturbance or, in rare cases, a companion system). In particular, unstable, i.e. amplitude-growing compression type waves, or density waves, can be self-excited in the main domain of the disk via the internal Jeans gravitational instability in a nonresonant wave–"fluid" interaction. The evolution of such self-gravitating disks is primarily driven by angular momentum redistribution so that growing gravity perturbations carry angular momentum from the inner parts to the outer parts, and

☆ Dedicated to the memory of Professors Alexei M. Fridman (1940–2010) and Chi Yuan (1937–2008).

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http://dx.doi.org/10.1016/j.newast.2014.01.001

gravitational forces are predominant. The system may then fall toward the lower potential energy configuration and use the energy so gained to increase its coarse grained entropy (Lynden-Bell and Kalnajs, 1972; Griv and Gedalin, 2004; Griv et al., 2008). In a general sense, the instability represents the ability of a gravitating system to relax from a nonthermal state by *collective* processes in much less time than the ordinary binary collision time (Morozov, 1978; Griv et al., 2001, 2002).

Because of the nature of the gravitation force, self-gravitating systems are always spatially inhomogeneous and rotate nonuniformly, i.e. the angular velocity of their rotation is a function of distance. The observed arms in these flat systems trail behind with respect to the direction of disk rotation (Pasha and Smirnov, 1982; Clampin et al., 2003; Fukagawa et al., 2004; Porco et al., 2005; Hedman et al., 2007). In the spirit of Lin and Shu (1964, 1966), Lin et al. (1969), Yuan (1969), Roberts and Yuan (1970) and Shu (1970), in this paper we regard the spiral structure in astrophysical disks as a Lin–Shu type density wave pattern, which does not remain stationary in a frame of reference rotating around the disk center at a proper speed, excited as a result of the Jeans instability of small-amplitude gravity perturbations. The classical Jeans gravitational instability is set in when the destabilizing effect of the self-gravity in the rotating disk exceeds the combined restoring action of the pressure and Coriolis forces. The instability is one of the most frequent and most important instabilities in the stellar and in the planetary cosmogony (Polyachenko and Fridman, 1972; Goldreich and Ward, 1973; Sekiya, 1983; Griv et al., 2003) and galactic kinematics and dynamics (Yuan, 1969; Shu et al., 1972; Rohlfs, 1977; Bertin et al., 1989; Griv et al., 2002, 2006), and deals with the question of whether initial density fluctuations will be amplified or will die down. Jeans instability identifies *nonresonant* instabilities of fluctuations associated with almost aperiodically growing accumulations of mass. In other words, the instability associated with departures of macroscopic quantities from the thermodynamic equilibrium is hydrodynamical in nature and has nothing to do with any explicit resonant $\omega = \boldsymbol{k}\cdot\boldsymbol{v}$ effects, where ω is the oscillation frequency, $\boldsymbol{k}$ is the wavenumber of excited oscillations and $\boldsymbol{v}$ is the particle's velocity. We do not discuss in the present paper the density wave structures that are associated with spatially limited wave–particle resonances (e.g. Lynden-Bell and Kalnajs, 1972; Griv et al., 2000).

Lin and Shu (1964, 1966), Lin et al. (1969), Roberts and Yuan (1970), Yuan (1969) and Shu (1970) stated clearly the concept of *quasi-stationary* density waves in spiral galaxies. See Rohlfs (1977), Fridman and Polyachenko (1984) and Binney and Tremaine (2008) for reviews of the original Lin–Shu density wave theory and its astronomical implications. Our present-day concept is somewhat different. This *generalized* wave theory was elaborated concurrently on the basis of the Lin and Shu original ideas by a number of authors, using both kinetic and fluid-dynamical approaches (e.g. Bertin and Mark, 1978; Lin and Lau, 1979; Bertin, 1980; Morozov et al., 1985; Bertin et al., 1989; Griv et al., 2001, 2002, 2006; Lou et al., 2001; Griv, 2011). Accordingly, a self-gravitating system of stars or gas clouds in a galaxy exhibits collective, gravitationally unstable modes of motions. Assuming the weakly inhomogeneous system, the behavior of small perturbations of equilibrium parameters is seeked in the form of a superposition of different Fourier harmonics corresponding to different normal modes of oscillation of the system, stable or otherwise,

$$X_1(\boldsymbol{r},t) = \sum_{\boldsymbol{k}} \Re\left\{\widetilde{X}_{\boldsymbol{k}}(r,z)e^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}-\mathrm{i}\omega_{\boldsymbol{k}}t}\right\}, \quad (1)$$

where (r,φ,z) are the cylindrical coordinates with the origin at the galactic center and the axis of disk rotation is taken oriented along the z-axis, $\widetilde{X}_{\boldsymbol{k}}(r,z)$ is an amplitude, the phase $\boldsymbol{k}\cdot\boldsymbol{r}$ is a large quantity, $\boldsymbol{k}$ is the real wave vector, $k=\sqrt{k_r^2+k_\varphi^2}$, k_r is the radial wavenumber, k_φ is the azimuthal wavenumber, $\omega_{\boldsymbol{k}} = \Re\omega_{\boldsymbol{k}} + \mathrm{i}\Im\omega_{\boldsymbol{k}}$ is some complex frequency of excited collective oscillations and suffixes $\boldsymbol{k}$ denote the $\boldsymbol{k}$th Fourier component. The amplitude $\widetilde{X}_{\boldsymbol{k}}$ is a slowly varying in space and time, and the rapidly varying part of X_1 is absorbed in its phase, $k_r r \gg 1$ where k_r is the radial wavenumber of the pattern. In a local WKB approximation we are actually exploring, both $\widetilde{X}_{\boldsymbol{k}} = \text{const}$ and $\boldsymbol{k} = \text{const}$. The constant phase velocity of spiral density waves is $\Omega_\mathrm{p} = \Re\omega_{\boldsymbol{k}}/m$ called the pattern rotation speed, where m is the positive azimuthal mode number (=number of spiral arms for a given harmonic). Since Ω_p is a constant, independent of time or radius, each component will remain identical with time and therefore spirals do not wind up by the general differential rotation. In a linear approximation, a perturbation is considered to be a superposition of different oscillation modes, and the coexistence of several spiral (and circular) waves is possible. This disturbance in the disk will grow until it is limited by some nonlinear effect. Thus, the imaginary part of the wavefrequency $\Im\omega_{\boldsymbol{k}}$ corresponds to a growth or decay of the components in time, $\propto \exp(\Im\omega_{\boldsymbol{k}}t)$, and $\Re\omega_{\boldsymbol{k}}$ corresponds to a rotation with constant angular velocity Ω_p. Unstable normal modes with higher $\Im\omega_{\boldsymbol{k}}$ are more likely to achieve a higher amplitude and play more important roles. The gravitational field of a traveling pattern results in the perturbed gas and stars motion in addition to the mean circular motion. A longitudinal Lin–Shu density wave is associated with compression and decompression in the direction of travel, which is the same process as the ordinary sound waves in gases (Fig. 1(b)).

Perturbations with $m=1$ prove especially interesting. This so-called lopsidedness, or the $m=1$ asymmetry, is oftenly seen in the distribution of stars and gas in the outer disks of many galaxies (e.g. van Eymeren et al., 2011).

Thus, when $\Im\omega_{\boldsymbol{k}} > 0$, the medium transfers its energy to the growing wave and oscillation buildup occurs. The wave propagation is a rigid rotation process at a fixed phase velocity, despite the general differential rotation of the system. At the same time the amplitude of the wave grows exponentially in the linear regime of the instability. As a result, the alternating density enhancements (circles and/or spiral arms) and depletion zones (interarm regions) consist of different material at different times. Lin–Shu unforced density waves cause a temporary bunching together of orbiting disk's particles and the material stream across the arms; spiral arms (interarm regions) are genuine indicators of higher-than-average (lower-than-average) galactic matter density.[1] This density wave structure may be excited by real instabilities of gravity perturbations. Low-m (say, $m \leqslant 4$) waves are the most important because they are associated with large-scale phenomena (Lin et al., 1969, 1978; Shu, 1970; Rohlfs, 1977). Following Lin and Shu (1964, 1966), Lin et al. (1969), Yuan (1969), Roberts and Yuan (1970) and Shu (1970), in the present paper we restrict the analysis to a treatment of even Jeans perturbations (Fig. 1(b)) which are symmetric with respect to the equatorial $z=0$ plane. It seems likely that these perturbations are associated with such phenomena as, for example, the appearance of the spiral structure of galaxies and protoplanetary disks (Rohlfs, 1977; Fridman and Polyachenko, 1984; Binney and Tremaine, 2008; Boss, 2008; Alexander et al., 2008; Cuzzi et al., 2008; Cossins et al., 2009; Boley et al., 2010; Griv et al., 2002, 2006; Griv and Gedalin, 2012) and the fine-scale ~ 100 m structure of Saturn's A and B rings (Griv et al., 2003; Griv, 2007). It was already proposed that all planets and planetesimals in the solar system, giant extrasolar planets, multiple star systems and small moonlets embedded in Saturn's rings form due to Jeans gravitational fragmentation

[1] If nonaxisymmetric features only consist of the same particles, then these features would rapidly "wrap up" around the disk center in the time of a single rotation and essentially smear out of visibility (Binney and Tremaine, 2008, chap. 6 therein).