Active states and structure transformations in accreting white dwarfs

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Abstract. Active states in white dwarfs are usually associated with light curve's effects that concern to the bursts, flickering or flare-up occurrences. It is common that a gas-dynamics source exists for each of these processes there. We consider the white dwarf binary stars with accretion disc around the primary. We suggest a flow transformation modeling of the mechanisms that are responsible for ability to cause some flow instability and bring the white dwarfs system to the outburst's development. The processes that cause the accretion rate to sufficiently increase are discussed. Then the transition from a quiescent to an active state is realized. We analyze a quasi-periodic variability in the luminosity of white dwarf binary stars systems. The results are supported with an observational data.
Key words: Accretion, accretion disks; (Stars): binaries: close; Hydrodynamics Waves

Introduction

In the great diversity of binary stars, variations in brightness that could appear in a stochastic way on timescales of a few minutes with amplitude of a few 0.1 magnitudes are observed. This variability is called flickering and has been detected in the three main types of binaries that contain white dwarfs accreting material from a companion mass-donor star: cataclysmic variables (CVs), supersoft X-ray binaries, and symbiotic stars (Sokoloski 2003). Warner (1995) and Babtista & Bortoletto (2004) describe flickering in CVs as continuous, random brightness fluctuations of 0.01 to 1 mag on timescales from seconds to dozens of minutes. Bisikalo in (Bisikalo et al. 2003) has detected significant brightness oscillations in CVs with aperiodic nature in part of them. This part is characterized by a small magnitude and short a timescale. On the other hand they have found that light curves in CVs demonstrate periodic or quasi-periodic photometric modulations with a typical period of $\approx 0.1..0.2$ Porb. The way the flickerings appear has been studied initially by Bruch (1992). He has proposed possible mechanisms responsible for the observed variations in brightness. In his later paper (Bruch 2000) Brush suggests that the flickering in CVs are located in the stream-disk interaction place or in the inner part of the accretion disc. Patterson (1981) also found the association of flickerings with the inner disc's part. Wynn et al. (1997) suggest a blob model as an ejection mechanism in AE Aqr. Their interpretation of the results shows that the rapidly rotating white dwarf in AE Aqr ejects most of the matter from the secondary. The model of flickerings developed by Dobrotka et al. (2010) is based on the angular momentum transportation in discs through the turbulent mechanism, which has been earlier introduced by Shakura & Sunyaev (1973). Zamanov et al. (2010) investigate the flickering variability of RS Ophiuchi in the UBV RI bands and discuss its possible origin. They have studied flickering's engines and found the relation mainly to the accretion process, such as: bright spot, boundary layer and inside the accretion disc. The analytical study has been performed by Pearson et al (2005) for the spectrum of flickering and flares. They have paid attention to the fact that the terms "flickering" and "flares" has been usually interchanged. For this reason they accepted the term "flickering" for the events of the small amplitude, continuous variations and the term "flaring" for larger scale events. It is common for all these studies that the flow fluctuations are coming to be in the base of those described processes. Recently, it is widely accepted that the high-frequency or small-scale fluctuations could arise as a result of instability in the accreting flow and a gas-dynamics source exists for each of these processes. The idea was proposed by Osaki (1989), who has investigated the superoutbursts of the SU UMa systems and suggested that tidal instabilities give rise to them. Hameury and Lasota (2014) have turned down the possibilities that the tidal instabilities are the reason of the light anomalies. They found that the Z Cam behaviour is reproduced by assuming the time profile of the mass transfer rate from the secondary. The investigation shows the instabilities cannot be explained by the methods of linear analysis. Otherwise, when a non-ideal disc parameters are implemented in the calculations (see: Kurbatov et al.(2014)), the instabilities can develop in the disc.

We follow the necessity to find a mechanism able to sufficiently increase the accretion rate on a time scale typical to the duration of flare-ups development. In the current survey, we present our suggestion of mechanisms and processes that could cause the flickering and flares to arise. We investigate the development of small-scale vortical formations that can cause accretion rate to increase and this way flickerings to be produced.

1. Theoretical considerations and computational approach

1.1 Basic equations

The nature of the interaction between a flow of matter and an envelope of two star components requires employment of gas-dynamics equations. Therefore, to obtain solutions of the above stated problem a system of equations is needed. Herein, the basic equations are presented in a form that has been suggested and affirmed by many authors: (Shore 2007; Clark & Carswell 2007; Thorn 2004; Frank et al. 2002; Graham 2001; Shu 1992). We have modified the parameters partially and thereafter the equations are presented in their applicable vector form, in (Boneva & Filipov 2012) and represented in this paper, as follows:

We present the equations in their vector form. The equation of mass conservation is:

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

The existence of viscous processes in the accretion flow, as well as influence of forces and rotation could be performed by the following Navier-Stokes equations. We suggest it in the next useful form:

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

There the basic notations are: ρ is the mass density of the flow, v - is the velocity of the flow; P is the pressure; ν is the kinematic viscosity; $\mathit{\Omega}$ is the angular velocity; $\mathit{\Omega} \times (\mathit{\Omega} \times r)$ is the centrifugal acceleration of the centrifugal force; and $2\mathit{\Omega} \times v$ - is the Coriolis acceleration in the mean of the Coriolis force. $\mathit{\Phi}$ is the Roche potential (Boyarchuk et al. 2002). In the current analysis $\rho \neq const$ and $\nu \neq 0$.

The energy balance equation for a viscous non-ideal fluid is:

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

where $\frac{\partial}{\partial t}\left[\rho\left(\frac{1}{2}v^2 + \varepsilon + \mathit{\Phi}\right)\right]$ 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. And $\left[\rho v\left(\frac{1}{2}v^2 + h + \mathit{\Phi}\right)\right]$ 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 the shear.

The equation of state for compressible flow is:

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

where c_s is the sound speed. We present the equations in the above system in their common form and we can easily transform them into quantities for each of the posted problems.

1.2 Modeling and methods

We establish a part of disc's configuration around the primary (white dwarf) star after the mass transfer started. In this case of the close components, it is necessary to include physical essence of the flow dynamics that reply to the interaction processes. Further, to examine the active states we use as a base the model of outburst in SS Cyg, presented in (Kononov et al. 2008 and Boneva et al. 2009). Here, we apply the same consequence of the proposed physical model of the bursts appearance. We modify the stage of instability processes in the disc flow adding different types of instability behavior. We suggest the next sequence of processes for the development of an outburst. At some time, an instability and the resulting flow fluctuations develop in the disc, leading to a considerable increase in the efficiency of angular momentum transport and an increase in the rate at which matter is accreted onto the white dwarf. The growing intensity of the radiation from the white dwarf inevitably results in heating of the nearest parts of the accretion disc, and hence to an increase of the thickness of inner parts of the disc. The gas between the toroidal shell and the accretor experiences strong heating that leads to its expansion. However, the expansion cannot be isotropic, since it is restricted in the equatorial plane by the accretor surface and the inner surface of the toroidal shell, whereas expansion orthogonal to the disc's surface is impeded only by the accretor's gravitational field. The increased velocity of the heated gas will probably be comparable to the local sound speed, which is insufficient to form a collimated jet. The expanding gas can have a low angular velocity, and is prevented from falling on the star primarily by the gas-pressure gradient rather than by the centrifugal force. This enables the gas to leave the toroidal shell and form an expanding spherical shell around the accretor. The increased size of this shell can explain the stronger emission during the development of the outburst.

Modeling the processes of the studied gas-dynamical problem requires numerical analysis of the corresponding equations listed above. We chose to insert into calculations the methods, which are employed in these codes, known as: the Runge-Kutta (implicit part) method (further referred to as RK), Alternating direction implicit method (ADI), CenteredTime1Space (CTS)[forward or backward], BackwardTime1Space (BTS)[forward/backward], based on finite difference scheme or Godunov's algorithm. More detail description for RK and ADI methods could be found in (Autar & Egwu 2008; Chang et al. 1991). All they are implicit methods, which are general in their application. It is suitable to use them in the solutions of partial differential equations, because of their high stability. The detail explanation is given again in (Boneva & Filipov 2012). We give here a short description of their operation. The method of Runge-Kutta is common for physical calculations. Since this method "treats every step in a sequence of steps in identical manner" it is easy to apply RK's method schemes into the system of equations posted above (Forsythe et al. 1977) (Cash & Karp 1990).

ADI method belongs to the group of finite difference methods and its function is to split the finite difference equations in two, in relation to the derivatives in coordinates taken implicitly. The system of equations then becomes symmetric and is usually solved with tridiagonal matrix solver. It is then convenient to reduce the equations to a simpler problem by applying the calculation tools, as they are part of the code structure. The numerical codes need some control during the processing. "Adaptive step-size control" is used here (Cash & Karp 1990; Hairer & Soderling 2005), with the reason of performing some prearranged corrections in the solution with minimum computational resources. Implementation of adaptive step-size control requires that the algorithm by steps returns information about the calculation performance and estimation of its error. The "pdetest" checking tool, for the solution correctness is also applied. The specifying initial and boundary conditions are assigned in accordance with the presented model. We suggest a "box-framed scheme" to apply it into the modeling. Then, we make the calculations inside the box, or the frame with different measurements. This gives the possibility to configure the scheme for each problem in limited regions of all disc's areas.

2. Results on the fluctuations and flow's transformations. Their relation to the active states in white dwarf binaries

2.1 Flow density fluctuations

As a result of tidal interaction in binary stars between out-flow from the donor star and the accretion flow, the flow could be disturbed. Then, following the perturbation theory of Papaloizou & Pringle (1984), the disturbances in the flow give rise to the fluctuations in velocity and density and this way its parameters values change. We apply free boundary conditions at the outer disc edge, where the density is defined to be in a range: $\rho_{out} = 10^{-8}\rho_{L_1}$, where ρ_{L_1} is the density of the inner Lagrangian point L_1. In the inner regions, where the mass transfer and the interaction of streams take place, the values of the density, as was shown, could not remain constant. The physical essence of the flow dynamics responses to the interaction processes in the binary. The disturbed flow's conditions can provoke periodic or quasi-periodic oscillations, giving rise to the light curve variations. Since the density decreases with increasing radius, approaching to the outer edge, the observed luminosities are in a connection with the distance from the inner Lagrange point L_1 (Kaygarodov et al. 2013). In this way, the amplitude of light curve variations should be approximately corresponding to the density contrast. We have obtained the density distribution along the line of density variations throughout the disc's plane in binary components for ten runs with different orbital periods. Figure 1 shows this distribution.

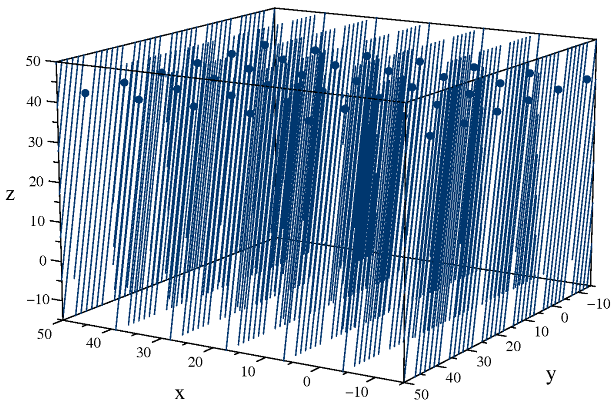


Fig. 1. Gradient of the density distribution in the field of calculation. The higher density areas are seen in the meaning of values heaping, modelled in the 3D box - framed scheme.

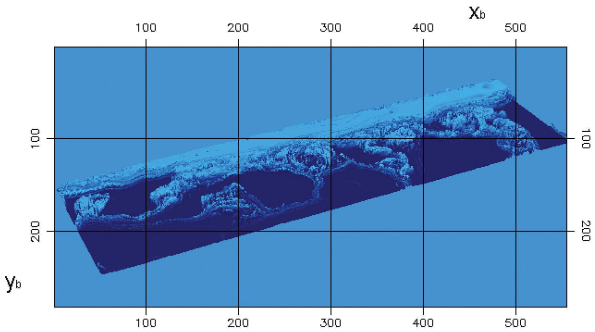
2.2 Wave-patterns formation and the disc's shape during the active states

As a consequence from the previous subsection, here we probe how the variations in the density impact on the flow structure. By applying the gas-dynamical numerical methods and following the conditions of (Klahr & Bodenheimer 2003) we have simulated the presence of two-dimensional vortical-wave patterns in the disc's flow. They are considered to be an effective mechanism of angular momentum transport (Barranco & Marcus 2005). We perform a computational analysis, previously presented in (Boneva & Filipov 2012), to track the sequence of their development in the flow by visual simulation. Our calculations are based on the vortical transport equation, because it includes the condition that could provoke baroclinic character of the flow, (Klahr & Bodenhiemer 2003). The box-frame model is used once again. The introduced boundary conditions are of Dirichlet- and Cauchy type: $r_{v(1+n)} = K(x,y) - \frac{\partial K}{\partial r_v}\frac{\partial}{\partial t}$; $r_{v0}(0) = 0$ is the radius of the vortex; $K(x,y)$ is the boundary area of equations activity. We place the cylindrical coordinates (r, φ, z) frame for the equations and quadratic (x, y) set for the numerical scheme. We perform a series of runs with zero initial vorticity, but different from zero initial turbulence values: $v(0) = v_0$, $\Psi_{r,\varphi}(t_0) = 0$, $\rho(t_0) = \rho_0 \approx 2.5 \times 10^{-6} kg/m^{-3}$, $t_0 \approx 1$, and $r_0 \approx 1$. Results of the simulations show a vortex type growth in r, φ plane of the disc zone. The box-frame values range from about $7.687 \times 10^{-7} AU$ to 6.68×10^{-7} AU and from $7.687 \times\ 10^{-8} AU$ to $6.68 \times\ 10^{-8}$ AU, corresponding to the above values of x and y, referred as x_b and y_b. We made several series of calculations. The results in stopover steps show the stages of vortices development. In contrast to the results in the papers (Boneva & Filipov 2012, Boneva & Filipov 2013), here we present only two of them, respectively in their 3D analogy view. First, a distortion of the flow laminarity is observed. In the next runs of calculations, the velocity values step to $(v(t_1, t_{n-1}) \approx v_0 + v_1)$ and the layers in the examined area undergo a weak undulation (Fig.2a). This means that the variations of velocity and density have significant impact on the flow's behavior. For the final round of calculations the density and velocity accepted values $\rho(t_n), v(t_n)$ are used as an input. Then, we consider the stage of vortex evolution in some steady period of their development, when they are "ready" for the angular momentum transport (Fig. 2b).

The development of vortices is more frequently observed along the outer sides, close to the disc's edges. According to the model above, when this kind of wave patterns leaves the disc zone, they could fall apart and come together into the matter of the curcumdisc hallo, influenced by the conditions of low density there. It follows from the results that the density of outer regions of the accretion disc drops substantially during an outburst.

Conclusion

We investigated the flow properties during flare-ups in accreting white dwarf binaries. We presented our modeling of the disc's flow morphology and its effect over the binaries' brightness variability. The interaction processes and



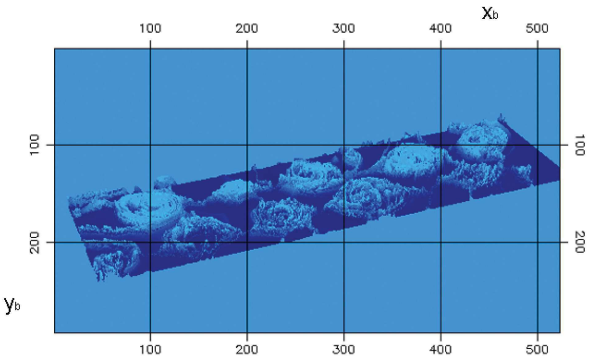


Fig. 2. 3D view of patterns formation in the disc flow. It is seen the distortion of laminarity of the layers and weakly undulations (a); the stage of vortical development in the flow (b). Each frame visualizes a covered range of the box-framed boundary conditions: $7.687 \times 10^{-8} AU$ to $6.68 \times 10^{-7} AU$ and $7.687 \times 10^{-8} AU$ to $6.68 \times 10^{-7} AU$ and $7.687 \times 10^{-15} AU$ to $6.68 \times 10^{-15} AU$, as referred to the boundary frame (x_b, y_b, z_b) of the calculation performance. The light Blue and dark Blue colours (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 light zone.

mass transfer in binary star could cause the disturbances in the flow parameters and this way the flow to be perturbed. The results of nonlinear study show that the instabilities arise as the result of this. The model is developed on the base of increasing density and local areas with growing matter saturation. Our computational analysis demonstrates that the variability of parameters of the unstable flow could provoke the development of pattern formations, such as vortical-like structures. We have analyzed the flow structures during the outbursts and we have indicated that flow's fluctuations grow up in the mass transfer area.

The casual low- or high-magnitude variations in the light curve can also be a consequence of the presence of the long-lived vortical-like patterns in the disc structure, which rise due to the tidal interaction in close binaries.

In addition to the theoretical considerations above, we suggest some observational results, which demonstrate the existence of the brightness variability in binary stars. The data of SS Syg, AE Aqr and G Cas is applied. The flickerings can be seen in the light curves of these three binaries (see figures 3,4,5).

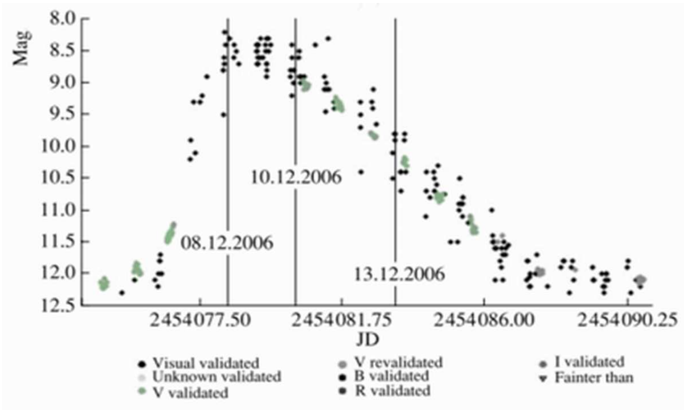


Fig. 3. Light curves of SS Cyg (CV star) during the outbursts (based on AAVSO light curve data generator). The vertical lines indicate the dates of our observational nights.

The light curves of AE Aqr show the typical flickering behavior. While for the SS Cyg, we report observations of the burst activity as seen in the light curves' shape of this CV star. For comparison, we create the light curve of γ Cas (Fig.5), which is a prototype of Be stars and is a wide binary primary star. Templeton M. in his AAVSO report (2013) gives an explanation that the γ Cas stars eruptions are possibly related to the formation and destruction of a circumstellar disc of material, and instabilities within this disk. In these two classes of binaries a different behavior of the flickering is detected. The difference could be caused by physical properties of the accreting flow, as well as by the dominating flickering mechanism or their orbital periods. Analysis of the resulting Doppler tomograms shows that the flow structure changes appreciably during the observed outburst, compared to its structure in the quiescent state (Boneva et al. 2009). The most important difference in the flow is a change in the shape of the accretion disc, from nearly circular in the quiescent state to significantly elliptical in the active state. The asymmetrical shape of the disc's projection indicates the existence of heated material in the "bow shock" area, which can be caused by the spiral density formation. Figure 6 shows the position of vorti-

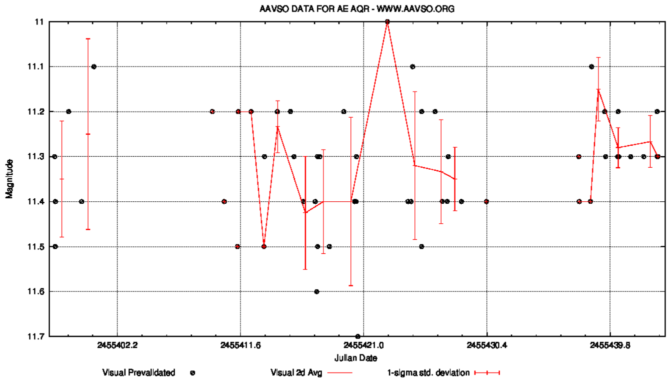


Fig. 4. AE Aqr (CV star) light curve. The AAVSO generated light curve indicates flickerings during the observational period. The white dwarf in the system ejects most of the matter transferred from the secondary in a form of fireballs (Zamanov et al. 2012)

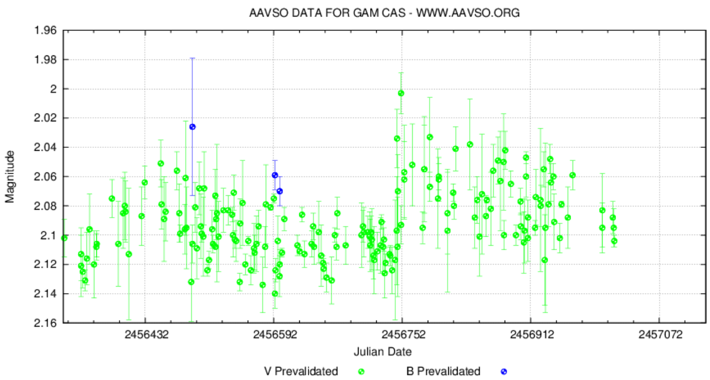


Fig. 5. Light curve of γ Cas (based on AAVSO light curve data generator). The figure shows low-magnitude flares activity.

cal patterns on the disc's plane and the superposition of the flow structure elements (Boneva 2015).

The disturbance, which is necessary for the vortex to grow, could be developed by the hot line seen in Doppler Tomogram.

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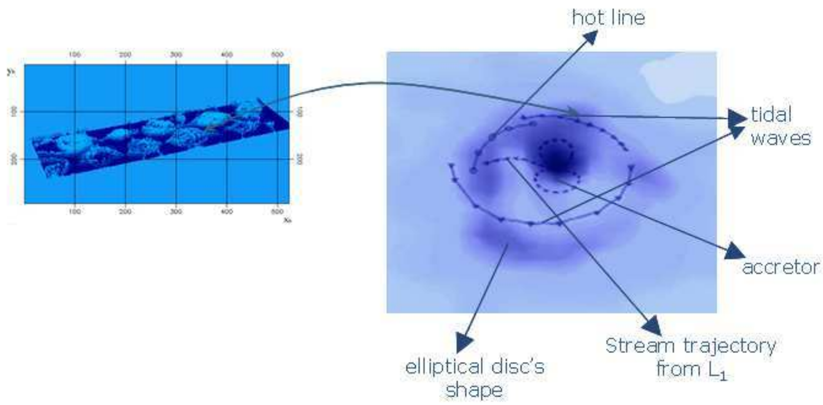

Fig. 6. Schematic view of the flow structure during the outburst. A result from the Doppler tomogram with superposed flow elements inferred from the numerical simulations.

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