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Polygonal structures in galactic gaseous disks

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This work is devoted to the numerical multidimensional computational modeling of a gaseous disk in an external potential of the spiral stellar density wave. The possibility of polygonal structure formation in spiral galaxies (see [1, 4, 5]) was studied. Our simulations demonstrated that polygonal structures result from spiral shock instabilities. Polygonal structures are essentially non-stationary patterns. The characteristic time of straightened segments formation does not exceed the period of revolution of the periphery of the stellar disk. Polygonal structures form in models with slow rotation of spiral arms, if corotation radius is at the periphery of the disk. We also compared polygonal structures in 2D and 3D models and found a good agreement between them.

Keywords: Galaxy dynamics; Spiral structure; Shocks instability

1 Introduction

Smooth, regular spiral arms of grand design galaxies are extremely rare. Typically, the global spiral pattern is characterized by a large number of inhomogeneities on small and medium spatial scales: spurs, feathering, branching and thickening of branches, quasiperiodic complexes along the spiral pattern.

Large-scale features of the spiral pattern are the so-called polygonal structures (PS), by which we mean the sequence of nearly straight segments that form the spiral structure of many galaxies.

Vorontsov-Velyaminov was the first who discovered the straight line segments (rows) on the images of the spiral galaxies [2, 3]. For example, the rows were found in grand design galaxies M101, M81, NGC 5247, M51, NGC 2805, 3124, 309, 509, 1073. The spiral pattern of these galaxies consists of the sequence of almost straight lines. The lengths of the rows increase almost linearly with the distance from the center of a galaxy [4]. Chernin and coworkers examined in detail the properties of polygonal structures (PS) for nearby galaxies [5, 6] and for our Galaxy [7]. There are indications of the presence of straightened segments of the spiral structure of the M31 [8]. Perhaps a similar nature has the so-called hexagonal shape of some internal ringlike structures of galaxies [9].

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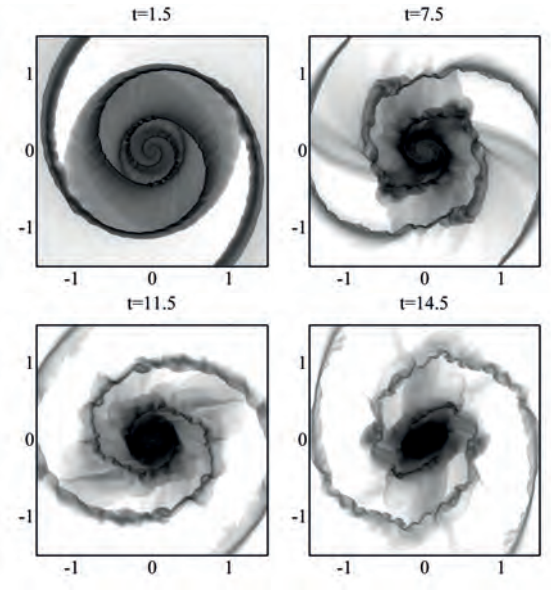


Figure 1 Evolution of a gaseous disk with transient polygonal structures. The logarithm of the surface density is shown. The model with $i = 15^\circ$, $\varepsilon_0 = 0.15$.

The polygonal structures are wide-spread in spiral galaxies. The straight line segments are observed in more than 200 galaxies with the grand design pattern. It is possible to observe rows in various galactic components of the disk in various ranges of spectrum (optical photographs, Hα, ultraviolet and far-ultraviolet images, CO, 21-cm and synchrotron emission maps, and K-band). In addition to the catalog of galaxies we identified 102 more spiral galaxies with typical PS fragments traceable in their images. We used data from LEDA, NED and SDSS to construct the sample [10].

It should be noted that several physical mechanisms were suggested for explanation of the straightened segments formation in spiral galaxies.

According to the hypothesis proposed in [11], the presence of polygonal structures is associated with the influence of the resonance region in the dynamics of the stellar population.

An alternative mechanism of the formation of rows is proposed in [7, 12]: the straightening of a spiral shock wave front is a result of hydrodynamical instabilities development in the spiral density wave of a stellar disk. The spiral shock front rearranged itself in a new configuration consisted of the straight line segments [6].

2 Model and numerical simulations

We have carried out 2- and 3-dimensional numerical simulations of the polygonal structures taking into account new factors:

- differential rotation of gas,

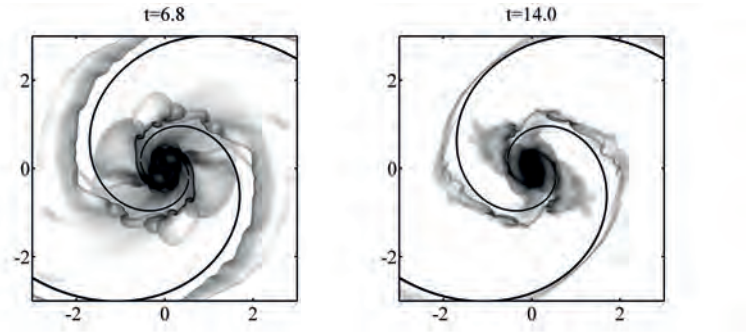


Figure 2 Polygonal structures with the minimum of potential well of stellar disk (black line). The models with two sets of parameters $i = 20°, M = 30, \varepsilon = 0.1, r_c = 5$ (on the left), and with $i = 20°$, $M = 30, \varepsilon = 0.1$, $r_c = 4$ (on the right) are shown.

- gravitational potential in the form of the spiral density wave of the stellar component (ε is an amplitude of wave , i is a pitch angle),
- solid body rotation of the spiral stellar pattern (Ω_p is an angular pattern velocity),
- spatial inhomogeneity of gas parameters (density, the sound speed, the Mach number M) and the vertical structure of a disk.

We have simulated the gas flow in the spiral logarithmic potential of a stellar disk using non-linear numerical scheme of the TVD MUSCL type in cartesian, polar (for a 2d disk) and cylindrical (for a 3d disk) coordinate systems. The intercell fluxes are computed by the HLLC method. The results of numerical simulations strongly depend on the order of the numerical scheme and used resolution. The numerical scheme of third order in space and second order in time guarantees the best convergence of results for the examined range of parameters (the best resolution in a polar coordinate system is 2400×720; in a cartesian coordinate system, 4096×4096; in a cylindrical system, 1000×360×400).

Figure 1 shows the evolution of the spiral structure in gaseous disk ($i = 15°, M = 30, \varepsilon = 0.1$). One can distinguish three main stages of the disk evolution: 1) the spiral shock wave formation in gas; 2) the development of the wiggle instability of shock waves (Fig. 1, upper left) that occurs in presence of strong shear flows [13]. 3) On the third stage the system of galactic shock fronts in a spiral stellar potential well does not precisely delineate its shape. The extended straight segments of density waves in the gas arise from hydrodynamical instabilities. A characteristic feature of the considered numerical models is the transient nature of polygonal structures. But if the potential well has a sufficiently large depth, PS formed in the gas subsystem, and existed for a long time (see Fig. 4).

The number of rows depends on the pitch angle. At small pitch angles $i = 5$–$20°$ the number of straight segments is large (usually five to seven or more) (Fig. 3 left). In the case of large pitch angles $i \geq 50°$ the number of bends is reduced to one or two (Fig. 3 right).

The formation of polygonal structures promotes the slow rotation of the spiral pattern when the corotation radius is at the periphery of the disk. At the speed of

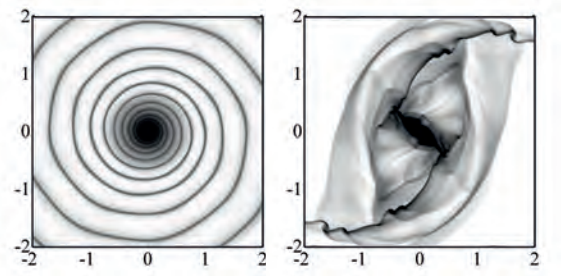


Figure 3 Models with different pitch angles. We demonstrate many PS in the left figure ($i = 5°$) and 2 PS in the right figure ($i = 50°$).

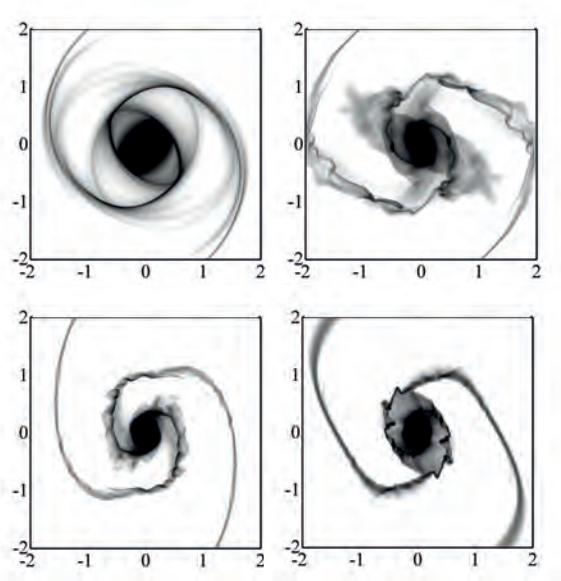


Figure 4 PS in models with different depth of potential well: (a) $\varepsilon = 0.01$, (b) $\varepsilon = 0.1$, (c) $\varepsilon = 0.2$, (d) $\varepsilon = 0.3$.

spiral pattern rotation $\Omega_p \geq 1$ the polygonals are not observed. It should be noted that the value of $\Omega_p = 1$ in our models corresponds to the corotation radius $r_c = 1$. Figure 2 shows PS with position of the minimum of the potential well of stellar spiral arms. The polygonal shock waves are located at the front edge of the spiral arm (spirals are leading ones in figures or rotate anticlockwise).

The evolution of the gaseous disk is significantly governed by the depth of the spiral potential well ε. For perturbations of a small amplitude $\varepsilon \leq 0.02$ the wiggle instability does not develop, however, the straightening of the spiral shock front takes place. In models with the large values of the potential well depth $\varepsilon \geq 0.25$ the stationary PS formed in the gaseous disk. In this case not only the effect of escape of a shock wave from a potential well takes place, but also the splitting of the spiral

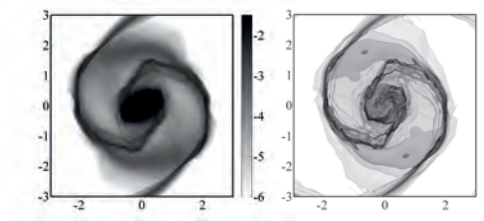


Figure 5 PS in the 3d model: (a) the surface density of the disk, (b) the isosurfaces of the volume density for the same model at plane $z = 0$.

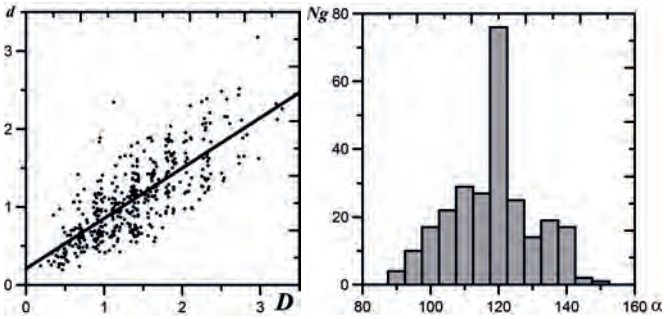


Figure 6 Statistics by PS in more than 40 models. (a) Row size versus galactocentric distance. (b) Histogram of angles between the adjacent rows.

shock wave into two or even more branches.

Our modeling demonstrates the possibility of polygonal structures formation in 3D gaseous disk. The surface gas density and the isosurfaces of the volume density for the same 3D model are shown in Fig. 5.

The spiral pattern speed is found to be the most important factor determining the formation of polygonal structures. The most favourable condition for straight arm segments formation corresponds to the value of pattern speed $\Omega_p \leq 25$ km/s/kpc for a galaxy like the Milky Way.

3 Discussion

We analyzed more than 40 numerical experiments and processed statistical data of PS. The histogram of angles between adjacent rows is shown in Fig. 6b. As we see, the maximum in the distribution of angles corresponds to the angle 120°, which is in good agreement with the observational data [12]. The function of segments length from the galactocentric distance is linear (Fig. 6a).

A characteristic feature of the numerical models is the transient nature of the polygonal structures. The parameters of PS, namely, the position of breaks, the length of segments, the angle between them and their number vary with time. Polygonal structures that emerge after the spiral shock comes out of the potential well almost disappear after some time and then are recreated again in another configuration.

In the case of the deeper potential well rows live over longer periods of time. The origin of polygonal structures is caused by the physics of shock waves in the spiral gravitational well. Our models are not self-consistent, because the opposite effect of gas influence on the geometry of the spiral pattern in the stellar component is not taken into account. In the case of self-consistent models, we should expect an increase of the transient nature of PS, but this is beyond the scope of this paper. It should be also noted that an increase in the number of galaxies with PS among interacting galaxies may be caused by the following effect: the external gravitational influence makes it easier for the galactic shock wave to leave the potential well of the stellar arm that promotes the straightening of the shock.

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