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THE FLOW EVOLUTION MODELS OF ACCRETING ASTROPHYSICAL OBJECTS

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Key words: *Astrophysical hydrodynamics; Stars and galaxies; Accretion discs.*

Abstract: *We present in this paper our recently results on the dynamics and structure of accreting flow in astrophysical matter. The research concerns the astrophysical objects, such as: binary stars with accretion discs and Active Galactic Nuclei. We make an analysis of the methods we have employed on the structure's evolution study. We investigate an accretion flow structure as a result of transitional processes dynamics. We develop a model, based on numerical codes and methods, which to explain the physical properties of the hydrodynamical matter in accreting astrophysical objects. The box-framed scheme is applied. The development of our theoretical models that aims to ensure the future application to the observational data analysis is presented. The results show that during the evolution process, the accreting flow undergoes through structural transformations, which could be responsible to the known observational effects.*

The results demonstrate of how the dense patterns and waves evolve in the studying astrophysical discs. An effect of their locally development in the inner disc's structure configuration is shown.

МОДЕЛИ ЗА ЕВОЛЮЦИЯ НА ТЕЧЕНИЕТО ПРИ АКРЕТИРАЩИ АСТРОФИЗИЧНИ ОБЕКТИ

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Ключови думи: *Астрофизична хидродинамика; Звезди и галактики; Акреционни дискове.*

Резюме: *В статията са представени досегашните ни резултати от изследвания върху динамиката и структурата на акреционно течение в астрофизична среда. В изследванията са включени астрофизичните обекти като двойни звезди с акреционни дискове и активни галактични ядра.*

Извършен е анализ на методите, които са използвани при изучаването на структурната еволюция. Ние изучаваме структурата на акреционното течение като следствие на динамиката от преходни процеси. Ние развиваме модел, на основата на числени кодове и методи, чрез който да дадем обяснение да физическите свойства на хидродинамичната среда в акретиращите астрофизични обекти, в следствие на тези процеси.

Приложена е схемата-модел "box-framed". Представянето на теоретичния модел е с тенденция да осигури използването и анализирането на наблюдателни данни при решението на проблема в бъдеще. Получените резултати демонстрират по какъв начин еволюират плътностните структури и вълни в изучаваните астрофизични дискове. Показан е ефекта от тяхното локално развитие във вътрешната зона на диска.

I. Introduction

Flow's evolution properties could be defined by the disc's morphology. The morphology is a composition of pattern formation in the disc's flow: appearance of turbulence, vortices, spiral-like structures, as a part of the complete whole disc's configuration and their dynamics.

In astrophysics, the problems of structures development have been investigated mainly numerically [11], [17]. Bracco et al. [6] by using two-dimensional, incompressible fluid dynamics, show that anticyclonic vortices "shift out" and that smaller vortices merge to form larger vortices. Godon and Livio [10, 11] confirm this result with two-dimensional, compressible, barotropic simulations. Shen et al. [21] examine the formation of 2D vortices starting from 2D turbulence in fully compressible simulations. Barranco and Marcus [2] compute the evolution of 3D vortices and show that part of the vortical formations could be destroyed, but the other part survive for several hundreds of orbits.

A significant part of astrophysical disc is related to the binary stars configuration. A critical stage in the evolution of binary is the period just after mass transfer has been initiated [8]. We have defined the states that are responsible for the appearance of instability in the flow, as well as patterns formation, variability in the whole disc' structure configuration and transformations within the vortex- and spiral-like structures, as transitional. A frequently considered reason that provokes the transitional states could be a shock's interaction due to the tidal waves.

The transient processes in the stars could be a short- such as a long-lived. Short-lived is usually associated with the bursts in CV binaries and they cause a significant variability in the system. In the context of long-lived we include the structures like: spirals, spiral's waves, density formations, vortices, which are well studied in the literature. J. A. Sellwood [20] gives a bit of complete analysis of the lifetimes of spiral patterns in disc galaxies. In his paper he has presented some theoretical and observational evidence for short- and long-lived behavior of spirals in the discs.

The theoretical study of Peralta et al., in the paper [19], has investigated the transitions between turbulent and laminar states of fluid's vorticity in a pulsar. By solving numerically the hydrodynamic equations for a rotating fluid in a differentially rotating spherical shell, they calculate the global structure of the flow with and without an inviscid component. They find the turbulent-laminar transition can occur through all examined flow or partially.

The aim of our theoretical research is to track the evolution and to interpret the mechanisms of the high energy behavior of sources, such as: CBS (Close binary stars) and AGN (Active Galactic Nuclei). We apply numerical codes and methods on hydrodynamics and magneto-hydrodynamics systems of equations. By applying numerical calculations on the gas-dynamical flow, we suggest modeling of patterns formation and explanation of supporting physical processes in interacting flows. We consider a gas-dynamical system that allows 2D and 3D modeling of physical processes in the binary components

II. The background of the problem solution

II.1. Basic equations

Therefore, to obtain solutions of the above stated problem a system of hydro- and magneto-dynamics equations is needed. Herein, the basic equations are presented in a form that have been suggested and affirmed by many authors: [9], [12], [22].

We present the equations in their vector form. In the gas-dynamical system of equations we consider the influence of viscous processes, gravitational forces, Coriolis force and we add the corresponding terms for viscous non-ideal fluid in the equations. Then our system of equations consists of: equation of mass conservation (Eq.1); the Navier-Stokes equations (Eq.2); energy balance (Eq.3); the equation of state for compressible flow (Eq.4); vortical transport equation (Eq. 5).

(1) $$\frac{\partial\rho}{\partial t} + \nabla.(\rho v) = 0$$

(2) $$\frac{\partial v}{\partial t} + v.\nabla v = -\frac{1}{\rho}\nabla P - \Omega\times(\Omega\times r) - 2\Omega\times v - \nabla\Phi + \nu\nabla^2 v$$

(3) $$\frac{\partial}{\partial t}\left[\rho\left(\frac{1}{2}v^2 + \varepsilon + \Phi\right)\right] + \nabla.\left[\rho v\left(\frac{1}{2}v^2 + h + \Phi\right) - 2\eta\sigma.v\right] = 0$$

(4) $$P = c_s^2\rho$$

(5) $$\frac{\partial\Psi}{\partial t} + \Psi(\nabla.v) + (v.\nabla)\Psi = -\frac{\nabla p\times\nabla\rho}{\rho^2} + D\nabla^2\Psi$$

Where the basic notations are as follows: ρ is the mass density of the flow, v - is the velocity of the flow; P - is the pressure; ν - is the kinematic viscousity; Ω - is the angular velocity; $\Omega \times (\Omega \times r)$ - is the centrifugal acceleration of the centrifugal force; and $2\Omega \times v$ - is the Coriolis acceleration in the mean of the Coriolis force. Φ is the gravitational potential and it depends on the density distribution inside of the each star's component [5]. c_s is the sound speed. Here Ψ - is the vorticity; D - is the diffusion coefficient (or matrix of the transport coefficient).

The expression in eq.3 $\frac{\partial}{\partial t}\left[\rho\left(\frac{1}{2}v^2 + \varepsilon + \Phi\right)\right]$ is the total energy density, where the first term on the left denotes the kinetic energy, the second is the internal energy and the third expresses again the full potential of the gravitational fields. Further, $\left[\rho v\left(\frac{1}{2}v^2 + h + \Phi\right)\right]$ is the total energy flux, where $h = \varepsilon + P/\rho$ is the enthalpy, η is the shear (or dynamical) viscosity of the flow, and σ is the rate of shear.

We also investigate the basic equations of magneto-hydrodynamics for non-stationary and non-axisymmetrical accretion flows. This could be seen in details in papers [14], [15]. The model contains mass continuity equation again (Eq.6), magnetic flux conservation (Eq.7), equation of motion (Eq.8), equation of magnetic induction (Eq.9), heat balance equation (Eq.10) and complete pressure equation (Eq.11).

(6) $$\frac{\partial \rho}{\partial t} + \nabla.(\rho \boldsymbol{v}) = 0$$

(7) $$\nabla.\boldsymbol{v} = 0 \qquad \nabla.\boldsymbol{B} = 0$$

(8) $$\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v}.\nabla \boldsymbol{v} = -\frac{1}{\rho}\nabla p - \nabla \Phi + \left(\frac{\boldsymbol{B}}{4\pi\rho}.\nabla\right)\boldsymbol{B} + \vartheta \nabla^2 \boldsymbol{v}$$

(9) $$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}$$

(10) $$\rho T \frac{\partial S}{\partial t} - \frac{\dot{M}}{2\pi \boldsymbol{r}} T \frac{\partial S}{\partial \boldsymbol{r}} = Q^+ - Q^- + Q_{\mathrm{mag}}$$

(11) $$p = p_{\mathrm{r}} + p_{\mathrm{g}} + p_{\mathrm{m}}$$

Here, v is velocity of the flux; Ω - angular velocity; ρ - mass density; B - magnetic field; Φ - gravitational potential; r_g - Schwarzschild radius; p -pressure; $\vartheta = \alpha v_s H$ - kinematical viscosity; $\eta = \alpha_m v_s H$ - magnetic viscosity; T - temperature; S - entropy; $\dot{M}$ - accretion rate; H -half thickness of the disc; Q_{adv} - advective term; Q^+ - viscosity dissipation; Q_{mag} - magnetic dissipation; Q^- - radiative cooling; χ - opacity; τ -optical thickness.

II.2. Numerical codes and methods.

The complexity of the studied hydrodynamical problem requires employing with an environment that supports a wide variety of mathematical operations. We employ with numerical codes as the version of Maple and PLUTO.

The Maple code is comprehensive enough for exploring the hydrodynamical system of equations, because of an extensive mathematical problem-solving tool [13].

PLUTO code is a multi-physics, multi-algorithm high resolution code, developed by Mignone in 2005 [18]. This code is suitable for time-dependent, explicit computations of highly supersonic flows. Its hydrodynamics (HD) module, loaded with a Roe solver, has been applied in our calculations.

Both these codes work with methods implied in their structures. The base ones we are using in the calculations: the Runge-Kutta (implicit part) method and those ones related to the Finite-difference schemes. The Runge-Kutta algorithm is applied to solve numerically the system of equations, approximately. The method treats every step in a sequence of steps in identical manner [1], [7]. The basis for the finite-difference method of solution of differential equations is the replacing of derivatives by decrements or difference derivatives. It splits the finite-difference equations in two. The functions of continuous argument are to be replaced by grid functions determined on the difference grid.

II.3. Models and conditions

It is used the cylindrical coordinates (r, φ, z) frame for the equations and quadratic (x, y) set for the numerical scheme. Box-framed scheme has been suggested and applied. We could perform the calculations in limited regions of all disc's areas by configuring a different scheme for each of the problems.

Then, we make the calculations inside of the box, or frame, with measurements defined by the boundary conditions. In this reason we submitted boundary conditions of Dirichlet- and Cauchy type in our calculations: $r_{v(1+n)} = K(x,y) - \frac{\partial K}{\partial r_v}\frac{\partial}{\partial t}$; $r_{v0}(0) = 0$ is the radius of vortex; $K(x,y)$ - the boundary area of equations activity. For more details, see the paper of Boneva and Filipov 2012 [3].

We suggest free boundary conditions at the outer disc edge with constant density $\rho_{out} = 10^{-6}\rho_{L_1}$, where ρ_{L_1} is the density of the inner Lagrangian point ~ L_1, and non-constant density in the inner parts of the disc's flow.

We submitted baroclinicity conditions of Klahr and Bodenhiemer [16], concern to both misalignment of the pressure and density gradient, and to the construction of the vortical transport equation (eq.5).

III. Results

III.1. Distribution of the flow parameters.

Tidal interaction of the streams in the close binary star system leads to a transformation in the flow's structure. This may cause the appearance of long-lived vortical like formations and waves.

In the next calculations, we can see that the changes in the mass transfer rate are in a close relation both with disturbances in the density and in the velocity. We have studied this in detail in [3], where we applied the modified perturbation function on the Navier-Stokes equations and obtain the ``term of instability". This term gives the relation of velocities, including perturbation value and angular velocity. We put values to the rate of accretion ranging: $\dot{M}_0 \approx 10^{-10}\dot{M}_\circ / year \div \dot{M}_{t_0+n} \approx 10^{-12}\dot{M}_\circ / year$.

The calculations here give the behavior of perturbed velocity for new values of the time averaged velocity, related to the current topic of consideration. Flow velocity variations in time in the area of the vortex zone formation depict the non-stable zone in the result of disturbances in the flow. We obtain the vector field distribution of the velocity gradient. The result is shown at the Fig. 1 in a 3D calculation frame of the vortical formation zone.

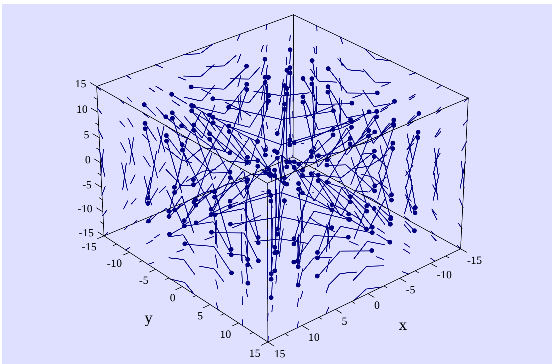

Fig. 1. Vector field of the velocity gradient, calculated in a 3D box-framed scheme. A Mesh grid refinement is applied.

Next, we integrate the solutions of all disturbed values and apply this process to the model. This gives a complex view of the formed inner structures' spatial distribution in the sense of flow's parameters values variation in a pure parametrical view. The box-framed boundary is limited to [-5 ÷ 8; -5 ÷ 8; -5 ÷ 8] in the grid measurement scale.

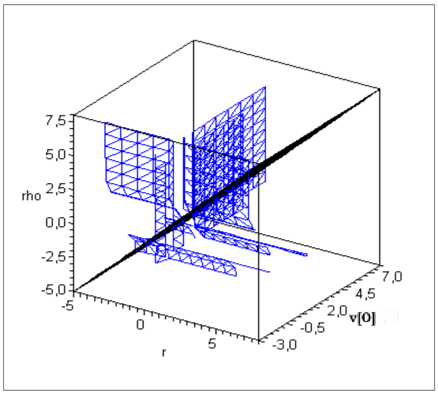

Fig. 2. A peculiar view of the patterns' distribution in the disc' flow. It is seen the density-velocity and radial gradient dependences. The concentration of value positions is in a relation with the flow's morphology and dynamics.

III.2. Patterns distribution on the accretion environment.

Further, we based on the results of [3] and [4], where we have shown our 2D results of vortex formation in the accretion zone flow, respectively the 3D view of vortical-like patterns distribution. The three stages development of this kind of vortices is depicted there: distortion of laminarity of the layers, weakly undulations, and the final stage of structures formation in the flow. Each frame visualizes a covered range of the box-framed boundary conditions.

According to the conditions of the general flow and by applying the simulations, we obtain the 3D view of vorticity time evolution in the accreting flow. The box boundary values in this case: K(x, y, z) є [8 x10 $^{-8}$ ÷ 7 x 10 $^{-7}$ AU]. The 3D "vortex"-like formation is presented as a patch graphics in the calculating mesh grid (Fig. 3b). Unlike the 2D calculations, here we perform the runs with non-zero initial vorticity and non-zero initial turbulization. Here we present the final stage of the development, which is calculated in the box-frame scheme's limitation again.

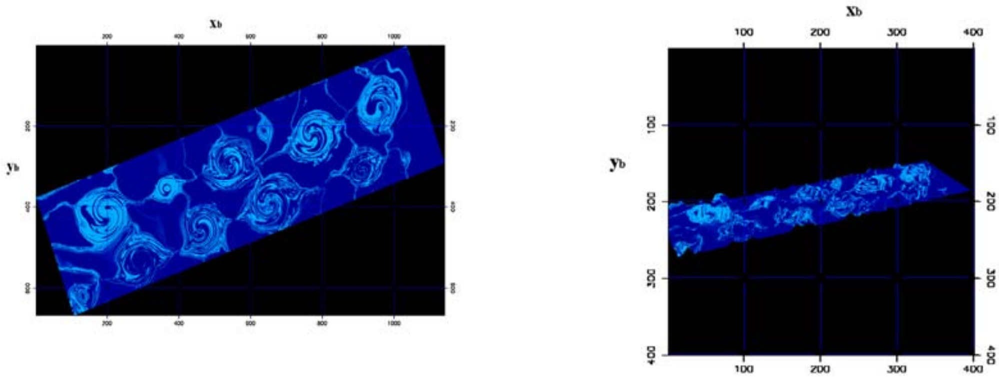

Fig. 3. Box-frame model of vortical patterns formation. Figure 3a (left) shows the 2D view, figure 3b (right) depicts the 3D view. It is used a different grid scale in the calculations of two images. The boundary values of the box-framed calculation schemes are: 7.687 x 10$^{\{-8\}}$ AU to 6.68 x 10$^{\{-7\}}$ AU and 7.687 x 10$^{\{-8\}}$ AU to 6.68 x 10$^{\{-7\}}$ AU. The axis's denotations of (x_a, y_b) are referred to the boundary frame of the calculation performance. The light Blue and dark Blue colors (light and dark in a grey scale for the printed version) show the difference in density in the interacting flow layers. The density values are increasing from dark to the light zone.

The existence of violation in the stable configuration is seen at the figure (3b). In a relation to the 3D view, the image there shows an initial deformation in the vortex-like 3D configuration and the splitting of the vortex structure wholeness is detected there.

III.3. Main types of structures in the magnetized disc.

We introduced a modification function $F_i = F_{i0}\Re_i(x = r/r_0)\exp[k_\varphi(x)\varphi + \omega(x)t] = F_{i0} f_i(x)$ for leading parameters of the disc and we obtain global solutions for the 2D and 3D structures and local evolution of accretion disk. The results are presented in cylindrical coordinates. Dimensionless distributions of the main physical features $f_i(x,\varphi)$ describe the decisions for radial and the local structures of the disc in eqatorial plane (X,Y). Where $X = x\cos\varphi$ and $Y = x\sin\varphi$, $x \in \lfloor x_g,1 \rfloor (x_g = r_g / r_{out})$ in radial structure and x is measured in r_g units for local structure.

Co-interpretation of radial and local distributions in the disc indicates the presence of a specific type of structures formed during evolution. The presence of helix' mega-structures can be registered by the result of mass density (Fig.4).

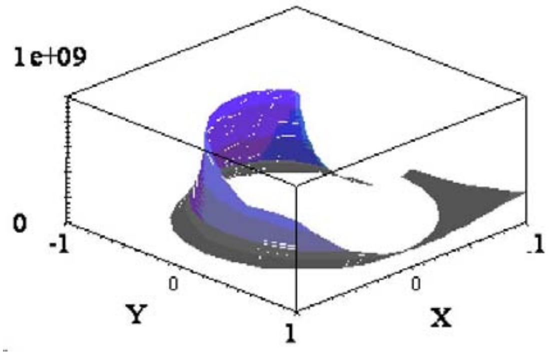

Fig. 4. The distribution of dimensionless density $f_1(X,Y)$ in non-axis-symmetric MHD model, presented in a 3D box-framed scheme [-1, 1], $x \in \lfloor x_g,1 \rfloor$. It is used a different grid scale in the calculations of two models.

Figure 4a shows two branches of the radial velocity function. Those two branches are individual throughout the disc (Fig.5a). The radial velocity increases along the lower branch while it decreases at the upper one. This means that the fluid freely and independently moves in the both directions. Such behavior clearly indicates the presence of micro-structures in the disc.

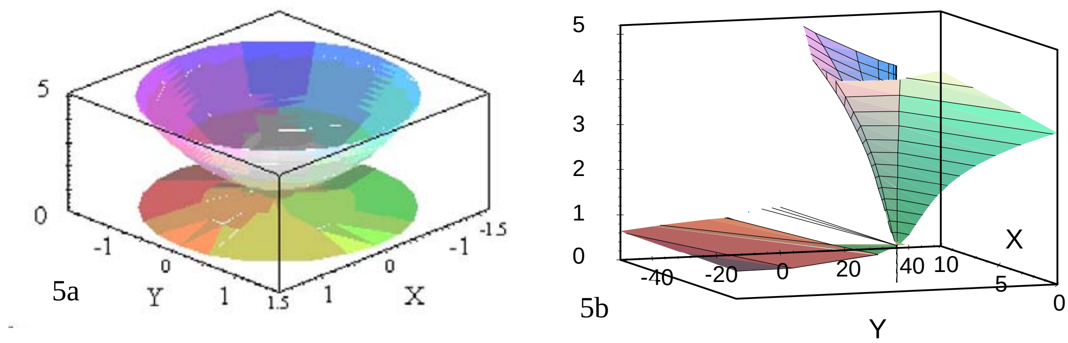

Fig. 5. Distribution of the dimensionless radial velocity $f_2(X, Y)$ (5a). It is seen the two individual branches of the function, which is in a direct relation with the flow's morphology and dynamics. Local development of the radial velocity (5b).

A behavior of the radial velocity's local development (Fig.5b) corresponds to its global distribution. We can see that the upper inflow branch is additionally undulated. In these places, the radial velocity rapidly decreases, and then the rotating component is only important.

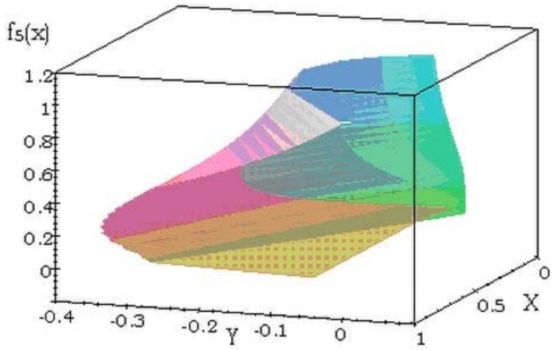

Fig. 6. Local development of the radial component of the magnetic field. It is seen the top speed branch is folded additionally.

In the area with plicated radial velocity, a rotation (Fig. 6) in the radial magnetic field indicates a vortex existence. Non - uniqueness in its development shows an overlaying and twisting of the magnetic lines and this confirms that there is a vortex. So we localize the existence of microstructure there (Fig. 5, 6).

IV. Conclusions

We investigated the evolution of astrophysical disc's flow, related to the problem of structures formation in accretion disc zone.

It is considered the behavior of disc's structure through the transitional states in hydrodynamic flow. In the mean of transitional states: stability-instability; laminar-turbulence; 2D-3D; hot-cold, we presented our study of patterns development in accreting flow in binary stars. The results show that during the mass transfer and interacting processes in the binary, the flow doesn't remain laminar or homogeneous. Our calculations reveal the character and dynamics of interaction in the binary star's flow. Multi-physics, multi-algorithm, adaptive numerical codes are applied. The codes are both suitable for time-dependent, explicit computations and imply a hydrodynamical module in their architectures. We have propounded box-framed sharing scheme-model and we have employed to the numerical calculations. We presented the 2D and 3D view of vortical patterns development, locally in the area of accretion disc in a binary star configuration. This result is based on the numerical codes and box-framed scheme employment, which have been explained in Sect. 2.

We presented our studies of the plasmas flow with the magnetic field interaction, and of how this affected on the disc's self-organization. It is suggested a pattern distribution model through the whole disc's structure. A future study of the flow structure in astrophysics could be used for the interpretation of observational data.

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