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# DYNAMICAL PROCESSES AND FLOW'S FORMATIONS IN ACCRETION DISCS OF BINARY STARS

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***Abstract:*** *We present our study on the transfers' mechanisms and gas-dynamical processes in accretion discs of binary stars with a compact object. Flow's formations that are developed in the disc are supposed to be a result of instabilities. The results reveal existence of vortical-like patterns and density wave structures, hot lines and hot spots. Since we assume a thin disc's approximation, a movement of these patterns is considered to be along the radial direction. An angular momentum transportation and conservation is connected to that movement. Mass-transfer mechanisms are discussed and proposed for individual astrophysical objects.*

# ДИНАМИЧНИ ПРОЦЕСИ И ФОРМИРОВАНИЯ В ПОТОКА НА АКРЕЦИОННИ ДИСКОВЕ В ДВОЙНИ ЗВЕЗДНИ СИСТЕМИ

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***Ключови думи:*** *Звезди: Двойни звезди; Акреция: акреционни дискове*

***Резюме:*** *Представено е нашето изследване върху механизмите на пренос и газодинамичните процеси в акреционни дискове на двойни звезди с компактен обект. Ние предполагаме, че структурите на потока, които се развиват в диска са резултат от неустойчивости. Нашите резултати разкриват съществуването на вихрови модели и плътностни вълнови структури, на горещи линии и горещи петна. Тъй като приемаме приближение на тънък диск, то движението на тези структури е в радиална посока. Това движение е свързано с транспортирането на ъглов момент и закона за запазването му. Обсъждат се и се предлагат механизми за пренос на маса при избрани астрофизични обекти.*

## Introduction

Binary stars are common astrophysical objects, usually consist of a compact object (as an accretor) and a main sequence star (as a donor). These two components are surrounding by an equipotential surface, known as Roche lobes. When the two objects are close enough in order of one of the Roche lobes to be filled, a specific process occurs. Matter from the donor star starts to transfer towards the accretor. Due to the fact that this matter possesses significant angular momentum, it becomes natural that a disc around the compact object is formed. This disc is called an accretion disc and the process is called an accretion [10]. The disc that is formed is axisymmetric, which means that the gravitation of the donor star does not influence the disc in a high extent [25].

The accretion happens by the tidal force, which transports the angular momentum through the disc towards the accretor [17]. When the Roche lobe overflow velocity is high enough, the so called stellar wind type of the incoming flow undergoes [24]. Another important feature is that the inflow velocity into the accretion discs could be "highly supersonic" [23]. Then, shock waves are possible to be produced, discovered by Sawada et al. (1986) [24], and they are thought to be the cause of losing angular momentum of the disc. At some conditions, as an example a high Reynolds number, turbulence in the disc flow is developed [25]. In this case, the turbulent viscosity is an active mechanism of the gas-matter transfer. According to the theory of Shakura & Sunyaev (1973) [26], magnetic stresses are the useful tools for the loss of angular momentum.

An important feature is also the Eddington limit or a limiting luminosity. The accretion can be stopped by crossing it. When it is exceeded, the pressure of luminosity would halt the accretion process, because the gravitational force would not be strong enough to keep the process running [10].

In this paper, we explore the essence of the accretion disc around the compact object, as well as the important features of angular momentum, hydrodynamical processes, what kind of instabilities and structures exist.

We present a retrospection of years of our study, with recent interpretations and results, on the gas dynamical processes and pattern formations in accretion discs of binary stars systems with a compact object (Section 2). We discuss on the mass-transfer mechanisms available in the studied binary stars (Section 3).

## Gas-dynamical processes: instabilities; pattern formations; angular momentum transportation.

### Equations

Here, we present only the equations that are used for the current results, written in their final form. First, it is the next form of the Navier-Stokes equations [30]:

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

and the vortical transport equation [12,18], obtained in the following expression (we explained in detail in [4]):

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

Eq. 2 expresses the relation between evolution of the vorticity with time, the non-conserve relationship between density and pressure in the flow and the transport coefficient, which takes part in the angular momentum transfer. In the current analysis, we accept $\rho \neq const$ and $v \neq 0$.

The denotations in Eqs. 1, 2 are as follows: $v$ - is the velocity of the flow; $\rho$ - is the mass density of the flow; $P$ - is the pressure; $\nu$ - is the kinematic viscosity; $\Omega$ - 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; $\Psi = \nabla \times v$ - expresses the vorticity in the flow; $D$ - is the diffusion coefficient (or matrix of the transport coefficient).

### Formation of dense zones in the accretion disc

The gas-dynamical analysis of the accretion flow structure in close binary star system has demonstrated tidal interaction between the inflowing mass-matter from the donor component through the point of libration L1 and the flow around the accretor [8, 11, 22]. It is shown that even a small variation in the mass transfer rate could disturb the equilibrium state of the hot accretion disc and this way the flow's structure to be fluctuated [3].

In [4] and [5], we obtained a dense formation development in the disc plane, called ”thickened zone”, appeared in the result of tidal waves and the corresponding tidal instabilities. Results of a numerical code application revealed that a damping in density fluctuations is observed for a period of time. Further, at the still active disturbances, they could increase again with such a sharp variability in the density values.

Later, the density around the flow's contact points undergoes transformations. This means that the disc's matter could be pumped out and concentrated in localized places, which tends to the density diluting in a close area.

Here, we present a thickened zone formation in a net-frame simulation, which follow the described processes (see Fig. 1). It is also depicted the density distribution in the same area.

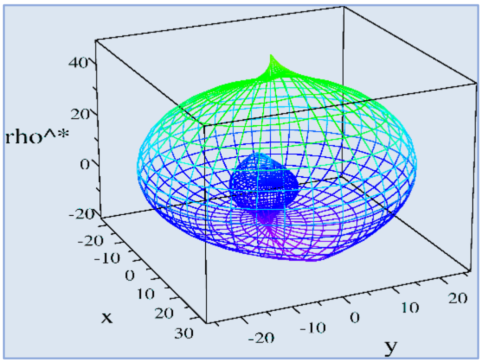

Fig. 1. A thickened zone formation, appeared in the result of tidal instabilities (the dark blue inside of the net-frame). The coordinates of the frame correspond to the density distribution $\rho_*$ $(rho^\wedge *)$ in a direction $r_*$ $(x)$ over the time $t_*$ $(y)$. Figure shows a stop-phase of one full rotational period.

### Vortical-like patterns in the accretion disc flow

In regions of the binary star configuration, where the magneto-rotational instability [1] does not operate, formations of vortices have a key role in the accretion disc dynamics, as an efficient mechanism of angular momentum transportation [2].

Vortices are mainly generated by Rossby waves instability [16, 19, 21]. We explained the process in detail in [5, 6]. It follows again the conditions for density accumulations in accretion flow. An important requirement for this instability is that the disc should be unmagnetized and differentially rotating.

Another instability, known as baroclinic [14], [15] is responsible for the vortex production, as well. In the baroclinicity conditions of (Klahr & Bodenhiemer 2003) [14], a misalignment of density and pressure gradients is required, even where there is an azimuthal density gradient. Then, a generation of vorticity in the region of the outer disc edge is possible.

The corresponding baroclinic term in the vorticity equation is the only source term: $\nabla\rho(r,\varphi) \times \nabla p(r,\varphi) \neq 0$. Here, we use it in two-dimensions, in accordance with the approximation of the thin disc.

Based on a vortical transport equation and a computational analysis, we revealed the vorticity formations [5], by series of runs that were performed. Then, stages of vortex evolutions could be able to track out: from distortion of the flow laminarity; a weak undulation of the layers in the examined box-frame; a vortex development in some ready stage of their evolution. Simulations show a vortex-like growth in $r,\varphi$ plane of the disc zone. Figure 2 shows the final 3-rd stage of the single vortex evolution, in the reduced boundary frame of computations.

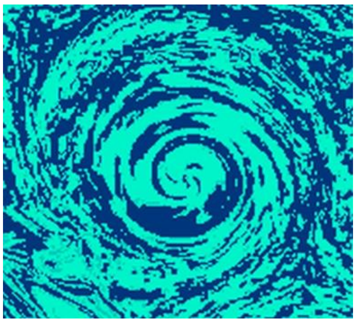

Fig. 2. A single vortical-like pattern formation in its final stage of evolution, through the performed simulations. The density increases from the light zone to the dark.

### Spiral waves development formations

The tidal waves also may cause a development of spiral waves, in local single zones or in accretion disc's configuration as a whole.

As taking into account the tidal interaction on the density variance, mentioned in the previous two subsections, we apply a numerical code (described in [5]) on the perturbed equations. Then, we observe an emerging spiral structure in the disc over ([4], figs. 3–5). In the case of a high temperature gas, an appearance of a spiral with one arm is detected. This tidal spiral wave is penetrating into inside part of the disc. When we assume an already cold disc, the possibility of a second spiral arm arises.

This means that the density in such disc places is increased, comparing to the stream matter density. In the cases, when a circumdisc halo exists, its size could decrease and then the second arm of the spiral shock wave could be formed. Here, figure 3 depicts the formation of one arm spiral wave with additional image processing that has improved the visualization of the results.

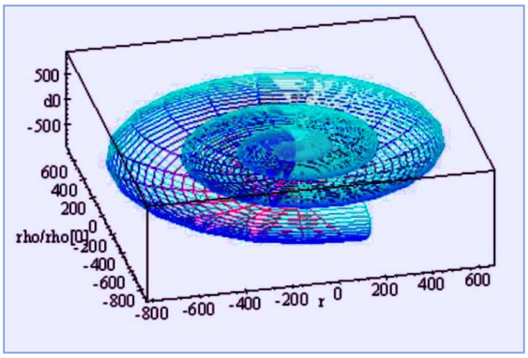

Fig. 3. One arm spiral wave development, in case of the hot accretion gas

- **Advective rings**

Advective rings are distinguished from tidal spirals by their nature and mobility. Rings retain their Keplerian nature due to its specific mechanism of moving in the disc, while spirals are logarithmic.

The advective rings are local dense formations that are formed in the inner regions of all types of accretion discs, ranging from cold to warm and hot. They keep part of the already formed radiation within themselves, because of their increased density and packet transfer along with the flow:

$$(3) \qquad \frac{\partial(\rho_e v_i)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho_e v_i v_j\right) = \rho_e\left(\frac{\partial v_i}{\partial t} + v_j \frac{\partial v_i}{\partial x_j}\right) = \rho_e \frac{D v_i}{D t},$$

where $\rho_e$ is an equatorial density; $v_i$ is the speed of the average flow; $i, j = 1,2,3$.

The operator $D/Dt$ defines the advective term as a stream with velocity $v_i$. This means that there is a displacement of the mean stream with velocity $v_i$ in some direction, preserving its character. The solution as a whole is carried over to smaller radii [31, 32]. Thus, the advective rings effectively maintain the cooling of the disc.

Vortices that are generated by an instability of the radial entropy gradient [14] may locally transport an angular momentum outwardly. They are moving in a radial plan direction and this way to transport mass throughout the disc. We suppose from our results that the movement of vortical-like formations in the final stage of their evolution could also be a transport mechanism of the angular momentum in the accretion disc configuration.

It is known that [28] a dissipation in the spiral shocks is responsible for the transport both the large quantities of angular momentum outwards and the disc materials inwards.

### Mass transfer mechanisms: available at different type of the studied binaries

Knowing the mass transfer process gives the possibility to better understand the resulting properties of the interacting area between the mass inflow from the donor star and the compact star's accretion zone [27]. We have confirmed that in the previous section.

Hydrodynamical approximations show that disturbances both in the density and in velocity are in a close relation with changes in the mass transfer rate. A stable binary star system requires the mass transfer to be stable too, which depends on the internal structure of the donor star, binary mass ratio, and the angular momentum transport mechanisms [13, 20].

Recently, two ways of the matter transfers between the binary stars' components are known. When one of the components in the binary starts to blow up, it fills its Roche lobe, then the matter starts to overflow through the Lagrange point L1 [10]. In some binary stars, usually in Symbiotic binaries, the donor component could throw out much of its material in a form of stellar wind, later attracted by the gravitational field of the accretor component. Both mechanisms are mostly applicable to the Cataclysmic variable (CV) stars.

By analyses of adopted astrophysical objects' parameters and observational data, we obtained for which of them the results of our study are relevant. As an example here, the AM CVn binary star CR Boo (Bootis) has a stable mass transfer of a first type, with a rate of $\dot{M}_2 = 1.41(\pm 0.5) \times 10^{-9} M_\odot\ y^{-1}$

[8]. Other object, the CV Dwarf novae (DN) star SS Syg (Sygnus), has a higher value of the mass-transfer rate. Its mechanism is of first type, through the L1 again. On the other hand, SY Cnc (Cancer) is a DN of a Z Cam - type object, where the changes in the mass-transfer through L1, with a relatively high rate, are of a big importance for the system activity [29], which could behave like U Gem or NL stars. In contrast, the symbiotic binary NQ Gem (Gemini) produces an average disc accretion efficiency in comparison to other three objects. The mass transfer is released via the stellar wind [7].

In these objects, there is a high possibility of development of patterns in the flow. A hot spot (at CR Boo) or a hot line (at SS Syg) could appear at the contact point between the incoming stream from the secondary component and the accretion disc's flow. A development of spiral density structure in SS Syg is of strong evidence. Some wave formations are rather seen in the CR Boo's outer's disc parts.

## Conclusion

The Cataclysmic variable stars are among the objects in which accretion occurs and the results in the above sections are mostly compatible with them. Accretion disc is the most efficient mechanism for extracting gravitational potential energy and turning it into luminosity.

Structures and dynamics of the disc's flow create the disc morphology. This includes pattern formation in the disc's flow, an appearance of turbulence, vortices and spiral-like structures.

We presented some gas-dynamical processes, such as instabilities in the accretion disc flow that are the main source of such patterns development. We proposed the tidal, Rosby and baroclinic instabilities to be responsible for their generation. The mass-transfer between the components is an essential part of the binary stars' evolution. The transfer mechanisms for selected objects are suggested. We also obtained what type of flow's formations is possible to appear in these objects.

All of these structures and formations are of a highly important part of the accretion disc mechanisms. By studying them we uncover how exactly the accretion process in binary stars occurs.

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