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WAVE DENSITY CONFIGURATION VIA THE VORTICITY PATTERNS FORMATION IN ACCRETING BINARY STARS SYSTEMS

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Abstract. We present our theoretical investigations on the local behavior of vorticity formations in accreting flow of binary stars. The vortices are considered as non-single patterns that are moving along with the flow, interacting with the matter there – maintained by gas - dynamical laws. The vortex - flow density relation factor is suggested. Then we study of how much its values are relative to the stability of the vortices themselves and to the entire accretion disc structure.

Further dynamics of the disc matter could result in the situation when a single vortex meets other vortical formations. According to the physical conditions and parameters, these vortices could merge, forming a new bigger and thick composition. In the second case, they could stay as individual vortices, which are held in a cluster and moving as a whole wave configuration.

1. INTRODUCTION

In binary stars with accretion disc, vortices may arise in conditions of tidally interacting flows – which is a common process in this type of stars. After they have appeared, the vortices could propagate globally throughout the disc.

Why we study vortices? As a result of some disc instability, they are responsible for the angular momentum transportation. A configuration of vortices in the regions with accreting flow is one of the most considered mechanisms as efficient angular momentum transportation (Barranco & Marcus 2005) in regions where the magneto-rotational instability (Balbus & Hawle 1998) does not operate. Further they could be considered as sources of brightness variability of the object.

At present, there are many studies in finding the way of vortices appear and behave in the flow. Considering the radial disc structure in a thin disc approximation, it can be followed out by the development of dynamic instability Lovelace et al. (1999). Such instability is the result of the extremum ratio between vortices and surface density Lin (2012). After a series of calculation, vortex formation in weakly self-gravitating discs could be associated with the gap edge.

Li et al. (2000, 2001) have shown that vortices are formed by Rossby waves instability, moving radially and thus transport mass through the disc. This instability, as a source of vortices in the disc, has also been investigated by Meheut (2010). It is usually proceeds in areas with variations in the density values and density accumulation. Vortices can also be generated by a globally unstable radial entropy gradient. The baroclinic instability (Klahr & Bodenheimer 2003, Petersen et al. 2007) has a major role in two-dimensional vorticity formation. We show this in detail in the next section. In our previous papers we obtained a 2D view of the vortex formation (Boneva & Filipov 2012) in the accretion zone flow and their 3D analogue of vortical-like patterns distribution (Boneva 2013).

The research in the current paper is made for close binary stars with tidally interacting flows. We consider the accretion disc flow with already established vortex configuration on the radial direction.

2. VORTEX CONCEPTS: CONDITIONS, MODELS

At a first step, the conditions required for vortex formation and longevity have to be pointed out. Several such models have been introduced in the literature in the last decade. We will show just few of them, which are most related to our study. Bracco et al. (1999) found that if the initial energy of the disturbance is less than about 10^{-3} of the energy in the Keplerian flow, the vorticity fluctuations shear away and the disc returns to its unperturbed velocity profile. In that mean, when we have $E_{init} > 10^{-3} E_{Kepl}$ - for larger initial energies, anticyclonic vortices form and merge, while cyclonic vortices shear out.

If we consider two-dimensional (2D) models of the disc flow structure, one basic source of vorticity, even the only one at some cases - is baroclinicity (Klahr & Bodenheimer 2003). It appears as a term - $\nabla p \times \nabla \rho$ - in the vorticity equation, and is derived by taking the curl of the pressure gradient in the Navier-Stokes equation, where p is the pressure and ρ is the density. The baroclinic term is a source of vorticity in the vorticity equation. The baroclinic term is nonzero when pressure and density gradients are not aligned: $\nabla \rho \times \nabla p \neq 0$. Then, the vortices could be formed.

According to the paper of Petersen et al. (2007), vortex strength increases with the existence and variations of several factors. These are: increasing of the background temperature gradients; warmer background temperatures; larger initial temperature perturbations; and higher resolution.

Godon & Livio (1999) studied vortex longevity with a compressible Navier-Stokes pseudospectral model. It is shown there that the vortex life-time, as measured by the maximum vorticity, is highly dependent on the Reynolds number.

In our current calculations and in the simulations presented here, we imply the conditions, as follows: vortices form when the background temperatures are

$\approx 200K$ and vary radially as $r^{-0.25}$ (r - the relative radius); the initial vorticity perturbations are zero; the initial temperature perturbations are ~5% of the background. When there is a radial variation of the background temperature $T \sim 1/r^n$. We assume that: at $\sim Re = 10^3 \div 10^4$ the maximum vorticity is exponentially growing and decaying in time for about 50 orbital periods (Petersen et al. 2007).

3. VORTEX DYNAMIC: RESULTS

Vortices are not isolated patterns and we consider them as a part of the whole disc structure. The properties of two types of interactions are presented in the next two subsections.

3.1. Vortex – matter interaction

In this first case, we consider vortices as they are moving along with the flow and interacting with the surrounding matter.

Given that we have the vorticity formation with some density ρ_{vort} and radius R_{vort} , which is interacting with the disc flow matter, while moving through it with a variable velocity v_{vort} . The disc matter has a different density ρ_{disc}(which is equivalent to the disc's surface density) and radius R_{disc} . Since the vortex is not an isolated formation and it is moving among the fluid matter, we can write the relative terms for the density, radius and velocity: $\rho_r \approx \dfrac{\rho_{disc}}{\rho_{vort}}$; $r_r \approx \dfrac{R_{disc}}{R_{vort}}$; $v_r \approx \dfrac{v_{flow}}{v_{vort}}$.

The vortex - flow density relation ρ_r is called "density factor" by Bisikalo et al. (2001). This factor could be responsible for the stability of both: the vortex, as a formation and for the entire accretion disc structure. The results here are intermediate and give some average values.

In our calculations for the average density of the flow, we have: $\rho_{fl} \approx 0.02 \div 0.035 \rho(L_1)$. L_1 is the first (or inner) Lagrangian point. The contrast between the densities of the vortex and the disc could reach the average value of ~ ***1.8*** (see Figure 1).

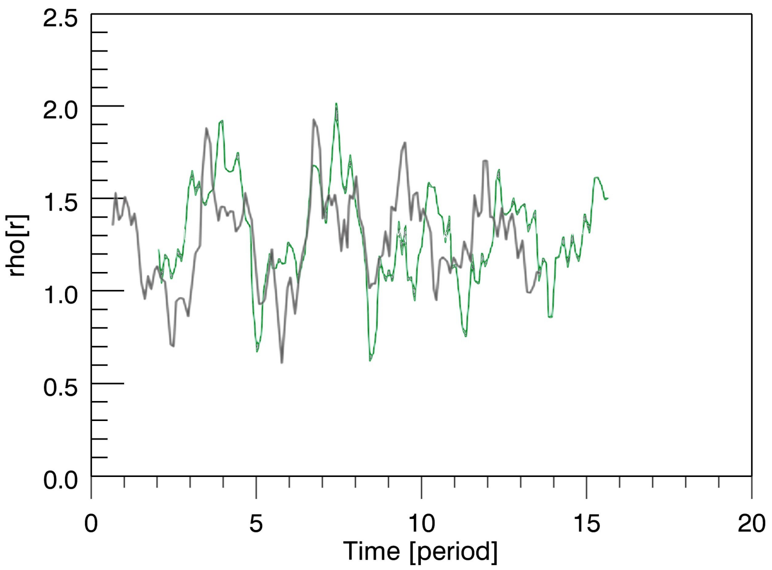

Figure 1: Variations of the density relative term or the "density factor" ρ_r v/s period of rotation. The green and black colors refer to two consecutive stages of calculations.

Following the data, presented at Figure 1, we give the next conditions, related to the values of the "density factor" ρ_r : a) When $\rho_r \approx 1$, we have stable flow and decaying vortices; b) in the case - $1 < \rho_r < 1.8$ - vortices exist in a stable configuration; c) when $\rho_r < 1$ - unstable configuration.

The density factor is not the unique parameter that could define the whole vortices - matter behavior in the disc structure. The physics of matter interaction is complicated and it requires implication of the gas-dynamical laws, deeper analytical and numerical analysis, which were a subject of other paper (Boneva & Filipov 2012).

3.2. Vortex to vortex impacts

In this section, we present one possible way of the vortices interaction activity and environment. The processing of the accretion flow highly influence on the vortex moving conditions.

The matter flux on the radial direction changes in dependence on the velocity v_r and density ρ_r of the moving formation: $\rho_r v_r \sim F_{flux}$ This means that if the density of vortex - like formation grows up, then the flux of matter increases as well. This moving and the growing-up density is in a relation with the accretion dynamic and the accretion rate. Following the denotations of the parameters in section 3.1, the expression for the accretion rate takes the form: $\dot{M} = -2\pi R_{co} v_r \rho_r$, where $\dot{M}$ is the accretion rate; v_r is the radial component of the relative velocity; R_{co} - the distance from the central object. The average value of $\dot{M}$ in close binary stars is: $\dot{M} \approx 10^{-10} \div 10^{-6} M_{o} yr^{-1}$.

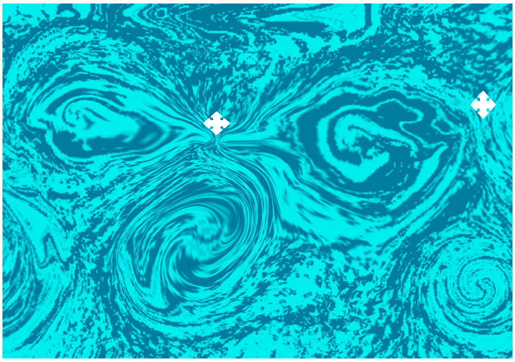

Figure 2: Visualization of the initial step of the vortex – vortex merger process. The contact points are marked with white crosses.

The increasing velocity gives rise to the vortex displacement along to the accretion disc. Than the vortices could contact each other (Figure 2) and their further interaction may lead to the merger of two, three or more vortices in one bigger and ticker vortical formation. Figure 2 gives an illustration of the first contact between the individual ones.

In the case, when the above parameters ($Fflux$, v_r) take lower values, each vortex could stay as a single formation. At some point of time, vortices are attracted to hold each other in a group pattern formation, and influenced by the entire accretion disc flux. Most likely it is affected by the differential rotation and self-gravity in the disc, which are not high enough to induce the merger of the vortices.

Initially, the vortices are formed somewhere locally in the accretion disc flow, they could move as a whole wave pattern throughout the disc on the r, φ direction. Then, the configuration could be transformed to the view, shown at Figure 3.

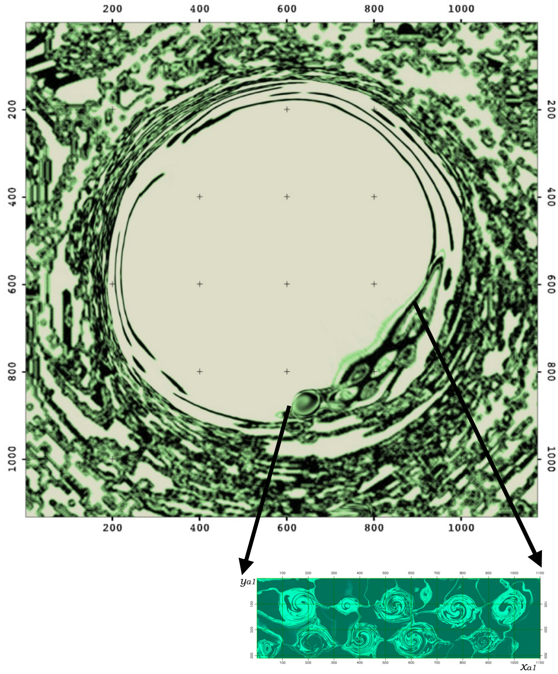

Figure 3: Development of small vortex formations along to the inner part of the accretion disc (Boneva 2017). The simulation presents the possible location of the group pattern, as a snapshot during the image processing. The arrows point the zoomed view of the vortical wave pattern in the calculation frame.

The grids of the Figures 3 correspond to the calculation frame scheme. Their sizes are not related to the boundary conditions, used in the model. The picture is not fully cleared by the side effects and errors, coming from the image processing.

The results in this section are parametric only. Further simulations would involve more data and extend the investigations of this study.

4. CONCLUSIONS

We presented some possible conditions responsible for the development of vortex – like formations, locally in the accretion disc flow, considered for the binary stars systems.

Vortices can be generated by two-dimensional instability as the Rossby wave instability or baroclinic instability, which have been investigated in recent years. In depend on the dominant activity both of the suggested in this paper generation engines and the operating parameters, vorticity could appear as single structures or in a group of several vortices.

In the cases, when the vortices are developed not as a single structure, they could be considered as a chain with tied to each other vortex formations. Further they can evolve as they start merge and form a larger vortex-like or other density structure. Or they could continue their movement throughout the whole disc until their decaying phase ends.

Vortices are initially modeling as local formations, but further under the appropriate physical conditions, they could propagate globally throughout the disc. It is expected for the later calculations that at the higher Reynolds number e-folding time would be at larger orbital periods: >50.

Acknowledgments

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