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Modelling of large-scale structures in the gaseous galaxies disks

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The results of numerical simulations aimed at studying large-scale morphological features in the structure of gaseous galaxies disks are presented. The behaviour of a gaseous disk in an external gravitational potential that does not contain spiral modes is analyzed. The formation characteristics of spiral substructures induced by tidal disturbances, which are produced in the interactions with companion galaxies is revealed. Slowly rotating two-armed spiral waves are generated. The question of the duration of arising spirals is discussed. The appearance of a global polygonal pattern in a differentially rotating gaseous disk is demonstrated. All the main geometrical properties of observed rows in spiral galaxies are satisfactorily reproduced.

Keywords: Spiral structure, galaxies, evolution of galaxies, numerical gas dynamics, shock waves, polygonal pattern

1 Introduction

Large-scale spiral structures in the galaxies disks can be excited by the central stellar bars (Sellwood and Sparke 1988; Binney and Tremaine 2008), they can also be self-excited and maintained without the gravitational perturbations in globally stable disks as proposed by Lin and Shu (1964). They are interpreted as stationary density waves propagating in a stellar disk (see also Bertin and Lin 1996).

The approach described below does not assume fixed forms for the wave patterns or propagating wave packets as in the classical theory. It also does not assume ongoing driving by bars or external forces beyond the initial impulsive disturbance. Rather it is based on the propagation characteristics of nonlinear gas shocks induced by the tidal disturbance.

The most obvious means of inducing two-armed grand design spirals is via tidal interactions with companion galaxies (e.g. Toomre and Toomre (1972) were the first to suggest that interactions "tend to bring deep into a galaxy a fairly sudden supply of fresh fuel in the form of interstellar material..."; Toomre 1981; Oh et al. 2008; Dobbs et al. 2010; Struck et al. 2011).

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Previous studies have shown that prominent spiral structure is more commonly observed in galaxies located within groups or with companions (Kormendy and Norman 1979; Elmegreen and Elmegreen 1982, 1983). These observations highlighted the importance of tidal interactions on the structure of galactic disks. It is now widely accepted that the gravitational pull exerted by a merging satellite galaxy can generate structure in the stellar disk of its more-massive host. Many galaxies are have recently been involved in an interaction with one or more companions, which explains their current spiral structure. A striking example of the outcome of these kinds of interactions is the system composed of M 51 and its companion galaxy NGC 5195. The pronounced spiral structure of the galaxy M 51 was formed under the influence of the gravitational interaction of the smaller galaxy NGC 5195. Moreover, such gravitational interaction seems to be the dominant mechanism determining the evolution of the galaxy on long time scales (see, e.g., Toomre 1978; Salo and Laurikainen 2000a,b; Wahde and Donner 2001; Laurikainen and Salo 2001, where models have been proposed involving either single or multiple close passages of the companion).

Although grand design spirals, such as the ones observed in M 51, are related to massive companions, recent theoretical studies lead to the conclusion that much less massive satellites can also create phase-space structure in galactic disks (Quinn et al. 1993; Tutukov and Fedorova 2006; Kazantzidis et al. 2008; Villalobos and Helmi 2008; Younger et al. 2008; Quillen et al. 2009; Minchev et al. 2009; Bird et al. 2012; Gómez et al. 2012). However, how long spiral structure persists after an interaction, and how far a perturbing galaxy have travelled is unclear so far.

Time-dependent, multi-dimensional simulations have shown that spiral shocks in spiral potentials can be hydrodynamically unstable (see Lugovskii and Filistov 2014, and references therein), and that spiral structures in stellar-gaseous galaxies disks are not stationary (Sellwood and Carlberg 1984; Sellwood 2000, 2011; Sellwood and Binney 2002; Fuchs et al. 2005; Fujii et al. 2011). These studies suggested that the constructed patterns have a transient character. Amplitudes of spiral arms change on a time scale of galactic rotation, or even shorter. The arms become faint or denser within one rotational period. There are no steady grand-design spiral arms. Any arms are stretched by the galactic shear and attenuated.

In many cases the arms of spiral galaxies have indications of the presence of almost straight segments forming the spiral patterns (Waller et al. 1997; Pohlen and Trujillo 2006). An example is the same grand design spiral galaxy M 51. The spiral M 51 (and also M 101) seen almost face-on reveal a polygonal two-arm pattern. According to Chernin (1999), "The two-arm polygonal pattern ... is well confirmed by the interstellar tracers...." Straight segments in spiral structure appeared quite frequently in numerical models of gaseous galactic disks (e.g., Combes 1994; Khoperskov et al. 2011; Filistov 2012, 2015). However, fully non-linear evolution of the realistic quasistationary configurations that develop in a substantially transient regime in a stellar-gas disk has not yet been investigated.

In this study, numerical simulations are used to demonstrate the appearance of a spiral pattern in a differentially rotating gaseous disk in an external gravitational potential field that does not contain spiral modes. Such a potential filed arises, for instance, as a result of a tidal perturbation from the satellite galaxies on the gaseous galactic disk. The relatively simple numerical simulations of interactions are performed. The rigid halo potential and a local selfgravity within the galaxy discs are

used. This facilitates study of the long-term evolution of waves in the disks. The question of the duration of induced spirals is discussed.

The formation of polygonal structures of spiral galaxies are demonstrated. It is argued that these non-linear quasistationary formations develop in a substantially transient regime. All the main geometrical properties characteristic of observed rows in spiral galaxies are satisfactorily reproduced, as well as the dynamical properties of the polygonal structure manifest during the evolution of a stellar-gas galactic disk.

The paper's outline is as follows. In Section 2 the model and the numerical method are described. The results of the numerical simulations are considered in Section 3, and the main conclusions are provided in Section 4.

2 The gas-dynamic model and numerical method

A gaseous galactic disk evolves under the influence of a gravitational potential formed mainly by the distribution of the old population of red stars. The external potential of the disk is determined by the gravitation of the spherical component (halo), the axially symmetrical distribution of matter in the stellar disk, and by the presence of additional gravitational potentials. At large distances from the disk center, the potential of the halo leads a rotation curve onto a plateau. The relative mass of the dark halo within the optical radius is a factor of 3.5 larger than the mass of the disk subsystem (stars + gas) (Zasov et al. 2004; Khoperskov et al. 2010). The additional potentials arise as a result of a tidal perturbation from the satellite galaxies on the plane of the gaseous galactic disk. The satellites are modelled as a point mass. In these calculations the ratio of the companion's mass to that of the main galaxy is $5 \cdot 10^{-4}$. The companion's initial velocity is 130 km/s (on length scale of 15 kpc). The satellites of the primary galaxy are in a nonstationary circular motion round the center of a disk.

In studies of the internal motions of gaseous galactic disks, light pressure is neglected compared to the gas pressure. In this case, the Clapeyron equation has the form of an isothermal equation of state for an ideal gas with temperature $10^4 K$, corresponding to a local isothermal sound speed of 13 km/s. It is assumed that the gas is ideal and polytropic with an adiabatic index $\gamma = 5/3$. The gas effects of self-gravitation is neglected.

The calculations also neglected the effects of viscosity, the diffusive transport of matter, radiation, and the evolution of the electromagnetic field. The gaseous component of the gaseous-stellar disk is fully immersed in the stellar component, whose selfgravitation is included in the gas-dynamical equations as a macroscopic external force. The gaseous disk was modeled in an inertial coordinate system. The effective center of the gravitational forces coincides with the center of the system.

Thus, the following factors act on the gaseous medium: pressure and the centrifugal force, which give rise to gas motions toward the periphery, and the gravitation of the stellar disk (as well as the halo, with a standard model potential), which counteracts this motion.

The flow of gas in the external gravitational potential of the stellar disk and halo is described by the Euler equations of classical gas dynamics (see, for example, Landau and Lifshitz 1979). The monotonic, first-order, TVD scheme of Roe (1986) was used

to solve the gasdynamical equations. To enhance the stability of the system, the initial scheme was modified using the method of Einfeldt (1988). We used the equations in flux form to ensure that the computations were conservative. The computations were carried out using the numerical algorithm described in Filistov (2013, 2014), which develops an economical method for computing complex, non-stationary, supersonic gas flows using a fully conservative difference scheme with appreciably divergent gasdynamical equations in the Euler variables in an axially symmetrical approximation.

Free boundary conditions were specified at the boundaries of the region. To exclude the influence of the boundary conditions on the behavior of inner regions of the disk, the radial size of the computational domain was chosen to appreciably exceed the characteristic size of the disk. Without introducing any perturbations, the gaseous disk maintains its equilibrium state over a fairly prolonged time. The outer layers of the disk evolved during the computations, but the bulk of the disk remained stable, with its density varying and the radial velocities changing only slightly.

3 Results of the numerical computations

The overall structure of the solutions obtained for an ideal gaseous flow in the equatorial plane is shown in Figs 1, 2, which depict the distribution of the surface density in a rectangular region in Cartesian coordinates. These diagrams illustrate the gas-flow pattern in the specified gravitational field, taking into account the external additional gravitational potentials without spiral modes. These additional potentials are created by the satellite galaxies which are in a nonstationary circular motion round the centre of a gaseous galactic disk. The solutions for twenty four times are shown, beginning with a time close to $t = 0$ (the first diagram in the upper row in Fig. 1; one time unit in our simulations corresponds to a physical time of ~ 200 million years). These times are different moments (with equal intervals) measured in time code units. The solutions represent a sequence of stages in the formation of the spiral pattern, and can be used to identify the main features of the flow, and also to draw certain conclusions about the development of perturbations that destruct the laminar flow. The shocks that form in the disk are visible as densifications of the density contours.

In the preliminary stage of the computations, the laminar flow structure in the initial rotating gas configuration (Fig. 1, $t = 0$) remains essentially unchanged over a fairly long period, confirming that this is an equilibrium configuration. This time was taken as the initial time for the subsequent evolutionary stages of the gaseous disk.

By time $t \simeq 0.5$, structures similar to a ring with weak nonhomogeneity, arise in the middle part of the disk. These changes in the behavior of the flow are determined by the gradient of the additional gravitational potentials.

The gas acquires a positive radial velocity component, and the distributions of the pressure and density become inhomogeneous along an azimuthal angle. The gas outflow and shifts of the pressure and density maxima increase toward the outer boundary due to gravitational influences of the companion galaxies. Since time $t \simeq 1.0$, a two-armed spiral gas-dynamical pattern starts to be formed. As can be seen at stage $t \simeq 1.5$, the shock fronts outline the global spiral pattern and move toward the periphery of the disk. They are almost circular by time $t \simeq 2.0$. But the spiral structure does not form a stationary pattern: subsequently, the outer sites located

farthest from the center begin dissipation due to the incoming gas flow. Further, the process is spread to neighboring sites, and the spiral pattern is essentially disrupted (by time $t \simeq 2.4$).

Note that the rapid disappearance of spiral waves by wind-up or dissipation has been a problem noted in many simulation studies. My simulation spirals are transient, but they continuously regenerate oneself via a recurring cycle of instability (cf. Sellwood 2011, 2012).

The rotation of the disk and the presence of radial inhomogeneities in the gravitational potentials and the gas density produce a specific set of conditions for the evolution of the new spiral structure in the gas. Already by moment $t \simeq 2.5$ the gas has accumulated intensively and concentrated in the inner parts of disk. Another factor contributing to change of the main gas-dynamical parameters is the external gravitation; all these factors act to appreciably reconstruct the entire flow pattern, and produce a new gas-dynamical configuration that includes the major structural elements, namely, shock fronts and the contact jump between them.

This new cycle of the evolution of a galactic gaseous disk lasts until time $t \simeq 4.0$. The inner region of galactic arms ($t \simeq 3.0 \div 3.5$) is formed of a layer of dense, heated gas bounded by diverging shocks that give rise to radiation at the edges of the arms. A contact jump is located along an extended region corresponding to the minimum of the gravitational potential wells.

A tangential discontinuity arises at the contact jump in the presence of an external gravitational field in this case. This kind of discontinuity is known to be unstable. The development of instability in the vicinity of the tangential discontinuity leads to the excitation and amplification of vorticity in the generally chaotic motions of the medium, and thereby to the formation of a system of small-scale shocks that develop with time into various types of inhomogeneities on small and medium spatial scales (Lugovskii and Filistov 2014; Filistov 2012; Khoperskov et al. 2011). The pressure gradient at the ends of the arms leads to their splitting into spur-like formations ($t \simeq 3.8$), which grow in both the azimuthal and the radial directions. By time $t \simeq 4.0$ the arms are subject to stress and twisting, and become appreciably stretched, so that they are restructured into linear segments. But already by the time of $t \simeq 4.5$ the segmentary structure of arms is destroyed, and by moment $t \simeq 5.0$ the spiral structure is reconstructed.

By moment $t \simeq 5.5$ an essential bar has developed as a consequence of the interaction (in isolation the model is stable against bar formation). In the experiment one can see, that the bar orientation matches quite closely the observed alignment toward the satellite galaxies.

The rows starting directly from one bar end that form a ringlike spiral going to the other bar end are clearly traceable starting from $t \simeq 5.5$. Such rows are a peculiarity of several barred galaxies (it is noted by Khoperskov et al. 2011). NGC 1097, NGC 2523, and NGC 4902 are typical representatives (also see the images of NGC 1300, NGC 1365). In numerical N-body models, separate straightened arm segments can be seen at the transient formation stage of the bar and spirals (Buta and Combes 1996). Most likely both of these peculiarities are associated with the interaction. The straight segments in gaseous disks appeared in models by Combes (1994), who studied the gas in flow in barred potentials. She explains the square-like shape of the spiral arms by the resonances and gas viscosity: the periodic orbits must change

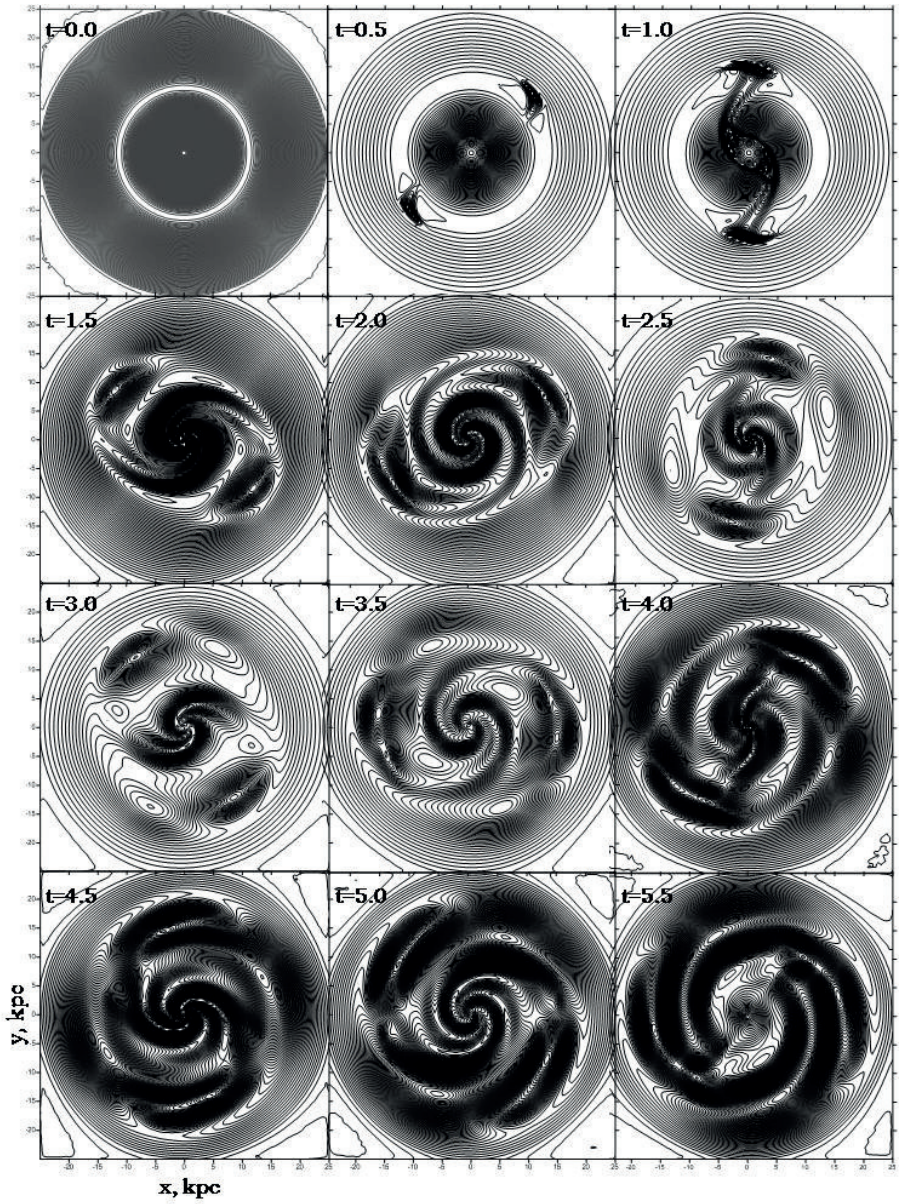


Figure 1 Distribution of the surface density in the gaseous disk. The solutions for twenty four times t (that are measuring in time code units) are shown. The time moment is exhibited at each frame. The frames have a width evaluating in kpc. These solutions are sequential sampling of stages in the formation of the spiral pattern (see details in text).

their orientation with respect to the bar in the Inner and Outer Lindblad resonances: ILRs, OLR (Buta and Combes 1996).

The results of the numerical simulations also demonstrate the time intervals with

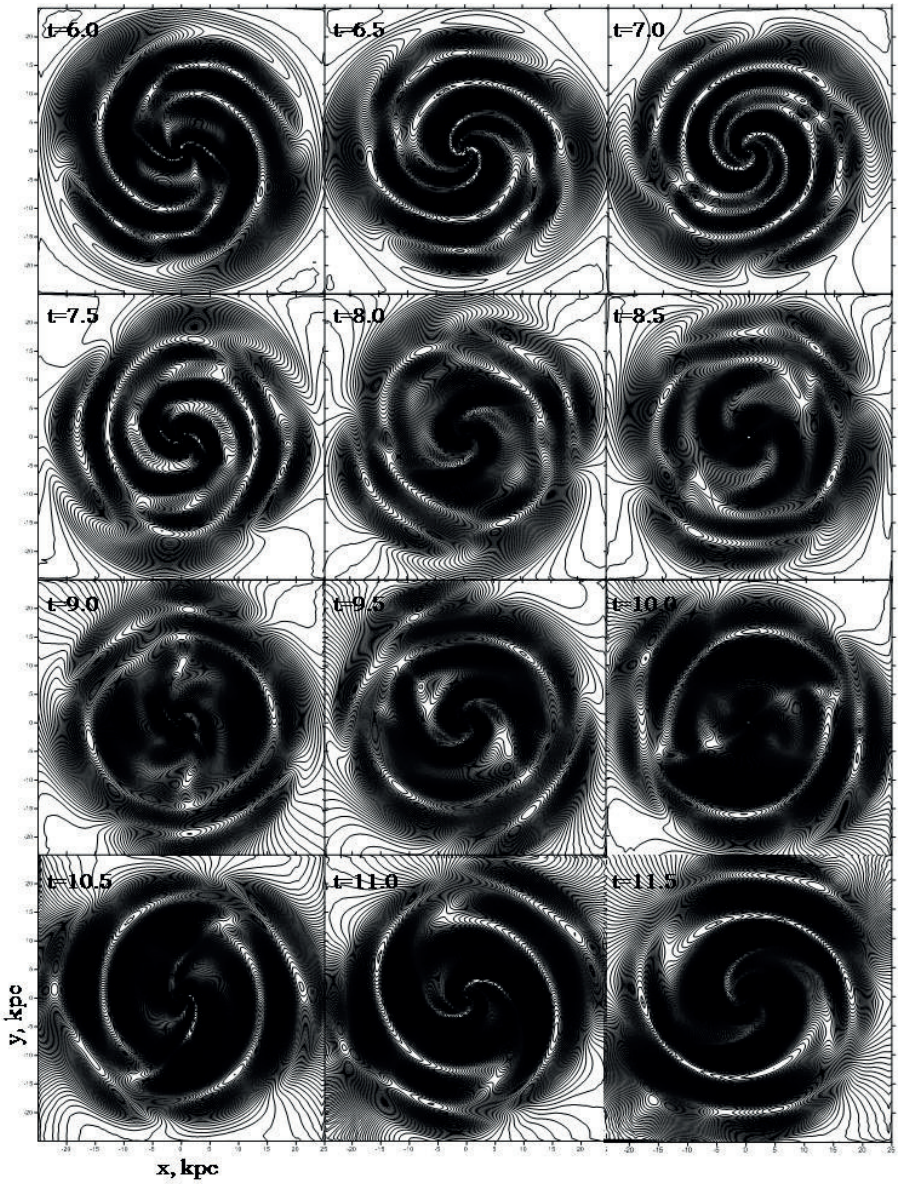


Figure 1 (Continued)

well-defined rows. In Fig. 1, there are several instants of time with a developed system of rows (it is $t \simeq$5.5–6.5).

Figure 2 shows density iso-surfaces of the gaseous disk at time $t \simeq 6.13$, when the very impressive pattern of polygonal spiral arms (or linear segments joined at kinks) is obtained, which form the global multi-armed spiral structure. The straight segments are almost everywhere and intersect one another, so that the polygonal geometry of

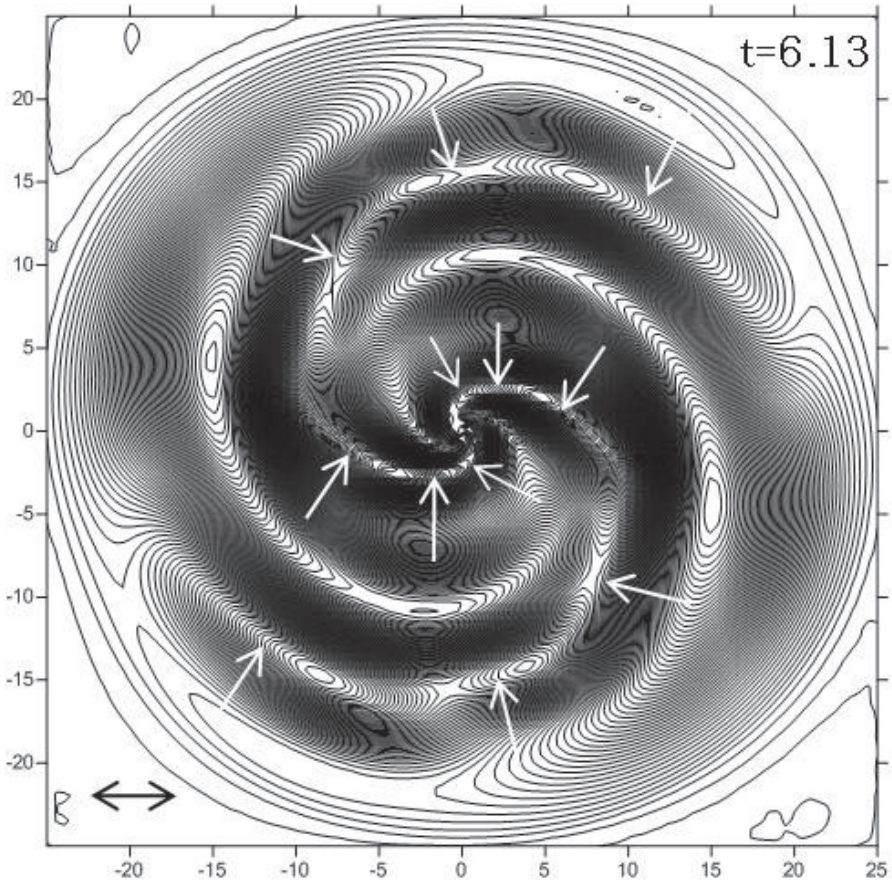


Figure 2 Isolines of the surface density at time $t \simeq 6.13$. The impressive pattern of polygonal spiral arms is observed. Separate straightened arm segments can be seen. The arrows shown in the frame indicate the locations of straight segments. The scale corresponds to the radius at which the rotation curve of the disk exits onto a plateau.

the spiral arms stretched over practically the entire length, including the inner region of the disk (cf. Fig. 2 in Filistov 2015).

As can be seen in Fig. 2, computations have reproduced the main geometrical properties of the rows observed in galactic disks: numerous straight segments, which are related to the spiral structure over the entire time of their existence, with the angle between neighboring segments being close to $2\pi/3$. The length of each of the segments is comparable to the distance from the center of the gaseous disk, and increases nearly linearly with distance from the center of the disk. Moreover, the system of segments is appreciably non-stationary — the number of segments changes during the evolution of the spiral structure (it is possible to see this in Fig. 1). Thus, the geometry of the polygonal pattern that arises in the gaseous component displays transient properties.

Returning to Fig. 1, we notice that the polygonal pattern quickly loses the expressiveness in a central region of the disk. Obviously spiral arms are not stationary on

a time scale of a few $t \simeq 6.5$–8.5. If we track one of the spiral arms, we observe that density of the arm is no longer constant – a part of the arm becomes faint or more rarefied within one rotational period, or even shorter. There are no steady grand-design spiral arms, in fact spiral arms are "wound up" to the moment $t \simeq 9.0$. At the same time, new spiral arms are generated in a central region of the disk. By the moment $t \simeq 9.5$ the spiral structure is reconstructed. It is possible to see two principal arms in $t \simeq 9.5$. They are short, wide and smooth. But this cycle of the evolution of a gaseous disk does not last long. Only a pseudoring emerges on the galactic periphery until the time $t \simeq 10.0$ (cf. Schwarz 1981, who was the first to show that the outer rings in galaxies result from the evolution of barred galaxies).

Lastly, we can see the more large-scale distribution of the gas after $t \simeq 10.0$. The perturbation is sufficient to produce very long, broad tidal arms of low density gas.

One should note that large-scale spiral structures in the gaseous galaxies disks, which have been simulated here and described above, are essentially different from the standing galactic shocks in a non-selfgravitating, isothermal gas in the spiral potentials.

In all of my calculations, the simulations revealed non-steady and nonlinear evolution of the gas spirals. The gas component of the grand-design spirals therefore cannot maintain their shapes over a rotational period. This is an essential difference from the classical galactic shock, where the gas passes through the potential and forms a oblique, global shock along the spiral potential.

4 Conclusions

The mechanism described in this paper does not apply to strongly self-gravitating spirals, nor to those driven by large-amplitude global disturbances, like bars. The approach described is based on the propagation characteristics of the nonlinear gas shocks induced by tidal disturbances. Such disturbances in the galaxies disks are produced by the interactions with satellite galaxies falling into groups. The gravitational potential generated by these interactions draw in the gas the large-scale spiral structures in the form of nonlinear global spiral shocks whose the kind and evolution are completely specified by a simple first-principles theory. The main conclusions are as follows.

The interactions between galaxies can produce the large-scale two-armed spiral shocks waves. The shocks develop on the background of the underlying grand-design and cover much of the disk. All of my models show that spiral shocks are hydrodynamically unstable, and that spiral structures in gaseous galaxies disks are not stationary. Thus the constructed patterns have a transient character. Amplitudes of spiral arms change on a time scale of galactic rotation, or even shorter (e.g., Fig. 1). In my simulation the spirals are transient, but they continuously regenerate themselves via a recurring cycle of instability. There are smooth and long cycles, there are shorter and vigorous cycles but there are no cycles present that are identical to one another. Therefore it is possible to say about cyclic development of the large-scale spiral structures in the gaseous galaxies disks. In cyclic development of gaseous disks there is an occurrence of a global bar after which the immediate appearance

of polygonal pattern and the form of jointed flat shocks follows. The straight segments form the polygonal structures when they touch each other by their edges. The computations have reproduced the main geometrical properties characteristic of the rows observed in galactic disks: numerous straight segments, which are related to the spiral structure over the entire time of their existence, with the angle between two neighboring segments, on average, close to 120°; the standard deviation is ∼10°. The length of each of the segments is comparable to the distance from the center of the gaseous disk, and increases nearly linearly with distance from the center of the disk. Moreover, the system of segments is appreciably non-stationary – the number of segments changes during the evolution of the spiral structure in the disk. Thus, the geometry of the polygonal pattern that arises in the gaseous component displays transient properties.

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