

Global Gravitationally-Organized Spiral Waves and the Structure of NGC 5247

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ABSTRACT

Using observational data, we build numerical N-body, hydrodynamical and combined equilibrium models for the spiral galaxy NGC 5247. The models turn out to be unstable towards spiral structure formation. We simulate scenarios of spiral structure formation for different sets of equilibrium rotation curves, radial velocity dispersion profiles and disk thickness and demonstrate that in all cases a simulated spiral pattern qualitatively agrees with the observed morphology of NGC 5247. We also demonstrate that an admixture of a gaseous component with mass of about a few percent of the total mass of the disk increases a lifetime of a spiral pattern by approximately 30%. The simulated spiral pattern in this case lasts for about 3 Gyr from the beginning of the growth of perturbations.

Key words: Galaxies: kinematics and dynamics — Galaxies: spiral — Interstellar Medium: structure — Physical Data and Processes: Instabilities

1 INTRODUCTION

Attempts to understand the phenomenon of spiral structure in galaxies have a long history. It has become clear nowadays that the spiral structure is a density wave (or waves) propagating in a multi-component stellar-gaseous disk. A universal mechanism for the generation of such spiral density waves that successfully explains the rich morphological variety of spiral galaxies does not yet exist. To describe the observed patterns, a few spiral-generation mechanisms are usually invoked. Some researchers treat the spiral structure as long-lived global modes that last in the galactic disks for tens of galactic rotations (Bertin et al. 1989a,b; Bertin and Lin 1996). Others consider the spiral structure as a transient phenomenon, so that the spiral pattern changes many times during the galactic evolution (see, e.g., Sellwood 2011, for references). Gerola and Seiden (1978) even suggested that spiral structure is merely a product of recent star formation, outlined by the new-born stars. On observational ground, the problem of the origin of spiral structure was raised recently by Eskridge et al. (2002); Elmegreen et al (2011); Kendall et al. (2011). These authors found that galaxies which are optically grand design spirals,

show a grand design structure in the near-infrared as well. The spiral structure therefore is not merely a manifestation of a recent star formation but represents also a spiral structure in the underlying stellar mass distribution. The paper by Elmegreen et al (2011) shows that some flocculent spirals remain flocculent even in the IR. This observational evidence rules out at least one approach which suggested that the spiral structure in galaxies is a pattern of a recent star formation and does not involve an underlying stellar mass distribution. To understand to what extent the various suggested explanations are consistent with the observed phenomena of spiral structures, a detailed, quantitative comparison between the theoretical predictions and the observed properties of the spiral patterns in galaxies should be undertaken. In this paper, we continue our efforts to compare the properties of the observed spiral structure with the theoretical predictions. In previous papers (Korchagin et al. 2000, 2005), we made such a comparison using a hydrodynamical approach to model the dynamics of galactic disks. In this paper, we simulate three-dimensional collisionless, and collisionless-gaseous models of galactic disks, aiming to determine the model parameters that most closely match the observed spiral pattern in the galaxy NGC 5247. We choose

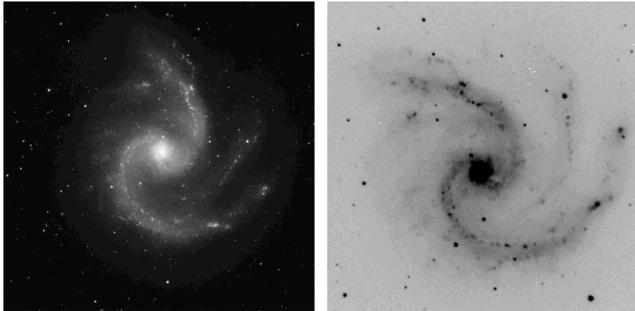


Figure 1. Left: optical image of the NGC 5247 galaxy (Eskridge et. al. (2002)). Right: HII regions outlining the spiral arms.

this galaxy for our comparison because it is well studied observationally, and its rotation curve as well as disk velocity dispersion and luminosity distribution have been accurately determined.

In the cases that have been studied, the admixture of a gaseous component increases the lifetime of a spiral pattern (Semelin and Combes 2002; Fux 1999). In general however, the lifetime of the spiral patterns in isolated galaxies and the role of gas remain an open issue, that we address in this paper.

In Section 2 we discuss the observational properties of the galactic disk of NGC 5247. In Section 3 we present the basic equations and discuss the disk equilibrium. Section 4 presents the results of numerical simulations of a gaseous and a collisionless stellar model of the galaxy NGC 5247. Section 5 presents the results of our simulations of stellar-gaseous models, and in section 6 we present the concluding remarks.

2 NGC 5247: CONSTRAINTS FROM OBSERVATIONAL DATA

NGC 5247 shown in Figure 1 is a nearby spiral galaxy which probably belongs to the Virgo Supercluster of galaxies (Binggelli et a. 1985). It has a strong, well developed two-armed “grand-design” spiral pattern and does not demonstrate any signs of interactions with other galaxies (Considerere and Athanassoula 1988). The spiral pattern however looks somewhat lopsided. A low-amplitude spiral pattern is detected in an interarm region. However the morphology of the galaxy is dominated by the two-armed spiral. The photometric data do not point to any noticeable bar in the central regions of the disk, therefore NGC 5247 is a classical example of a grand-design spiral galaxy.

Our numerical modeling is based on photometric data taken by Zhao et al. (2006). We take as the radial scale length of the disk $r_d = 4.8$ kpc as determined by these authors. The inclination angle of NGC 5247 is rather uncertain. Measurements range from $i = 20^\circ$ (Zhao et al. 2006) to $i = 40^\circ$ (HyperLeda). In this paper we adopt an inclination of 28° which is close to an average from these references, and a distance to the galaxy of 17.4 Mpc (HyperLeda)

The vertical scale of the disk (z_0) significantly influences its stability properties. Unfortunately, an accurate estimate of the vertical thickness of the galactic disk is not simple.

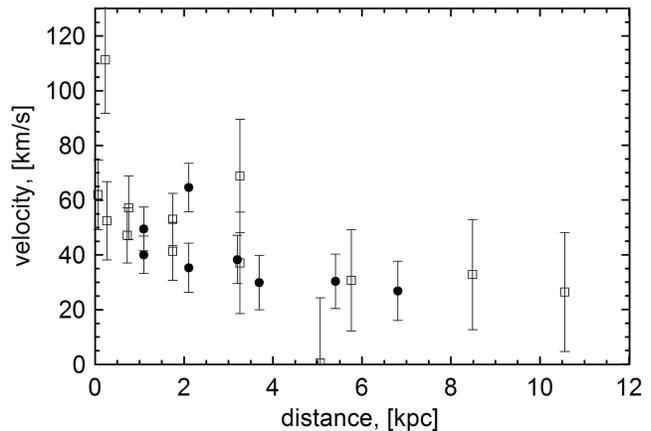


Figure 2. Radial dependence of the observed velocity dispersion of the stellar disk of NGC 5247. Filled circles — data from van der Kruit and Freeman (1986), open squares — measurements of Bottema (1993).

Zhao et al. (2006) tackled this problem by using the Jeans equations applied along the vertical axis of the disk, and estimated the disk thickness of NGC 5247 to be $z_0 = 1.5 \pm 0.6$ kpc. With this value, the ratio of the radial to vertical scale length is $r_d/z_0 = 3.2^{+2.1}_{-0.9}$.

The line-of-sight velocity dispersion as a function of galactocentric radius for NGC 5247 has also been determined from observations (Bottema 1993; van der Kruit and Freeman 1986, see Fig. 2). The measurements by both groups agree with each other and show approximately exponential decrease of the velocity dispersion with radius, which is typical for disk galaxies.

3 MODELING NGC 5247: BASIC EQUATIONS

We assume that the potentials of the dark halo and the stellar bulge are static and remain axisymmetric. Such an assumption does not affect the dynamics of a galactic disk because a contribution of high velocity dispersion components to the spiral density waves is insignificant even if they involve most of the galactic mass (Marochnik 1972). The galaxy does not have a large central bar, and we exclude from a consideration the models with a bar which is considered to be an effective generator of the spiral density waves (Korchagin and Shevelev (1981); Buta et al. (2009); Kaufmann and Contopoulos (1996)). Second, observational data do not allow us to estimate the degree of asymmetry of spheroidal subsystems, and the emergence of new free parameters greatly complicates the analysis. Moreover, an interaction with a live bulge or a halo can not be decisive.

To simulate the dynamics, we use a set of equations which self-consistently describe the behavior of a stellar-gaseous disk in equilibrium with an external gravitational field Ψ_{ext} . The set of equations for the stellar disk consisting of N gravitationally interacting particles is written as:

$$\frac{d^2 \mathbf{r}_i}{dt^2} = -\nabla [\Psi_s(\mathbf{r}_i) + \Psi_{ext}(\mathbf{r}_i) + \Psi_g(\mathbf{r}_i)], \quad i = 1, \dots, N. \quad (1)$$

Here Ψ_s is the gravitational potential of the stellar component of the disk, Ψ_g is the potential caused by the gaseous

component, and Ψ_{ext} is the combined gravitational potential of the galactic halo (Ψ_h) and the bulge (Ψ_b). Therefore $\Psi_{ext} = \Psi_h + \Psi_b$.

The set of equations describing the dynamics of the gaseous component are given by:

$$\frac{\partial \rho_g}{\partial t} + \nabla \cdot (\rho_g \mathbf{u}) = 0, \quad (2)$$

$$\frac{\partial \rho_g \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla (\rho_g \mathbf{u}) + \nabla p + \rho_g \nabla [\Psi_g + \Psi_{ext} + \Psi_s] = 0, \quad (3)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + p)\mathbf{u}] + \rho_g \mathbf{u} \nabla [\Psi_g + \Psi_{ext} + \Psi_s] = 0, \quad (4)$$

here ρ_g , p , and \mathbf{u} are the volume density, the pressure and the velocity vector of gas. The energy density of gas E is given by the expression $E = \rho_g |\mathbf{u}|^2/2 + p/(\gamma - 1)$. We use an adiabatic equation of state $\rho_g = K_s p^\gamma$ for the gas, where the value of the adiabatic index is assumed to be $\gamma = 1.1$ and the constant K_s was chosen so that the sound speed is equal to $c_s = 10 \text{ km s}^{-1}$ in central regions of the disk. The sound speed of the gas decreases slowly with radius, reaching approximately 8 km s^{-1} at the periphery of the disk. Self-gravity is taken into account by the Poisson equation applied for the gaseous and stellar components:

$$\Delta \Psi_g = 4\pi G \rho_g, \quad (5)$$

$$\Delta \Psi_s = 4\pi G \rho_s. \quad (6)$$

To model the gravity of the halo, we use the potential:

$$\Psi_h = \frac{GM_h}{C_h} \cdot \left\{ \ln(\xi) + \frac{\arctg(\xi)}{\xi} + \frac{1}{2} \ln \frac{1 + \xi^2}{\xi^2} \right\}. \quad (7)$$

Here $\xi = r/a_h$, a_h is the scale length of the halo potential, M_h is the mass of the halo within radius $r_h = 20 \text{ kpc}$ and $C_h = a_h(r_h/a_h - \arctg(r_h/a_h))$. Such a choice provides a constant rotation velocity at large radii $r > 2a_h$, so we have a rotation curve typical for disk galaxies.

The King model with a cutoff a density distribution of large radii $r > r_b^m$ is used to model the potential of a stellar bulge:

$$\Psi_b = -\frac{GM_b}{C_b r} \ln \left[\frac{r}{r_b} + \sqrt{1 + \left(\frac{r}{r_b} \right)^2} \right], \quad (8)$$

here r_b is the bulge scale length, M_b is the bulge mass within r_b^m and $C_b = \ln \left(\frac{r_b^m}{r_b} + \sqrt{1 + \left(\frac{r_b^m}{r_b} \right)^2} \right) - \frac{r_b^m/r_b}{\sqrt{1 + (r_b^m/r_b)^2}}$.

The observed rotation curve of the disk can be reproduced by varying the parameters of the dark halo (M_h , a_h), the stellar bulge (M_b , r_b) and the stellar disk (M_s , r_d , z_0).

To analyze a behavior of a one-component collisionless model, we assume that the gas density ρ_g is equal to zero, and solve equation (6) using TREE-code (Barnes and Hut 1986) adapted to the parallel calculations. The number of particles used in our collisionless models range from $N = 10^6$ to 10^7 . To build a self-consistent model of a stellar-gaseous disk, the set of hydrodynamical equations for a gaseous disk rotating in a self-consistent gravitational potential is added to the equations of motion for a stellar disk.

We apply a TVD MUSCL type scheme in the cylindrical coordinate system (van Leer 1979) to solve the equations (2)–(4). To preserve conservation laws at a grid level, a finite-

volume approximation of the variables is used:

$$(q)_{i+1/2} = q_i + 0.25((k+1)D_+ + (k-1)D_-)_i,$$

here $(q)_i, (q)_{i+1/2}$ are the conserved variables at a border of i -th cell and at its center correspondingly; $D_+ = \text{minmod}(d_+, bd_-)$, $D_- = \text{minmod}(d_-, bd_+)$, where d_-, d_+ are the variations of the conserved variables to the left and to the right of a cell border. The parameter $b = (3-k)/(1-k)$ determines an order of approximation in space. We use the value $k = 1/3$, corresponding to the third order of spatial approximation. The function

$$\text{minmod}(x, y) = \frac{\text{sign}(x) + \text{sign}(y)}{2} \text{min}(|x|, |y|)$$

is used to reconstruct the discontinuous functions between the nodes of the computational grids.

Interaction between the stellar and the gaseous components of the disk occurs due to gravity. Similar to the one-component models, such interactions are computed using the TREE-code.

At the beginning of the simulations, the stellar disk is in an equilibrium in the radial and the vertical directions with its density given by:

$$\rho_s = \rho_{s0} \exp(-r/r_d) \cdot A(z/z_0),$$

here r_d , z_0 are radial and vertical scales of the stellar disk. Function $A(z)$ determines a vertical distribution of density of the stellar disk: $A(z) = \text{ch}^{-2}(z/z_0)$.

The equilibrium of the stellar disk in the vertical direction is determined by solving the Jeans equation:

$$\rho_s \frac{d}{dz} \left(c_z^2 \frac{d\rho_s}{dz} \right) - c_z^2 \left(\frac{d\rho_s}{dz} \right)^2 + \rho_s^2 \frac{d^2 c_z^2}{dz^2} + 4\pi G \rho_s^2 (\rho_s + E + \rho_{ext}(z)) + \rho_s^2 \frac{d}{dz} \frac{E\alpha}{\rho_s} = 0, \quad (9)$$

$$E = -\frac{1}{4\pi G r} \frac{\partial V_c^2}{\partial r}, \quad E_\alpha = \frac{\partial(r\rho_s\alpha_{rz})}{r \partial r}.$$

Here c_z is the stellar velocity dispersion in the vertical direction, $\alpha_{rz} = \langle uw \rangle$ is the result of averaging the product of the radial u and vertical w velocity components, ρ_{ext} is the total density of the halo and the bulge.

By using Jeans equation in the radial direction, we determine the rotational velocity of the stellar disk in the disc plane $z = 0$ (Khoperskov et al. 2010)

$$V^2 = \langle v \rangle^2 = V_c^2 + c_r^2 \left\{ 1 - \frac{c_\varphi^2}{c_r^2} + \frac{r}{\rho_s c_r^2} \frac{\partial(\rho_s c_r^2)}{\partial r} + \frac{r}{c_r^2} \frac{\partial \alpha_{rz}}{\partial z} \right\}, \quad (10)$$

here V_c is the circular velocity of a test particle in an axisymmetric field Ψ : $V_c^2/r = -\frac{\partial \Psi}{\partial r}$, $c_r/c_\varphi = 2\Omega/\kappa$, $\Omega = V/r$ and $\kappa = \sqrt{4\Omega^2(1 + r d\Omega/(2\Omega dr))}$ is the epicyclic frequency.

The gaseous disk extends in our models beyond the optical radius of the stellar disk to the distance $r = 16r_d$. The density distribution of the gaseous disk is modeled by the expression

$$\rho_g = \rho_{g0}(1 - r/(16r_d)) \cdot B(z)$$

where the function $B(z)$ is determined by the balance of the gravity force and the gas pressure gradient. With such a distribution, the gas density decreases by a few times within

the optical radius, and goes to zero in the ghost zones of the computational grid at $r = 16r_d$. The Euler equation uniquely determines the rotational speed of the gaseous disk:

$$-\frac{v_\phi^2}{r} = -\frac{1}{\rho_g} \cdot \frac{\partial p}{\partial r} - \frac{\partial}{\partial r} [\Psi_g + \Psi_s + \Psi_{ext}]. \quad (11)$$

We build a set of models for a stellar-, and a stellar-gaseous disk of the galaxy NGC 5247 such that the model predicted quantities like rotation curve and velocity dispersion are consistent with the observational data (and the uncertainties associated with the observations). In the following sections, we explore the model parameter space and discuss the dependence of the morphology of spiral pattern on the rotation curve, the stellar velocity dispersion, the vertical thickness of a stellar disk, and mass ratio of gaseous to stellar component of the galactic disk.

4 DISK EQUILIBRIUM

4.1 Rotation curve

A small inclination angle of the galaxy influences significantly a reconstruction of its rotation curve. Using the Tully-Fisher relation, Patsis et al. (1997) found the maximum rotational velocity of the galaxy to be: $V_{\max} = 205$ km/s. Other measurements give the values $V_{\max} = 165 \pm 20$ km/s (Bottama 1993) and $V_{\max} = 300$ km/s. Following the paper of Contopoulos and Grosbol (1986), we build a set of rotation curves that have a quasi-solid rotation in the central regions of the disk, and are flat in its outer regions. Such a shape of the rotation curve is typical for a large spiral galaxy. To build more realistic models, we take into account the gravitational potentials of the halo, of the bulge and of the galactic disk. The parameters of the potentials and corresponding properties of the rotation curves are listed in Table 1. To take into account observational uncertainties in our knowledge of the rotational curve of the galaxy, we vary the rotational velocity of the disk. Namely, the model A has the largest rotational velocity, B – middle one and model C has the lowest rotational velocity. The resulting rotation curves are shown in Fig. 3. A large spread in the rotational velocities reflects an uncertainty of observational data for this galaxy.

4.2 Velocity dispersion

To constrain the radial component of the velocity dispersion of the stellar disk c_r we use observed line-of-sight velocity dispersion data of NGC 5247. For the nearly face-on orientation of NGC 5247, the line-of-sight velocity dispersion is close to the component of the velocity dispersion in the direction perpendicular to the disk.

To mimic the observational uncertainties in our knowledge of the velocity dispersion, we choose three profiles as shown in Fig. 4. In this Figure, index 1 corresponds to the hottest disk, and index 3 corresponds to a model with the lowest velocity dispersion.

Observational data of the external galaxies show that the ratio of the vertical velocity dispersion to the radial velocity dispersion is approximately constant along the radius of a galactic disk, and varies from galaxy to galaxy within

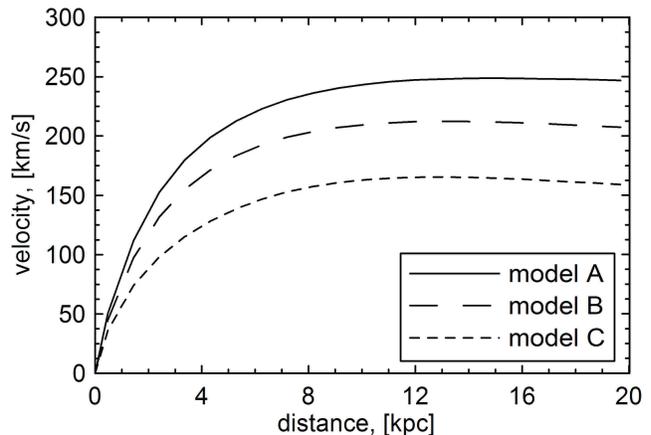


Figure 3. Rotation curves for one-component models. The maximum values of the rotation curves are equal to 245 km/sec (Model A), 205 km/sec (Model B) and 153 km/sec (Model C).

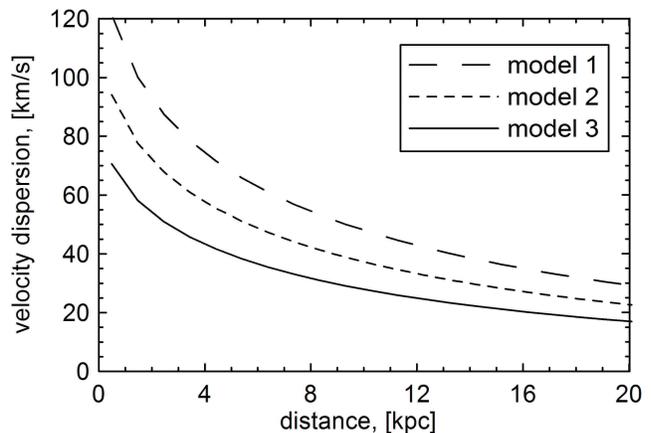


Figure 4. Radial velocity dispersion as a function of galactocentric distance. In model 1 — $c_z/c_r = 0.43$, model 2 — $c_z/c_r = 0.6$, model 3 — $c_z/c_r = 0.8$

$c_z/c_r = 0.3 - 0.8$ (Korchagin et al. 2000; Khoperskov et al. 2010). In our models we choose this ratio equal to $c_z/c_r = 0.43; 0.6; 0.8$ in central regions of galaxy.

4.3 Disk thickness

A direct measurement of the vertical scale of the disk of NGC 5247 is impossible. Zhao et al. (2006) solved this problem by applying the Jeans equation in the direction perpendicular to the collisionless stellar disk. They found the value of the disk vertical scale to be $z_0 = 1.5 \pm 0.6$ kpc. Taking into account this result, we additionally consider two variations of the model C3 with larger thickness of the disk equal to $z_0 = 2.1$ kpc, and the lower disk scale length $z_0 = 0.9$ (model D3).

A variation of the thickness of the stellar disk is taken into account in a set of models D with thickness of the disk decreasing from model D1 to model D3.

5 ONE-COMPONENT MODELS

5.1 Hydrodynamical model

The simplest model to study the dynamics of an unstable galactic disk is the hydrodynamical approximation. In this approximation, a stellar-gaseous gravitating disk is represented by a gravitating compressible fluid. There are some arguments justifying the hydrodynamic approximation for a description of stellar disks: Marochnik (1966), Hunter (1979), and Sygnet et al. (1987) demonstrate that the behavior of perturbations in collisionless disks can be approximately described by introducing an isotropic pressure with polytropic constant $\gamma = 2$. Using the hydrodynamic approximation Kikuchi et al. (1997) made a direct comparison of the global stability properties of gravitating disks with the solution of the collisionless Boltzmann equation given by Vauterin and Dejonghe (1996). Kikuchi et al. (1997) found a qualitative, and in most cases a good quantitative agreement between the results found in a hydrodynamic approximation and by the direct solution of the Boltzmann equation.

To study the dynamics of the disk of NGC 5247, we use the parameters of model C1, listed in Table 1. This model was studied by using the linear global stability analysis as well as two-dimensional nonlinear simulations. Both methods are described in detail in papers by Korchagin et al. (2000) and Korchagin et al. (2005). The linear analysis yields the most unstable global mode as the $m = 2$ mode with eigenvalues $\text{Re}(\omega_2) = 1.67$, $\text{Im}(\omega_2) = 2.77$. Its nearest competitor, $m = 3$ mode, has the imaginary part of the eigenfrequency that determines the mode's growth rate equal to $\text{Im}(\omega_3) = 2.43$. With such values, the dynamics of perturbations is determined by a two-armed spiral pattern.

To analyze quantitatively the large-scale morphology of the spiral structure formed in the disk, we use a Fourier decomposition of the surface density $\Sigma(r, \varphi) = \int_{-\infty}^{\infty} \varrho_s(r, \varphi, z) dz$ of the disk.

Figure 5 plots the time dependence of the global Fourier amplitudes for modes $m = 1 - 4$

$$A_m = \frac{\left| \int_0^{2\pi} \int_0^1 \Sigma(r, \varphi) e^{-im\varphi} r dr d\varphi \right|}{\int_0^{2\pi} \int_0^1 \Sigma(r, \varphi) r dr d\varphi} \quad (12)$$

growing from random initial density perturbations. Snapshots of density perturbations in the nonlinear simulations are shown in Figure (6), which clearly illustrates how the two-armed spiral structure evolves out of the initial random density perturbation.

5.2 Collisionless models

Although the hydrodynamical approximation reproduces qualitatively the morphology of NGC 5247, the lifetime of the spiral pattern is short. After approximately 0.3 Gyrs the spiral pattern is destroyed in these hydrodynamical models and they no longer resemble the observed spiral structure. A mechanism that destroys the spiral structure is not completely understood. Using hydrodynamical model, Laughlin et al. (1997) showed that a nonlinear spiral mode causes a hollowing out of the surface density profile in a vicinity of a corotation resonance. This stops the spiral

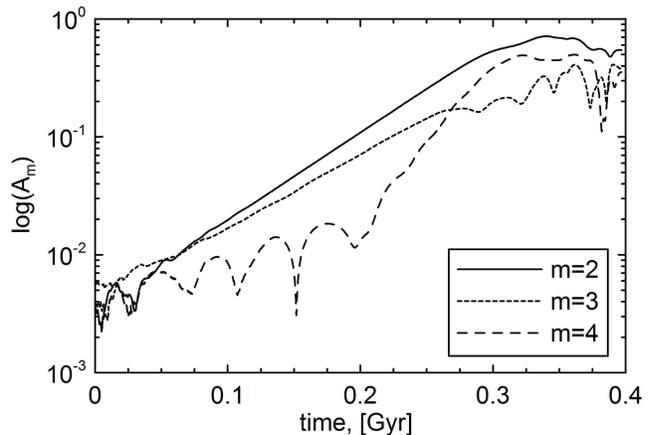


Figure 5. Time evolution of the $\log_{10}(A_m)$ for $m = 2 - 4$ global Fourier amplitudes. The most unstable mode is the $m = 2$ spiral. The instability saturates at level of $\log_{10}(A_m) = 0.5$.

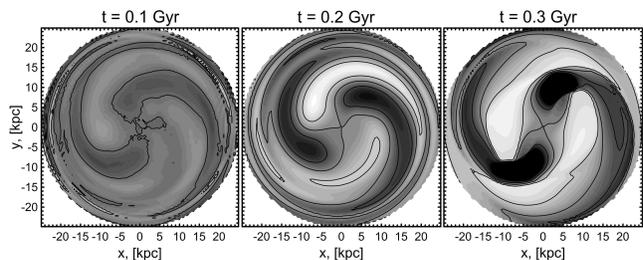


Figure 6. Time evolution of density perturbations in galactic disk in model C1. The spiral is in a counterclockwise rotation

growth and eventually destroys the spiral itself. For the collisionless disks, the mechanism remains unclear. We explore therefore the collisionless models to study to what extent the collisionless nature of the galactic disk increases the lifetime of the spirals.

Using distributions shown in Figure 7 we build a set of models for a stellar disk that have stability Q -parameter larger than unity:

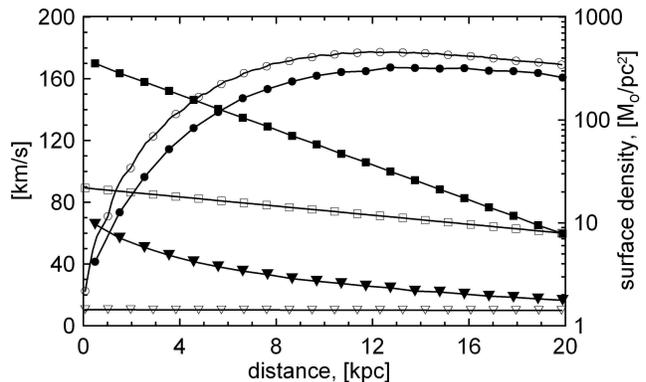


Figure 7. Initial distributions of the stellar-gaseous disk parameters in model E2: velocity of stars (open circles), velocity of gas (fill circles), radial velocity dispersion of stellar disk (fill triangles), speed of sound in gaseous component (open triangles), stellar surface density (fill squares) and gaseous surface density (open squares)

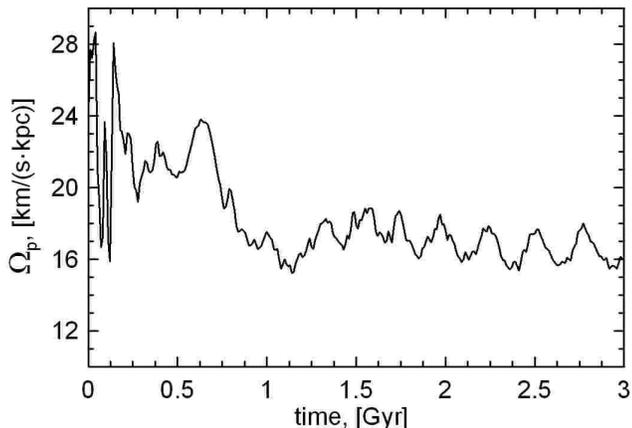


Figure 9. Time dependence of angular velocity of two-armed pattern in model C3.

$$Q_{Ts} = \frac{\kappa C_r}{3.36G\Sigma} \geq 1. \quad (13)$$

If condition (13) does not hold for the whole disk, then the perturbations grow significantly during a short evolution time, and the parameters of the disk change within 1–2 disk rotations. We exclude such cases from our consideration.

The rotation curve significantly influences the dynamics of a collisionless disk. Figure 8 shows evolution of the Fourier harmonics A_m in three models with different rotation curves. In the fast rotating model A3, the disk is stable due to the presence of a massive halo. The model with the fastest disk rotation therefore can not explain the observed spiral pattern in the galaxy NGC 5247. In model B3 (middle frame), the perturbations slowly grow with the most unstable mode two-armed spiral. During approximately three Gyr from the beginning of simulations, the wave amplitude reaches about 2–5% of disk unperturbed values which is significantly lower than the amplitude of the observed spiral pattern. Apparently, the models A and B can not explain the observed spiral structure of the galaxy NGC 5247.

Let us examine model C, which has a more massive stellar disk compared to models A and B. The minimum value of the Toomre Q -parameter indicates that this model is gravitationally unstable. Similar to model B, there is a well defined two-arm global spiral structure that extends to about four scalelengths in the disk. The amplitude of the perturbations is much higher compared to the other cases. During the initial stages ($t < 0.5 \times 10^9$ years) one can see a three-arm spiral, and the spiral pattern is a superposition of a two- and three-armed modes. However, in the nonlinear stage a two-armed pattern dominates. Figure 9 shows a typical dependence of an angular velocity of a two-armed spiral pattern generated in model C3. Between approximately 0.2 – 0.7 Gyr when an exponential growth of a spiral perturbation is observed, a spiral perturbation has an angular velocity equal approximately to $22 \text{ km s}^{-1} \text{ kpc}^{-1}$. After 0.8 Gyr, a nonlinear saturation starts, the angular velocity decreases to $18 \text{ km s}^{-1} \text{ kpc}^{-1}$ and remains approximately constant during the rest of simulations.

Despite significant difference in the values of radial velocity dispersion used in our numerical simulations, the spiral patterns are quite similar as can be seen by comparison models C1, C2, and C3 in Figure 11. On a qualitative

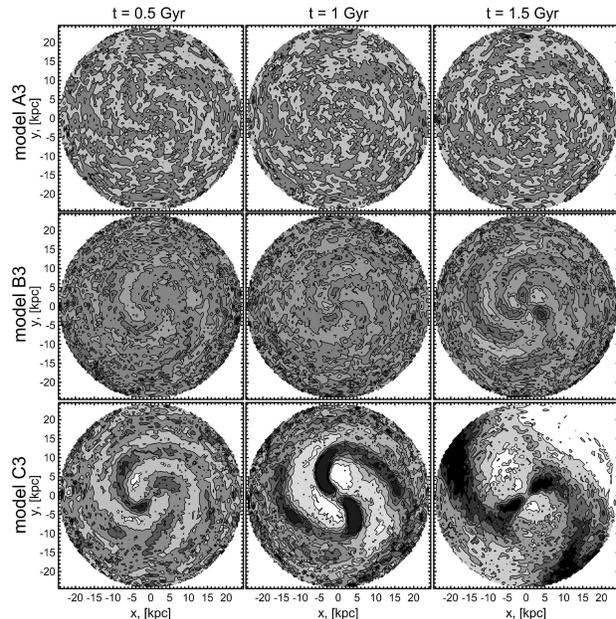


Figure 10. Evolution of the surface density in the numerical simulations of the collisionless disks with different rotation curves

level one can conclude that morphological properties of spiral structure are independent on variation of the radial velocity dispersion within observational errors. The growth rates however are different ranging from 0.7 Gyr in the coldest disk to 1.5 Gyr for model with the largest velocity dispersion (Figure 12).

The value of the disk vertical scale used in our simulations is close to the value estimated by Zhao et al. (2004) 1.1–2.5 kpc, implying a large range of values to be explored. Figure 13 shows that the spiral patterns in collisionless cases D1–D3 are similar, and independent of the disk thickness.

Taking into account the third dimension, i.e. the disk thickness, is important in disk dynamics to simulate correctly the density growth in spiral arms. The vertical motions lead to a decrease of the growth rate of an unstable spiral wave. Under similar conditions, the amplitude of the spiral wave grows faster in a thinner disk (Fig. 13). In the model with a relatively large scale length of $z_0 = 2.1 \text{ kpc}$, the structure of the spiral arms and their lifetimes are qualitatively similar to the behavior of model C3. However, the disk with a small thickness is significantly more unstable, resulting in a rapid growth of multi-armed perturbations and formation of a flocculent spiral pattern.

In general, the lifetime of the global two-armed spiral pattern in our collisionless models is about 1.5 Gyr. As was mentioned, a gaseous component in the disk increases the

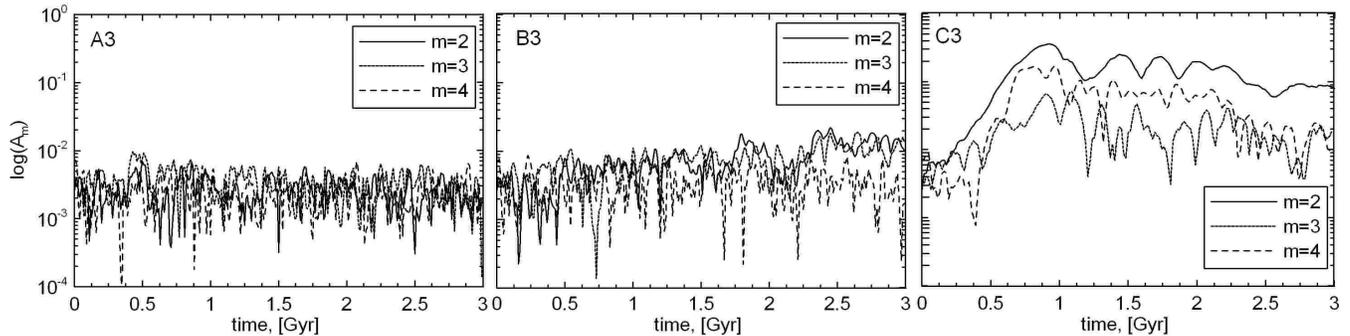


Figure 8. The amplitudes of the Fourier harmonic for models with different rotation curves. Left frame — Model A3, central frame — Model B3 and right frame — Model C3. Parameters of the models are given in Table 1.

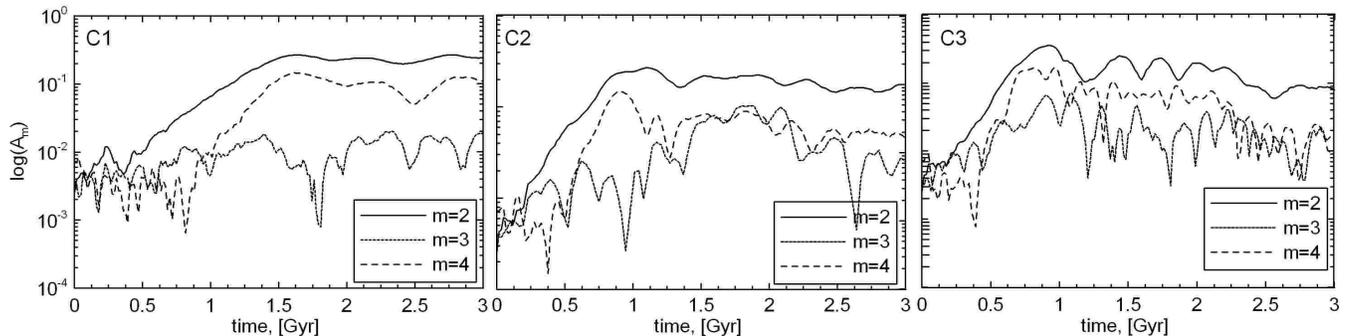


Figure 12. Fourier harmonics in models with different radial velocity dispersions: left frame $c_z/c_r = 0.8$, central frame $c_z/c_r = 0.6$, right frame $c_z/c_r = 0.43$.

lifetime of the spiral structure. In the following section we will consider this effect in detail.

6 TWO-COMPONENT MODELS

In our two-component models, we take into account the gravitational interaction between the gaseous and the stellar components of the disk. Effects of star-formation or exchange of matter between the stellar and gaseous subsystems are neglected. It is known that gas has a strong destabilizing effect on a gravitating disk even if its surface density is much smaller than the surface density of the stellar disk. We build our stellar-gaseous models based on the one-component model C3, and by varying the total gas mass within the radius of the stellar disk. Namely, we analyze the models with the relative mass of a gaseous component equal to:

$$M_g/M_s = \{0.01; 0.05; 0.1; 0.2\} .$$

For a two-component gravitating disk, each subsystem has its own spatial density distribution, rotation curve and velocity dispersion profile. Figure 7 shows initial equilibrium distributions of basic quantities for a stellar-gaseous disk. A difference between the rotation curves of stellar and gaseous components is caused by a difference in their radial velocity dispersions, and influence of the velocity dispersions on disk equilibrium. The stellar disk has an exponential density distribution with a radial scale length of $r_d = 4.8$ kpc. The velocity dispersion of the stellar disk in the direction

perpendicular to the disk decreases from 70 km s^{-1} in its central regions to about 20 km s^{-1} at disk periphery. The gaseous disk is cold compared to the stellar one. Its velocity dispersion is close to 10 km s^{-1} in the disk's central regions and changes slowly within the stellar disk.

For a two component gravitating disk, the stability criterion needs to be modified. A few such modifications of the stability parameter have been suggested in the literature. A simple stability criterion has been proposed by Wang and Silk (1994):

$$\frac{1}{Q_{WS}} = \frac{1}{Q_s} + \frac{1}{Q_g} . \quad (14)$$

Here Q_s and Q_g are the values of the Toomre Q -parameter for the stellar and the gaseous components respectively. Romeo and Wiegert (2011) demonstrated that such an approach is not suitable for three-dimensional systems. Romeo and Wiegert (2011) suggested an expression for the effective stability criterion that takes into account the finite thicknesses of a stellar and a gaseous disk:

$$\frac{1}{Q_{RW}} = \begin{cases} \frac{W}{T_s Q_s} + \frac{1}{T_g Q_g}, & T_s Q_s \geq T_g Q_g; \\ \frac{1}{T_s Q_s} + \frac{W}{T_g Q_g}, & T_g Q_g \geq T_s Q_s. \end{cases} \quad (15)$$

Here $W = 2c_r c_s / (c_s^2 + c_r^2)$, $T_s = 0.7 + 0.8(c_z/c_r)_s$, $T_g = 0.7 + (c_z/c_r)_g$. The radial dependence of the stability parameters Q_s , Q_g and Q_{RW} are shown in Figure 14.

The evolution of the surface density perturbations in a stellar disk in models with different admixtures of gas is shown in Fig. 15. During $t < 1$ Gyr, a spiral pattern

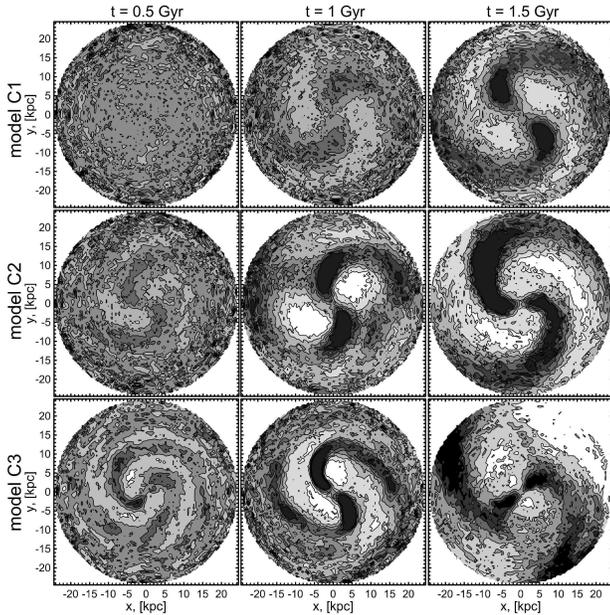


Figure 11. Evolution of the perturbed surface density of the stellar disk in simulations with different radial velocity dispersion profiles.

is formed in all models. Later on ($t > 1.5$ Gyr), the spiral wave dissipates in the purely collisionless model, and becomes indistinguishable from a background of low-scale density perturbations. A small gas admixture with a mass of a few percent of the total mass of the disk significantly increases the life time of the spiral structure, and spiral pattern exists up to 3 Gyr. If mass of the gas is increased to one-tenth of the total mass of the disk, then a strong gravitational instability is created, leading to the formation of a complex, highly transient multi-armed spiral structure. The disk changes significantly from its initial state during about 0.5 Gyr. In such a case, star-formation should be taken into account which is beyond the scope of our paper.

The self-consistent stellar-gaseous models allow reproducing a long-living two-armed spiral pattern. We find however, similar to Elmegreen and Thomasson (1993) and Thomasson et al. (1990), that the morphology of the spiral pattern evolves with time, with overall lifetime of the spirals being about ten disk rotations. In comparison, lifetime of spirals in the one-component models do not exceed 1.5 Gyr.

Figure 16 shows the azimuthal density distribution at $r = 4.9$ kpc in the gaseous, and in the stellar components. The figure clearly demonstrates formation of shock fronts in the gaseous component located at the inner edge of the stellar arms.

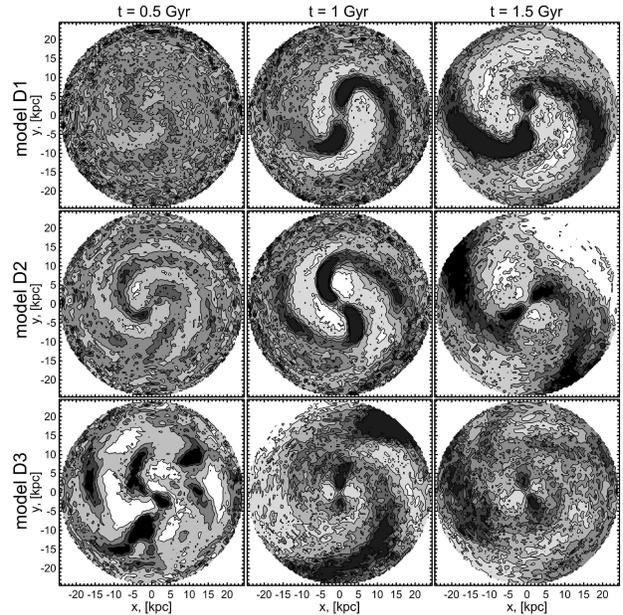


Figure 13. Evolution of the surface density perturbations in stellar disk in numerical simulations with different thickness of the stellar disk: D3 – $z_0 = 0.9$ kpc, D2 – $z_0 = 1.5$ kpc, D1 – $z_0 = 2.2$ kpc.

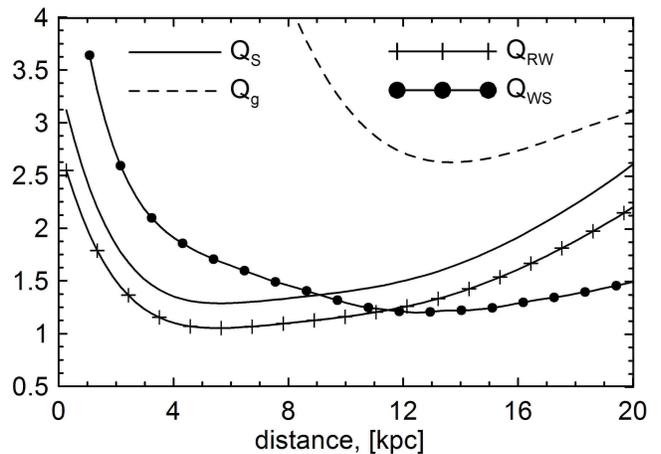


Figure 14. Radial distribution of Toomre parameter: gaseous, stellar and both stellar-gaseous disk for model E2

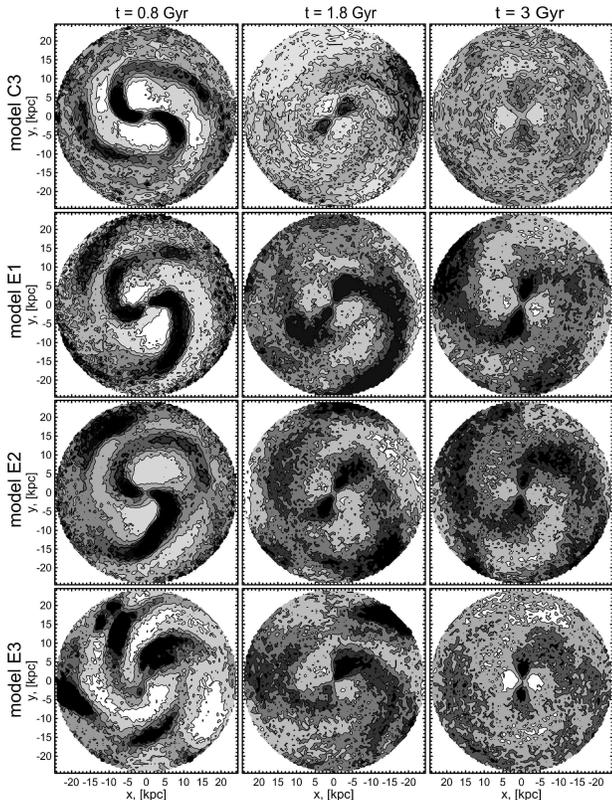


Figure 15. Comparison of the evolution of the surface density perturbations of a stellar disk in numerical simulations with different amount of a gas-component

The shock front is formed when the supersonic flow of interstellar gas passes through the density wave of the spiral arm (Roberts 1969). Distribution of gas along the azimuth indicates the position of the shock wave on the inner edge of the stellar density wave in our simulations. In the presence of a strong shear flow the system of shock fronts is unstable to hydrodynamical instabilities (Wada 2004; Khoperskov et al. 2011). We can not reveal such an instability due to the low resolution of our simulations.

Figure 17 shows azimuthal dependence of the stellar surface density at different radii in the disk. As one can judge from the figure, the amplitude of the spiral perturbation decreases with radius in a stellar component. The shift in phase of the density maxima with radius reflects the spiral nature of the perturbations.

7 DISCUSSION

7.1 Toomre’s parameter

Sellwood (2011) reviewed observational as well as theoretical arguments and came to the conclusion that spiral patterns are short-lived. A qualitative counterargument against this picture is that if spirals recur often enough a large fraction of galaxies should have a low-amplitude spirals. This is not the case in the most of observed cases. Below we discuss

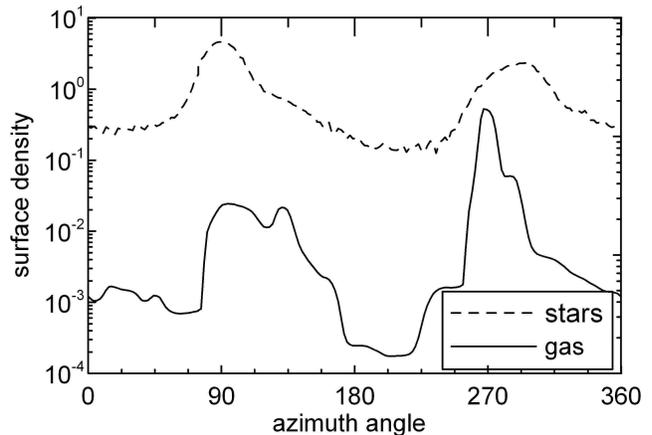


Figure 16. Azimuthal layer of the gaseous and stellar surface density at $t = 1.5$ Gyr and $r = 4.9$ kpc for model E2

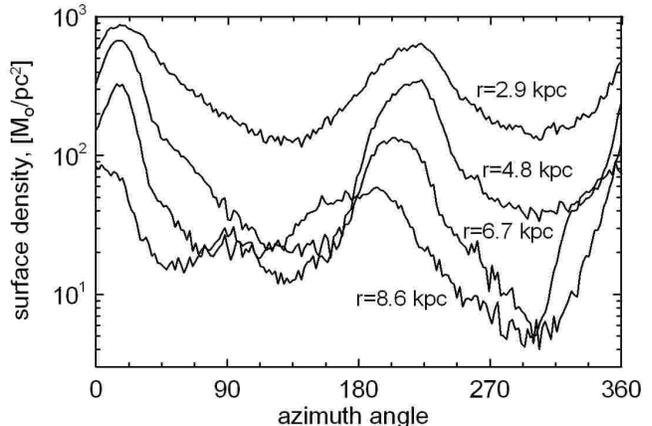


Figure 17. Azimuthal layers of a stellar-component surface density for various values of radius — from top to bottom: $r = \{2.88; 4.8; 6.72; 8.64\}$ kpc for model E2.

in detail two factors, considered by Sellwood as arguments against long-lived spiral structure.

One of his arguments is that the theory of spiral modes requires galactic disks to be dynamically cool. Namely, Toomre’s axisymmetric stability parameter should range within $1 \leq Q \leq 1.2$. As a test of applicability of a modal approach in such systems, Sellwood simulated the dynamics of a disk that has Q -parameter equal to unity everywhere except the disk’s central regions where the Q -parameter rises steeply. Via this experiment Sellwood demonstrated that such a low value of Q -parameter supports vigorous collective responses that change the disk properties during a short dynamical time.

We repeat the experiment of Sellwood in 3D simulations assuming that the disk of the galaxy NGC 5247 has $Q = 1$ everywhere except its central regions. We find a qualitative agreement of our simulations with the results of Sellwood (2011). During approximately one disk rotation a complex multi-armed transient spiral structure is formed that causes disk heating and a quick dissipation of the spiral waves. Figure 18 shows the radial profile of disk radial velocity dispersion at different moments of time. After a violent disk heating, it comes to a stationary stage.

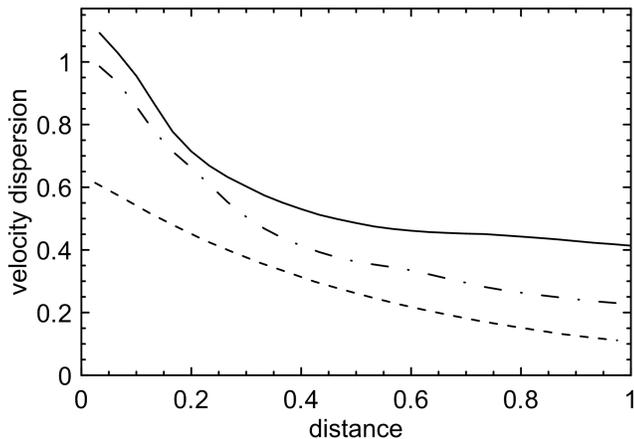


Figure 18. Radial distribution of the radial velocity dispersion at different times: dotted line is initial statement ($t = 0$), dash-dot line is distribution after one rotation period ($t = T$), full line is stationary distribution ($t/T = 3 \div 10$).

The assumption about a radial profile of Toomre’s Q -parameter invoked by Sellwood is not related to the spiral galaxies. It is known from the direct measurements that velocity dispersion in the galactic disks decreases exponentially with radius and has a larger scale length compared to the scale length of the surface brightness (or density). In combination with the fact that the disks are nearly flat and self-gravitating in the vertical direction, this leads to a bell-like shape of Toomre’s Q -parameter rising towards the center of a disk and on its periphery. With such a Q -profile, the disks are globally unstable and support a spiral structure during tens of galactic rotations.

We note also that if real galaxies were to have a Q -parameter profile close to that assumed by Sellwood, they would be in a phase of violent evolution and have a very short dynamical time. This would be difficult to reconcile with the number of observed spiral galaxies and their lifetimes. The density wave theory (the disk’s instability towards the global spiral modes) does not require the Q -parameter to be in a narrow range $1 \leq Q \leq 1.2$ as it was demonstrated by a number of examples in hydrodynamical simulations by Korchagin et al. (2000, 2005) and in collisionless models by Khoperskov et al. (2007).

7.2 Resonances

After the work of Toomre (1981), the swing amplification of perturbations in a differentially rotating gravitating disk is regarded as one of the key mechanisms that amplifies the spirals. The swing amplification works in the presence of a shearing disk. The orbital clock is faster at the interiors of the galactic disks, and the mechanism runs more rapidly at smaller radii. The important part of the swing amplification mechanism is a propagation of the waves in a radial direction with a group velocity. A propagating wave reflects from the center and/or from a corotation region, changing from trailing to leading, and simultaneously changing a sign of the group velocity and serves, according to Toomre, as “fresh grist to a swing amplified mill” to operate continuously in a disk.

In this mechanism, the inner Lindblad resonance is con-

sidered as the most important in generation of the spiral density waves. This resonance must be shielded to prevent a fierce damping of the waves. To check the importance of the inner Lindblad resonance in generation of spirals, we performed an artificial experiment with our hydrodynamical model imposing an absorption region in the inner regions of the disk where all perturbations are zeroed out. This cuts the feedback loop and destroys amplification of spiral perturbations. We performed a series of 2D simulations of the unstable 2-D gaseous disk with such an artificially imposed “absorption ring” where all perturbations are forced to be zero and macroscopic characteristics of the disk are set to be unperturbed in a smooth way. Fig. 19 shows angular velocity, epicyclic frequency and positions of resonances for such a disk. As one can see, the model does not harbor the inner Lindblad resonance, so an absorption ring was imposed artificially to mimic its influence.

Fig. 20 shows a result of such simulations. On the right panel of Fig. 20 is shown a two-armed spiral pattern developing in an unstable ‘template’ gravitating disk. The left panel shows the results of simulations when an absorption ring has been imposed close to the disk center. The disk remains unstable and a two-armed spiral is developing out of noise perturbations. We find that the spiral perturbations develop in the disk independently of the position of the absorption ring, be it inside, or outside the corotation resonance.

An instructive experiment is to impose the absorption ring at corotation. The behavior of perturbations changes dramatically in this case (Fig. 21). The growth of a two-armed spiral is totally suppressed, and a multi-armed spiral starts to grow with a four-armed spiral prevailing. These experiments illustrate that the qualitative picture of spiral growth by swing amplification is not necessarily as relevant as once thought. Instead, the corotation resonance may be more important in spiral generation.

The issue of transient spirals is currently a topic of heated debate. Zhang (1996, 1998, 1999) finds that galaxies undergo a secular evolution that leads to a redistribution of the disk matter and heats the disk stars so they gradually rise above the galactic plane in the disk central regions. Both effects are the natural ingredients of a presence of the spiral density wave. Stars migrate inside and outside the corotation region, and a more and more centrally concentrated density distribution is achieved with time together with the buildup of an extended outer envelope. Similar effect was found in hydrodynamical simulations by Laughlin et al. (1997).

8 CONCLUSION

We have built one-component collisionless and hydrodynamical models as well as multi-component stellar-gaseous models of the disk galaxy NGC 5247. The models are unstable to $m=2$ global modes that form a two-armed spiral pattern with amplitudes of about 10–20%, qualitatively similar to the observations.

Our simulations show that in purely collisionless models the lifetime of the spiral structure is about a few galactic rotations, and does not last longer than one Gyr. An admixture of a gaseous component with mass of a few percent of the mass of the stellar component significantly increases the

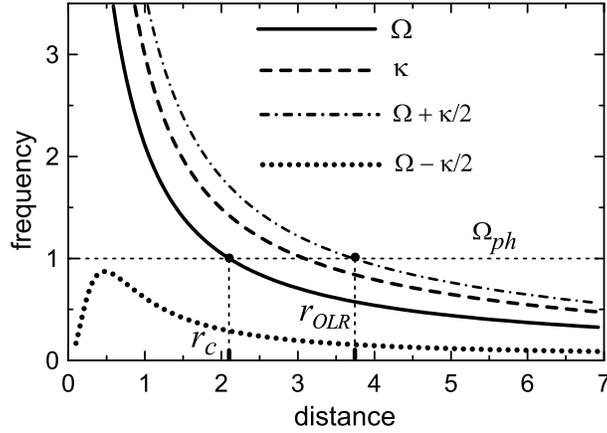


Figure 19. Angular velocity, epicyclic frequency, and the positions of principal resonances for a gaseous disk (r_c – corotation radius, r_{olr} is the outer Lindblad resonance). The inner Lindblad resonance is not achieved in this model. The units of length and frequency are 2 kpc and $72 \text{ km s}^{-1} \text{ kpc}^{-1}$ correspondingly.

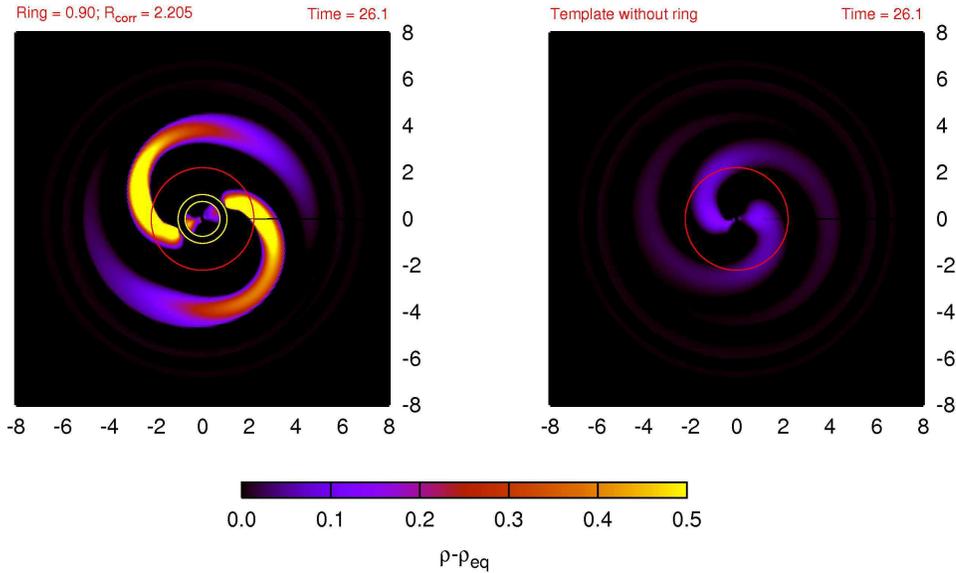


Figure 20. The right panel shows a two-armed spiral pattern developing in an unstable ”template” gravitating disk (see section 7.1 for details). The location of the corotation radius is shown by red circle in both the right and the left panels. The left panel shows the results of a simulation when an absorption ring (whose inner and outer extent are shown by yellow circles) has been imposed close to the disk center. Note that the development of the 2-armed spiral pattern is not inhibited by the presence of the absorption ring, in contradiction to the expectations from standard swing amplification mechanism.

lifetime of the spiral structure. In the simulated model of galaxy NGC 5247, the spiral lifetime increases up to 3 Gyr, and comparable with the lifetime of galaxies.

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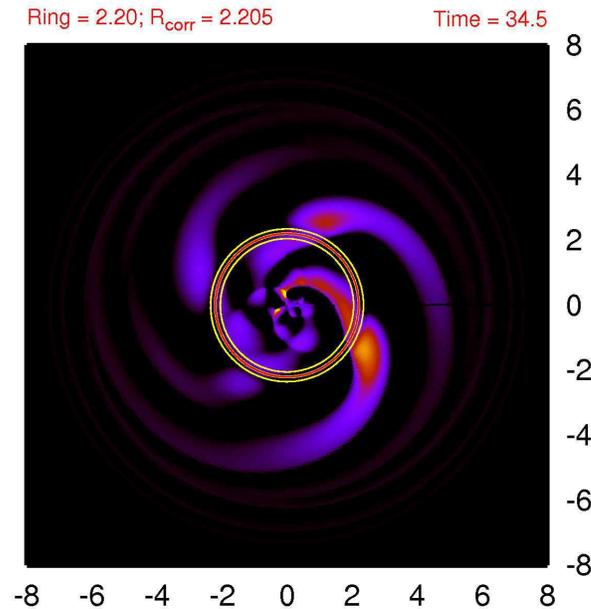


Figure 21. The figure shows the results of a simulation when an absorption ring (whose inner and outer extent are shown by yellow circles) has been imposed at the corotation radius. Note that unlike Fig. 20, growth of a two-armed spiral is completely suppressed due to the presence of the absorption ring, and a multi-armed spiral starts to form.

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REFERENCES

- Barnes J., Hut P.A., 1986, *Nature*, 324, 446
 Bertin, G., Lin, C. C., 1996, MA MIT Press, p. 271
 Bertin G., Lin C.C., Lowe S.A., Thurstans R.P., 1989, *ApJ*, 338, 78
 Bertin G., Lin C.C., Lowe S.A., Thurstans R.P., 1989, *ApJ*, 338, 104
 Bottema R., 1993, *A&A*, 275, 16
 Bournaud F., Combes F., Jog C.J., Puerari I., 2005, *A&A*, 438, 507
 Buta R.J., Knapen J.H., Elmegreen B.G., Salo H., Laurikainen E., Elmegreen D.M., Puerari I., Block D.L., 2009, *AJ*, 137, 4487
 Gerola H., Seiden P.E., 1978, *ApJ*, 223, 129
 Contopoulos G., Grosbol P., 1986, *A&A*, 155, 11
 Considere S., Athanassoula E., 1988, *AASS*, 76, 365
 Elmegreen B.G., Thomasson M., 1993, *A&A*, 272, 37
 Elmegreen D.M., Elmegreen B.G., Yau A., et al, 2011, *ApJ*, 737, 32
 Eskride P., 2002, *ApJ Sup*, 143, 73-111
 Fux R., 1999, *A&A*, 345, 787
 Hunter, C., 1979, *ApJ*, 227, 73
 LEDA: <http://leda.univ-lyon1.fr/>
 Kaufmann D.E., Contopoulos G., 1996, *A&A*, 309, 381
 Kendall S., Kennicutt R.C., Clarke C., 2011, *MNRAS*, 414, 538
 Khoperskov A.V., Just A., Korchagin V.I., Jalali M.A., 2007, *A&A*, 473, 31
 Khoperskov A., Bizyaev D., Tiurina N., Butenko M., 2010, *AN*, 331, 731
 Khoperskov S.A., Khoperskov A.V., Eremin M.A., Butenko M.A., 2011, *Astr. Letters*, 37, 563
 Kikuchi N., Korchagin V., Miyama S.M., 1997, *ApJ*, 478, 446
 Korchagin V., Kikuchi N., Miyama S.M., Orlova N., Peterson B.A., 2000, *ApJ*, 541, 565
 Korchagin V., Orlova N., Kikuchi N., Miyama S.M., Moiseev A.V., 2005, eprint arXiv:astro-ph/0509708
 Korchagin V.I., Shevelev Yu.G., 1981, *Astrophysics*, 17, 254
 Laughlin G., Korchagin V., Adams F.C., 1997, *ApJ*, 477, 410
 Marochnik L.S., 1966, *Astronomicheskii Zhurnal*, 43, 919
 Marochnik L.S., Mishurov Yu.N., Suchkov A.A., 1972, *ApSSL*, 19, 285
 Patsis P.A., Grosbol P., Hiotelis N., 1997, *A&A*, 323, 762
 Romeo A.B., Wiegert J., 2011, *MNRAS*, 416, 1191
 Roberts W.W., 1969, *ApJ*, 158, 123
 Sellwood J. A., 2011, *MNRAS*, 410, 1637
 Semelin B., Combes F., 2002, *A&A*, 388, 826
 Sygnet J.F., Pellat R., Tagger M., 1987, *Physics of Fluids*, 30, 1052
 Thomasson M., Elmegreen B.G., Donner K.J., Sundelius B., 1990, *ApJ*, 356, 9
 Toomre A., 1981, *Proceedings of the Advanced Study Institute, Cambridge and New York, Cambridge University Press*, p. 111
 van der Kruit P.C., Freeman K.C., 1986, *ApJ*, 303, 556
 van Leer B., 1979, *Journal of Computational Physics*, 32, 101
 Vauterin P., Dejonghe H., 1996, *A&A*, 313, 465
 Wada, K., Koda, J., 2004, *MNRAS*, 349, 270

- Wang B., Silk J., 1994, ApJ, 427, 759
Zhang H., 1996, ApJ, 457, 125
Zhang H., 1998, ApJ, 499, 93
Zhang H., 1999, ApJ, 518, 613
Zhao Y., Peng Q., Wang L., 2004, Chinese J. of Astr. &
Astroph., 4, 51
Zhao Y., Peng Q., Hu T., 2006, A&A, 452, 451

Table 1. The parameters of one-component (N-body) and two-component models. c_{r0} is the radial velocity dispersion in center of the disk, V_{max} — the maximum value of the rotation velocity, percentage of gas - M_g/M_s , one-component model if equal zero.

Model name	c_z/c_r	c_{r0} (km/s)	z_0 (kpc)	V_{max} (km/s)	M_g/M_s
A1	0.43	120	1.5	245	0
A2	0.6	92	1.5	245	0
A3	0.8	70	1.5	245	0
B1	0.43	120	1.5	200	0
B2	0.6	92	1.5	200	0
B3	0.8	70	1.5	200	0
C1	0.43	120	1.5	153	0
C2	0.6	92	1.5	153	0
C3	0.8	70	1.5	153	0
D1	0.8	70	2.2	153	0
D2	0.8	70	1.5	153	0
D3	0.8	70	0.9	153	0
E1	0.8	70	1.5	153	0.01
E2	0.8	70	1.5	153	0.05
E3	0.8	70	1.5	153	0.1
E4	0.8	70	1.5	153	0.2