Spiral and vortical formations in accretion close binary stars due to the tidal waves

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Abstract. The research of this survey is related to the formation of structures as a resulting effect of tidal interaction in close binary systems. As the tidal effects are taken into account, the thicken zone in the contact area of two flows is revealed. By applying of numerical methods, it is obtained the solutions, which show the appearance and development of spiral structure. Such spiral formation could be considered as a consequent of processes, caused from tidal waves. Depending on conditions in accretion flow, especially temperature, the spirals arise with one arm or with two arms. Considerations are performed, by applying a 2D numerical code on the perturbed values of the flow parameters. Thereafter another effect or structure appears in close binaries flow - a vortical configuration or simply - vortices.
Key words: accretion disc, Stars: binaries, shock waves;

Спирални и вихрови образувания предизвикани от приливните вълни в тесни двойни звезди

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Изследването в настоящия труд е свързано с образуването на структури, като резултат от приливното взаимодействие в тясно двойната система. Разкрито е образуването на зона на сгъстяване в областта на контакт между двете течения, като е отчетен приливния ефект. Чрез прилагането на числени методи, са получени решения, които показват появяването и развитието на спирална структура. Това спирално образувание е продължение на процесите, причинени от приливните вълни. Получено е, че в зависимост от условията в акреционното течение, по-специално температурата, спиралите се образуват с един ръкав или с два ръкава. След извършените пресмятания, чрез прилагането на двумерен числен код върху пертурбираните стойности на параметрите на течението, се появява и друг ефект - вихрова конфигурация или вихър.

1. Introduction

More than half of the stars are dynamically bounded by the companion. Binary stars are natural place, where the accretion has an important role. Although, more of them have a period, mass transfer could realize trough different circumstances. The mass transfer and the resulting accretion flow determine evolution continuance of the binaries and their stellar components (Boyarchuk et al. 2002).

At the present time a still more narrow definition is recognized, that close binaries are double stars, which in the course of their evolution experienced at least one stage of intensive mass transfer, i.e. the semidetached phase of evolution (Ritter 1996). For more close pairs, for example, such as those where one or both components fill their Roche lobes, the mutual effect cannot be neglected. The study of the flow structure is of great importance, and the results can be used both for consideration of the evolution status of binary stars and for the interpretation of observational data. Therefore, when investigating the evolution of the components of binaries, it is necessary to take into account many more physical processes and, in particular, the response of inner layers of the star to its mass loss.

The presence of a gravity-connected companion of the star can affect the physical processes in the star and appreciably change its evolution. Studying of accretion disc's structure in binary stars by using numerical methods proves that the gravitational effect of the second component may cause an appearing of spirals shocks. These effects are richest when the binary is eccentric and the component stars are rotating asynchronously with respect to the orbital motion. The tidal force is then time-dependent and the tides are known as dynamic tides. Due to viscous and dissipative effects, the tidal distortion lags behind the position of the companion, creating a torque which tends to circularize the orbit and synchronize the components. Steeghs in (Steeghs et al. 1997) use hydrodynamical simulations to calculate the properties of thin accretion disc trough the sense of tidal density waves. One hydrodynamical phenomena was brought into attention by Sawada, Matsuda and Hachisu (Sawada et al. 1986). When they performed 2D simulations of mass transfer via Roche lobe overflow, a strong two armed spiral structure developed in these disc simulations. Their research has followed by a number of groups, as Rozyczka & Spruit (1993), which found such prominent spiral arms to develop in 2D disc simulations, for various mass ratios. During the stage of spirals development, it is observe the appearing of vortices, following the interaction event. Such vortical formations are studied mostly numerically, which is seen in papers of Shen et al. (2006), (Lithwick 2009), (Godon & Livio 1999). Johnson and Gammie (Johnson & Gammie, 2005) says that the vortices are long-lived, but he supposed they could not be survived in 3D calculations. This key answer is still unresolved completely.

In the current survey, effects that are the results of tidal interaction between the close binary components are present. This tidal influence is acting along with disturbances in the flow. In the next few sections, it is presented the results of applied numerical methods on the gas dynamical expressions of the processes in the interacting flows. It is obtained variations in the density of such flow and in the neighborhood around of the disc, which is followed by the structures formation, such as spiral waves and vortices. In the following two sections these effects are presented, separately.

2. Density distribution and spiral wave development in the accretion flow.

Analysis of the processes of heating and cooling in accretion discs matter show that for realistic parameters of accretion discs, the gas temperature of the outer parts is in the range of $10^4 \div 10^6$K. This means that in the considered binary systems, the hot accretion disc may form, as the cold too. After the analysis of the flow structure, it is observed tidal interaction between the outflowing matters from donor trough the point of libration and flow around the accretor. It is found in the work of Bisikalo et al. (2001) that even a small variation in mass transfer rate of the binary system, could disturb the equilibrium state of the hot accretion disc and this may cause a formation of area with increased density - thickening zones. We receive in this survey the similar density formation, as we use a method different of their (see Figure 1). The results of considerations show that the thicken zone could exists for a long time and it doesn't change its mean characteristics for the time of several of ten orbital periods of the system.

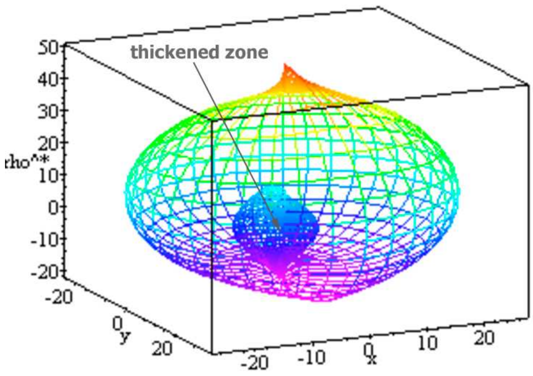

Fig. 1. Thickened zone formation, as a result of disturbances in the stability state, caused by mass transfer in the binary system.

The density variations are received by applying the Runge–Kutta numerical method. It is observed a damping of fluctuations for a period of time. Further, at the still active perturbations, they increase again and such sharp variability in the density values is in accordance with the decrease of its values, also. Thereafter, the density around of contact places undergoes significant changes. This means that the matter from disc could be pumped out or concentrated in given places, which tends to the density diluting in close area. The thickening places can be viewed graphically as density columns (see Fig.2)

The tidal shocks in astrophysics are rather a normal event than an exception. These tides may cause a development of spiral waves, locally or globally in accretion disc's area. It is well known that (Steeghs et al. 1997) angular momentum dissipation in the spiral shocks is responsible for the bulk transport of angular momentum outwards and disc materials inwards. This non-local way of transporting angular momentum is possible since the tidal torques of the companion star effectively extract the disc's angular momentum trough such tidally generated waves. Further, it is used perturbed hydrodynamical equations from (Boneva 2009) and the numerical method is applied over the variations of matter density and flow velocity. The disc temperatures are chosen to correspond the conditions of Cataclysmic variables accretion discs in a high mass transfer state. Consequently, alleging perturbations terms and relevant events in the velocity and density, we must understand the flow behavior to the formation of what structure leads.

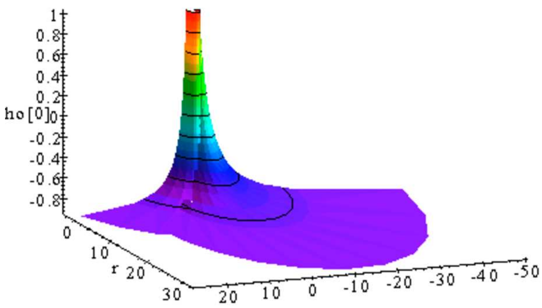

Fig. 2. A density column. This is a graphical expression of the matter concentration in close area.

Applying the same numerical code, as taking into account the tidal interaction on the density variance, we are observing the following picture, shown in Fig. 3, 4, 5 - the emerging spiral structure in the disc over. The contact moment between the two flows of accretion matter is shown in Fig.3.

In the case of a high temperature gas, it is seen the appearing of a spiral with one arm - Fig.4. We have to mention, also, that in the current case, the tidal spiral wave is deeply penetrating into inside part of the disc. On the assumption that the disc is already cold, there is the emergence of a second spiral arm - Fig.5, which means an increased density in the disc, comparing with density of the stream matter. The size of circumdisc halo is decreased and in such way the second arm of spiral shock wave is formed. In the same time, the two arms are located in the outer parts of the disc and they haven't approach to the accretor.

3. Vortical structures formation.

According to the spiral wave theory, the existence of one arm spiral waves in the disc could be accompanied by anticyclonic vortices, how it could be seen in (Fridman 2007). It is a well known fact of their vital meaning role in accretion disc dynamic. The vortices are considered as a strong mechanism of angular momentum transport (Barranco & Marcus 2005). Here we give one purely hydrodynamic study and result of such vorticity formation.

The equations, which describe such vortex formation, are in a connection with the next form of Navier-Stokes equations, given in (Thorn 2004):

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

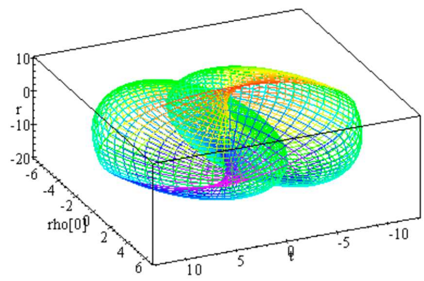

Fig. 3. Spiral's formations in the disc flow area. First is the process of contact between the flow around of the accretor and the donor.

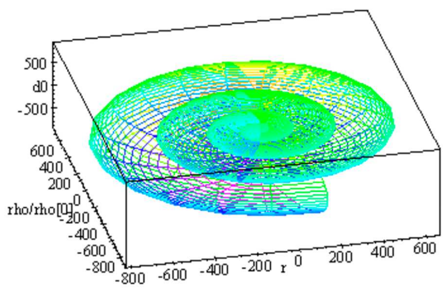

Fig. 4. Development of one spiral arm, when the gas is hot

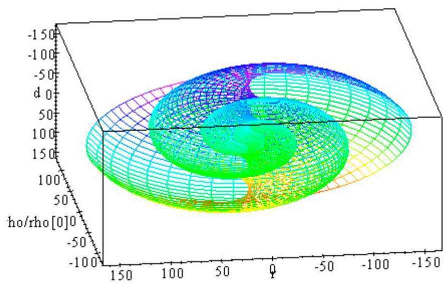

Fig. 5. Cold disc flow and two-arms spiral structure.

If we take the curl of Navier-Stokes equations, then we have the next expression:

$$\left(\frac{\partial \Psi}{\partial t} + v.\nabla\right)\frac{1}{\rho} = \frac{\nabla\rho \times \nabla P}{\rho^3} \tag{2}$$

The term $\Psi = \nabla \times v$ expresses the vorticity in the flow.Thereafter, we assume that the right-hand side of this equation to be different of zero, in contrast to the common case in the paper of Nauta (2000), where the expression of vortical equation is equal to zero . In such way the vorticity can be generated by the non-alignment of $\nabla\rho$ with∇P,which is the condition related to baroclinicity in the gas dynamical flow and it had been suggested by Klahr and Bodenheimer (2003).

Further, we have analyzed the interaction of tidal wave with forming accretion flow. As a result of this interaction, the flow goes through some level of perturbations, which brings in flow variations in velocity and density. These perturbed quantities are expressed as follows:

$$\begin{aligned} \rho^{'} &= \rho + \delta\rho\,(r,\varphi,t) \\ P^{'} &= P + \delta P\,(r,\varphi,t) \\ v^{'} &= v + \delta v\,(r,\varphi,t) \end{aligned} \tag{3}$$

Then replaced them into the Navier-Stokes equations, we obtain the next system:

$$\begin{aligned} &\tfrac{\partial\rho^{'}}{\partial t} + v.\nabla + \rho^{'}\nabla.v^{'} = 0 \\ &\tfrac{\partial v^{'}}{\partial t} + v.\nabla = -\tfrac{1}{\rho^{'}}\nabla P^{'} - \nabla\Phi \\ &\left(\tfrac{\partial}{\partial t} + v.\nabla\right)\left(\tfrac{P^{'}}{\rho^{'\gamma}}\right) = 0 \end{aligned} \tag{4}$$

In the last of the above equations the relation $P^{'}\big/\rho^{'\gamma}$ expresses the entropy of the disc flow, which radial variation refers to the existence of vortices. However, if this equation is working in current conservative form, then the vortices cannot start to form. Instead of this, we suppose to include in the system vorticity equation with the perturbed quantities from eq (3):

$$\left(\frac{\partial \Psi}{\partial t} + v.\nabla\right)\frac{1}{\rho^{'}} = \frac{\nabla\rho^{'} \times \nabla P^{'}}{\rho^3} \tag{5}$$

Then we have performed series of runs applying 2D numerical code, with zero initial vorticity, but with initial present of turbulization value different from zero. As a result, we present the simulation of vortex kind of pattern growth in r, φ plane of the disc zone The pictures' frames are visualizing an isolated vortex, which is part of a covered range of about $7.687 \times 10^{-6} AU$ to $6.68 \times 10^{-5} AU$. We confine to the stage of the vortex evolution in some steady period of their development, when they are "ready" for the angular momentum transportation (Fig. 6, 7, 8). It is consecutively shown at the figure the stages of image processing. Figure 6 – contour profile of vortex, received as a result of initial numerical simulations on the parameters of the tidal flow; Figure 7 – view of such vortex after applying the method: convolution: high pass Gaussian. Figure 8 – final model is obtained by detachment and neglecting "dirty" data from the image map, because of the necessity to resolve the result of simulations. Such vortices may propagate throughout the disc, according to the baroclinicity global character, but they are local, temporal formations.

Fig. 6. A single vortical formation. Contour profile of vortex, received as a result of initial numerical simulations on the parameters of the tidal flow.

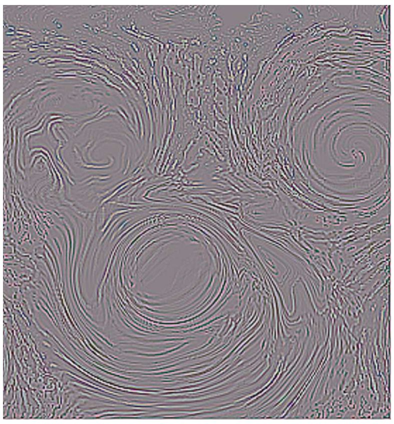

Fig. 7. A single vortical formation. View of the vortex after applying convolution with high pass Gaussian.

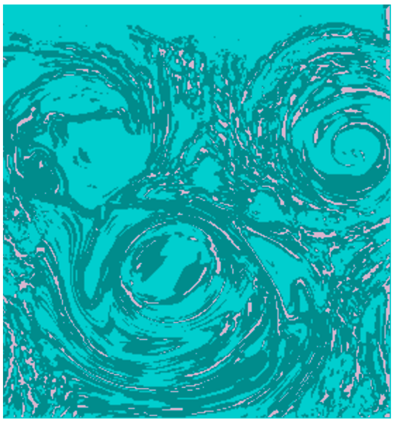

Fig. 8. A single vortical formation. Final view, after neglecting "dirty" data from the image map.

How long these vortices will live and what would be destroyed them is another unanswered questions and undecided problems. Our thought is that two-dimensional simulations have served to identify physical processes that will likely play a role in a fully three-dimensional simulation. If vortices primarily form on the upper and lower surfaces of discs, then the radiative cooling rates can be more rapid than if the vortices were buried in the optically thick midplane of the disc. It could be expected therefore that vortices confined to the surface of a disc could have longer lifetimes due to their ability to transport heat radially outwards.

Conclusion

This survey concerns the behavior of the flow in the interaction area of tidal flux with accretion disc area. Applying numerical codes on gas-dynamical equations, we have studied the processes and resulting effects, during the mass transfer between the components of binary stars and corresponding tidal waves. We may summarize our results in this paper shortly, as follows:

• It is observed variations in flow density, which is expressed as accumulation the matter in some places and dilutions in others. This situation tends to appearance of "thicken zone" that have stayed stable on consequently influence of mass transfer and dissipation processes.

• The tidal wave from donor star has caused a development of density spiral wave. Depending on the temperature of the flow it is formed a spiral wave with one arm – when the disc is high temperature, and with two arms – in conditions of cold gas flow.

• In the studied interaction parts of binary star flow, the incoming speed of flux is close to the sound value. Then, this tide may cause some perturbations in quantities, which rule the dynamics of the gas flow. After applying a 2D numerical code the result shows the presence of configurations of two-dimensional vortical structures. One of the base and common conclusion in this study is the particular evidence of the suggestion that under the influence of tidal wave, the accretion flow couldn't remain stable and the conditions of structure formation are arised. In such a way the transportation of angular moment is supported via the movement of spirals and vortices throughout the accretion stream.

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