Astronomical & Astrophysical Transactions

The Journal of the Eurasian Astronomical Society

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GASEOUS DISKS OF SPIRAL GALAXIES: ARMS AND RINGS

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An improved linear stability theory of small-amplitude oscillations of a self-gravitating, infinitesimally thin gaseous disk of spiral galaxies has been developed. It was shown that in the differentially rotating disks for nonaxisymmetric perturbations Toomre's modified critical Q-parameter is larger than the standard one. We use hydrodynamical simulations to test the validity of the modified local criterion.

1 RESULTS

Lin *et al.* (1969) and Shu (1970) developed a linear theory of tightly wound density waves to solve the problem of the spiral structure in disk galaxies. An important discriminant in the original Lin–Shu dispersion relation which connects frequency and wavenumber of excited waves is Toomre's local stability parameter Q (Toomre, 1964): when $Q \geq 1$, the self-gravitating disk is stable against axisymmetric (ringlike) perturbations. This local criterion gives a necessary condition for radial stability. It does not obviously address the stability of nonaxisymmetric modes. Lau and Bertin (1978), Lin and Lau (1979), Morozov (1980), Polyachenko (1989) and Griv *et al.* (1999) extended the original works of Lin *et al.* (1969) and Shu (1970) by including the azimuthal forces. It was demonstrated that the presence of differential rotation (or shear) results in quite different dynamical properties of the axisymmetric and nonaxisymmetric perturbations. A dispersion relation for arbitrary perturbations has been rederived. This generalized Lin–Shu–Kalnajs dispersion relation leads to the following modified local stability criterion obtained, e.g. by Morozov (1980) and Griv *et al.* (1999):

$$Q \geq \{1 + [(2\Omega/\kappa)^2 - 1]\sin^2 \psi\}^{1/2}, \tag{1}$$

where the condition $2\Omega/\kappa > 1$ always holds in the differentially rotating system. The quantities $\Omega(r)$ and $\kappa(r)$ denote the angular velocity of galactic rotation and the epicyclic frequency, respectively, at the distance r from the center. The pitch angle ψ between the direction of the wave front and the tangent to the circular orbit in Eq. (1) is $\psi = \arctan(m/k_r r)$, where m is the number of spiral arms, and k_r and $k_\varphi = m/r$ are the radial and the azimutral wavenumbers. The parameter $\{1 + [(2\Omega/\kappa)^2 - 1]\sin^2\psi\}^{1/2}$ is an additional stability parameter which depends on both the pitch angle and the amount of differential rotation in the galaxy.

It is clear from the modified criterion (1) that in a nonunxformly rotating disk for nonaxasymmetric perturbationo the modified stability criterion is larger than $Q = 1$ (although still of the order of unity). A relationship exists between Eq. (1) and what Toomre (Binney and Tremaine, 1987) called 'swing amplification'. The free kinetic energy associated with the differential rotation of the system under study is one possible source for the growth of the energy of these spiral perturbations, and appears to be released when angular momentum is transferred outward.

As one can see from Eq. (1), the critical stability parameter grows with ψ. Consequently, in order to suppress the most 'dangerous', in the sense of ths loss of gravitational stability, open perturbations ($\psi \gtrsim 05°$), Q should obey the following modified criterion:

$$Q \geq Q_{\text{mod}} = 2\Omega/\kappa. \qquad (2)$$

One should keep in mind that Eq. (2) is clearly only an approximate one. It is clear, however, that the modified criterion for the local stability of a gaseous disk against arbitrary Jeans perturbations should be approximately of the form of Eq. (2): the condition for the spiral Jeans instability onset is $Q < 2.0$–2.5 at all radii.

The value of Toomre's stability parameter Q is critically important for any gravitational theory of spiral structure in galaxies. The modified local stability parameter has been discussed at length by Griv and Peter (1996) and Griv *et al.* (1999), using a kinetic approach. Here we discuss the problem using a gasdynamic approximation.

The main objective of the current work is to check the modified local stability parameter (2) numerically using the method of hydrodynamical simulations. In particular, we focus on the thermal motion effect in differentially rotating disks. A nonuniformly rotating gaseous disk is considered. Angular velocity of the disk is defined by the stellar gravitational potential because the mass of gas is much smaller the stellar system. We solve the gasdynamical equations numerically in two-dimensions using an Eulerian hydro-code. The hydrodynamic part of the basic equations is solved by the implicit 'upstream–downstream' scheme. At the symmetry axis we require that no mass flows through the axis. At the other boundaries we require that the gas should not be able to leave the grid. We use 1024×1024 Cartesian grid points covering a 20×20 kpc region. Therefore, the spatial resolution is about 20 pc. A periodic Green function is used to calculate the self-gravity. The initial conditions are an axisymmetric and rotationally supported disk. Small random density and velocity fluctuations are added to the initial system. The problem
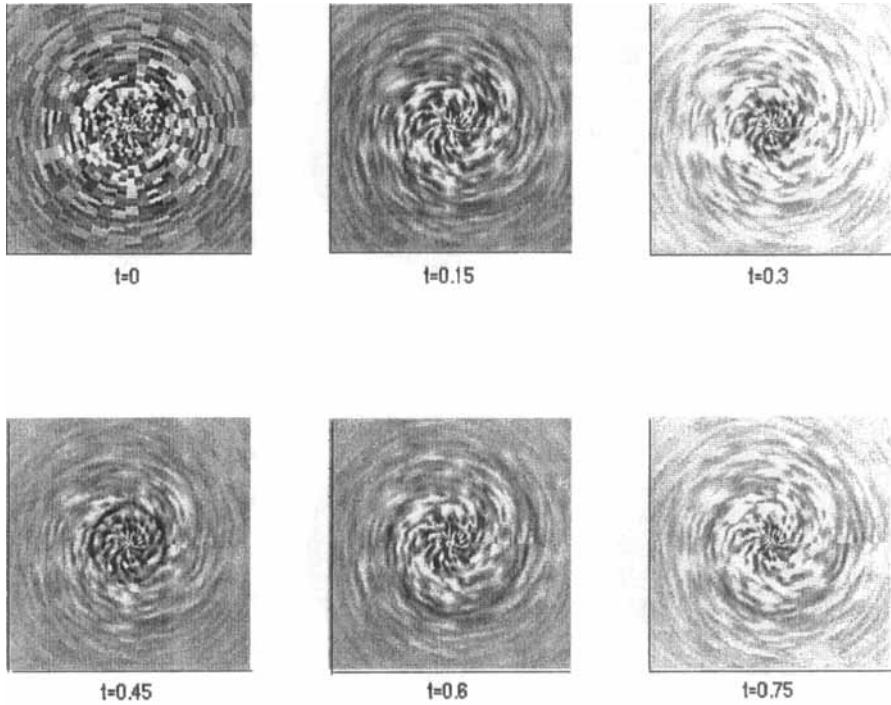
Figure 1 The nearly-isothermal differentially rotating system with $Q = 1$ is found to be unstable with respect to almost circular perturbations growing on a dynamical time scale. Eventually, the almost circular structure converts into a one-armed spiral. The underlying potential in a large fraction of spiral galaxies, e.g. in M101, is now believed to have this lopsided form.

consists in calculating the reaction of the gas to the fluctuations. (A time $t = 1$ is taken to correspond to a single revolution of the initial disk.)

In Figure 1 we show a series of snapshots from a run with the cool model, namely, Toomre's $n = 4$ model (Binney and Tremaine, 1987, p. 44), in which Q-value is equal to 1 over the whole system. As has been predicted in the theory, the spiral Jeans instability develops quickly in the system during the time of the first rotation. A typical wavelength (a typical distance between the spirals) is $\sim 2\lambda_J$, indicating that perturbations with Jeans–Toomre wavelength $\sim \lambda_J$ have the fastest growth rate. Such a size of density wave is in agreement with the theory (Griv et al., 1999).

In the second set of experiments with Toomre's $n = 4$ disk, we set at $t = 0$ the parameter $Q = 2\Omega/\kappa \approx 2$. The results of the experiment are shown in Figure 2. As one can see, the system becomes hydrodynamically stable. The result agrees with the theoretical explanation described in the paper.

We conclude that in agreement with the theory, the disks become progressively more stable as Toomre's Q-parameter grows. In order to suppress the instability of
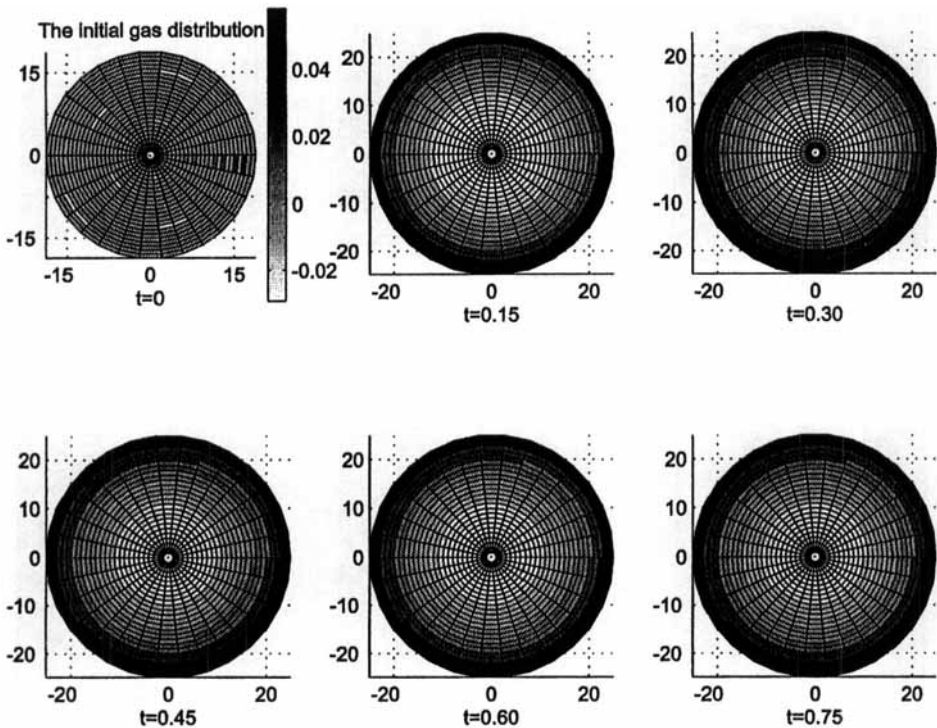
Figure 2   Time-development of Toomre's $n = 4$ gaseous model with $Q = 2$. In agreement with the theory, all Jeans type perturbations are suppressed including the most unstable nonaxisymmetric ones.

arbitrary Jeans type perturbations in a differentially rotating gaseous disk, Toomre's Q-value must exceed Q_{mod} (Eq. (2)).

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