NUMERICAL MODELLING OF GAS DYNAMIC STRUCTURES IN SPIRAL GALAXIES

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ABSTRACT. Observations show that in the global morphology of spiral galaxies appear and form multi-scale features that are embedded in a complex complete picture of the galaxy. The origin and nature of the observed heterogeneity of the global spiral pattern of galaxies are not firmly established at this time. Based on the numerical simulation a possible new mechanism of appearance and formation in the two-armed global spiral galaxies' morphology of a number of gas-dynamic elements similar to each other in shape and independent in brightness is analyzed. Numerical simulation of unsteady gas-dynamic processes occurring under the influence of an external gravitational field is done. It is shown that as a result of the nonlinear supersonic interaction of occurring spiral formations with the flow of the matter features with hydrodynamic nature are appeared, with modeling results well matching with the observations.

Key words: numerical modeling, spiral galaxies, gas-dynamic structures, shock waves, contact discontinuities

Introduction

Based on the numerical simulation study a new possible mechanism (the idea and the theoretical justification are offered in the Chernin, 2002) of appearance and formation in the two-armed global spiral galaxies' morphology of a number of gas-dynamic elements similar to each other in shape and independent in brightness is analyzed in this paper. The arms are taken as two related distributions, each of which contains the shock fronts bordering the arm, contact discontinuities between them and also the emerging system of small-scale shock waves. The physical conditions that give rise to this kind of non-linear quasi-stationary gas configuration can be implemented in a global two-armed spiral gravitational field and can be connected, either to the nature of the spiral density wave, or with the specific behavior of a large-scale shock compression of the gas flowing through the gravitational potential profile of the density wave. The presence of this kind of dynamic structure of the matter flow in the disks of spiral galaxies is shown by observations (eg: Zwicky, 1957; Sandage, 1961; Vorontsov-Vel'yaminov, 1978; Elmegreen et al., 1984; Sandage et al., 1994; also refer to: Block et al., 1994; Block et al., 1999; Block et al., 2001; Zhang et al., 2012).

At the gas-dynamic framework for the interpretation of this phenomenon also points morphological difference of images of the galaxy NGC 309 seen nearly flat when viewed in the light of different ranges of wavelengths (see Fig. 1) obtained in the paper Block et al. (1991).

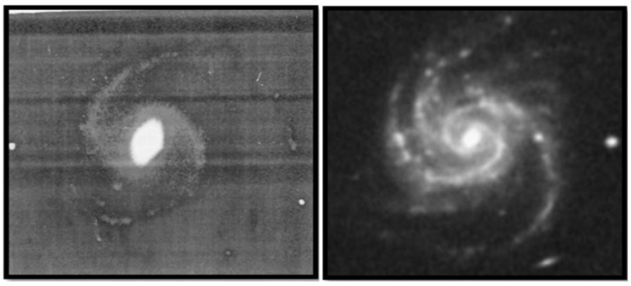

Figure 1: Various images of the spiral galaxy NGC 309. On the left – image received using near-infrared light: two short, wide and plain major arms, originating from the ends of the central bar.

On the right – image received using blue light: well distinguishable multi-armed expanding from the disk center geometrical structure.

The origin and nature of the observed heterogeneity of the global spiral pattern of galaxies are not firmly established at this time. Mesoscale features such as spurs , feathers , etc. are found in the major geometric structures - representatives of the spiral Grand Design galaxies of Hubble type. They appear as feeble intermediate links that are embedded in a complex complete picture of the galaxy. Even in very small (located around the nucleus) volumes special methods of processing of images clearly enough indicate the presence of regular substructures in the spiral arms.

Our calculations allow to monitor the complex shockwave configuration with contact discontinuities. The structure of the resulting flow pattern has been studied and it was found that the emerging series of interacting wave disturbances can create a new quasi-stationary configurations developing in an essentially nonlinear transient mode.

Mathematical model and numerical method

Without going into detail to the description of the model (for details see: Landau, 1979; Lugovskii, 2012; Abakumov, 1996) let us say that we consider the dynamics of an axisymmetric gas disk is immersed in a gravitational field created by a rotating stellar disk.

The gravitational influence at the gas environment is determined by gravitational potentials formed mainly by external sources located both inside and outside the area of modeling. The total gravitational potential is represented by the algebraic sum of the axisymmetric and non-axisymmetric parts. The axisymmetric part of the gravitational potential is the algebraic sum of the potential of self-gravitating stellar disk, bulge potential and potential of the dark halo (the explicit form of the axially symmetric gravitational potentials is represented, for example, in: Morozov, 2005). Additional non-axisymmetric gravitational spiral potential is the potential associated with a density wave in the disk, and providing two-armed spiral pattern of the galaxy (Toomre, 1964). This potential is a small perturbation introduced at the initial time to the equilibrium state eventually leading to the formation of large spiral-shaped structures that cover the entire volume of the disk.

The flow of gas in an external gravitational field is described by the Euler equations of classical gas dynamics. For the solution of gas dynamic equations the monotonic 1st order approximation TVD scheme by Roy with the limiters of antidiffusion flows in the form of Osher which increase the order of scheme approximation (up to the third order in space) with minimal numerical dissipation and preserving the property of monotony was used. Moreover initial scheme was modified by the method of Einfeldt to improve stability. General description of the method can be found in (Velikhov, 2007). TVD-method is effective for describing significantly unsteady, for example, turbulent flow (Velikhov, 2007; Lugovskii, 2008; Lugovskii, 2012) as well as flow wherein small-scale system of shock waves is formed (see, eg, Filistov, 2012; Khoperskov, 2003).

For the borders of the area free boundary conditions were set. To eliminate the effect of boundary conditions at the behavior of internal regions of the disk its configuration was selected so that the radial dimension of the computational domain significantly exceeds the characteristic size i.e. bulk concentration region of the disk and the density at the outer border is significantly lower than in the central zone. Note that without making any perturbation gas disk retains its equilibrium state for sufficiently long time period; during the calculations the outer layers of the disk evolved while at the same time the bulk of the disk remained stable, density changed slightly and the radial velocities developed insignificantly.

Results

The results of the numerical simulation allow to distinguish several stages in the evolution of the gas disk in which the phenomenon of formation of transient non-stationary configuration of a global two-armed spiral pattern is observed including a series of hydrodynamic discontinuities such as shock waves and contact discontinuities between them.

The general structure of the solution for an ideal gas flow evolving over 6 characteristic times (one unit of time in our model calculations correspond to the physical time in 68 million years) is shown in Fig. 2. This figure shows the gas pressure distributions in the equatorial plane of the system illustrating the flow dynamics and its state at different equally spaced time points. Shock waves formed in the disk are seen in the figures as a condensation of pressure contours.

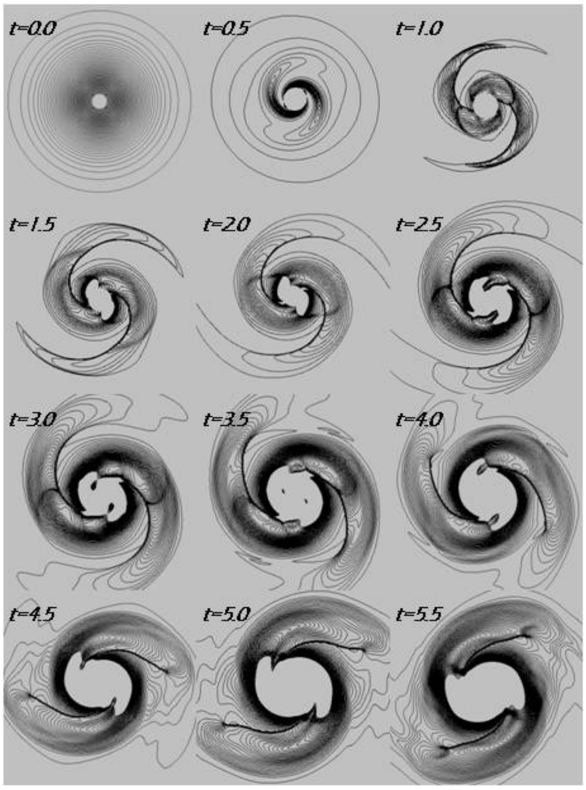

Figure 2:

t=0 – equilibrium configuration

t=0.5 – appearance of smooth spiral shock waves

t=1.0 – small-scale secondary shock waves

t=1.5 – increasing the size of spiral structures

t=2.0 – blurred main shock waves

t=2.5 – spurs inside the arms

t=3.0 – 3.5 – transient nature of the spurs, beginning of the polygonalization (straightening segments of the shock wave front)

t=4.0 – arc-shaped spiral shock waves

t=4.5 – straight line segments of shock waves (length is proportional to the distance from the center)

t=5.0 – development of the structural instability of the shock wave, interaction with the contact discontinuity

t=5.5 – the formation of the spur in the spiral design, the development of polygonal pattern of the spiral arm

Numerical simulation shows the formation of some spiral elements in the global two-armed spiral galaxy morphology similar to each other in shape and independent in brightness. These series of strong shockwave disturbances interacting with each other create new small-scale irregular secondary shock waves which develop over time in different kinds of heterogeneity in small and medium spatial scales that contribute to the generation of polygonal structures in the gas disk. This paper is not aimed at exploring and embracing of the entire spectrum of phenomena arising in a rotating gas disk with formation of transient global morphology of the spiral structures in the two-arm gravitational potential. The general course of the evolution of spirals for ~6 characteristic times is studied. However, it is natural to assume that at this stage of the appearance of two straight segments the gasdynamic process of general polygonalization is not finished. This circumstance is also indicated by the fact that the presence of straight-line segments (rows) in the spiral arms of galaxies is not an exception (Chernin, 1999; Chernin, 2000) at least for late-type ordering spirals (Grand Design Sbc-Sc).

Analysis of the distribution of the geometric parameters of the individual structural elements obtained in the course of numerical simulation of the gas disk in the potential of spiral density wave of stellar component and analysis of fragments of the spiral pattern of the galaxy M51 shows a good agreement (Fig. 3).

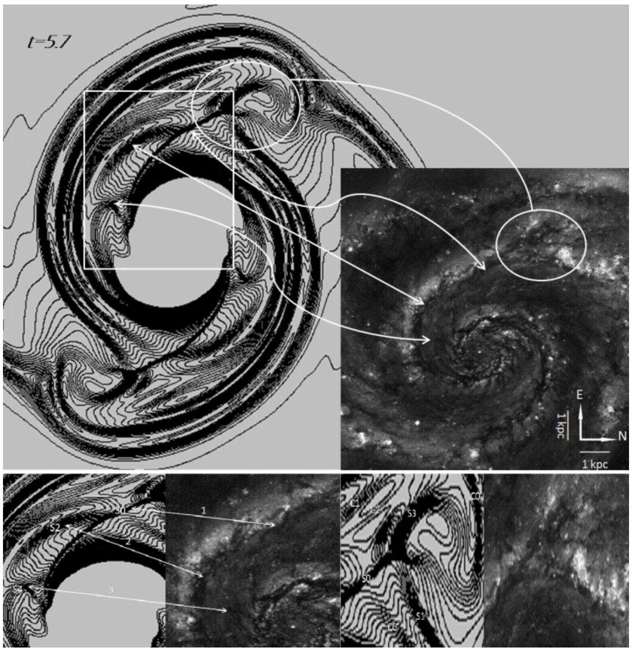

Figure 3:

Top: the nonlinear stage of the formation of the spiral pattern, gas density contours are shown at the time t = 5.7. The inset – the image of the spiral galaxy NGC 5194 (M 51).

Bottom left: at the left – an enlarged image of the part of the spiral arm bordered by the rectangle in the top figure; at the right - a fragment of the picture of the galaxy M 51.

Bottom right: at the left – an enlarged image of the part of the spiral arm bordered by the ellipse in the top figure; at the right – photo: Northwestern fragment of the galaxy M 51 bordered by the ellipse in the top figure.

Thus it is found that the behavior and geometrical properties of the resulting transient structures in the numerical simulation in the constructed model agree well with the behavior and basic properties of the global picture of the observed spiral patterns.

Conclusions

Based on numerical simulations the possibility of the formation of non-stationary transient gas configuration in the global two-armed spiral gravitational potential was investigated and the analysis of emerging complex wave pattern of the flow was made in this paper.

The results of numerical simulation and flow features identified during the gas dynamic calculations lead to the following conclusion confirming the theoretical basis for this phenomenon provided in the article [Chernin 2002]: configurations of this kind can be formed as a result of a non-linear supersonic interaction of the spiral formations with the flow of the disk matter and the appearance of the hydrodynamic discontinuities including the fronts of varying intensity shock waves and contact discontinuities separating these fronts.

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