On possible observational evidences of spiral shocks in accretion disks of CVs

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ABSTRACT

The results of three-dimensional numerical simulations of mass transfer in binaries with spiral shocks are presented. It is shown that the mass transfer rate variation disturbs the equilibrium state of accretion disk and results in formation of the blob. This dense formation moves on the disk with variable velocity. The results of our simulations show that the blob lives long enough and retains its main characteristics for the time of order of tens orbital periods. Analysis of the results shows that the action of dissipation is negligible on these timescales and the blob smearing out due to differential rotation of the disk is stopped by its interaction with spiral shocks.

Light curves of some CVs show periodic or quasi-periodic photometric modulations with typical width ~ \(0.1 \div 0.2\) (i.e. with period ~ \(0.1 \div 0.2P_{\text{orb}}\)). We suggest to consider the formation of the blob in binaries with spiral shocks as a possible reason for these modulations. The efficiency of this mechanism is confirmed by good qualitative (and, in part, quantitative) agreement between the results of our simulations and observations of binaries IP Peg and EX Dra.

1 Introduction

Analysis of light curves in CVs with high orbit inclination and especially eclipsing binaries permits to get information on the flow structure between the components of the system. The shape of light curves in these binaries is very sophisticated and even uneclipsed parts of light curve show significant brightness oscillations (see, e.g., Hack & La Dous 1993; Warner 1995). A part of these oscillations, the so called flickering has aperiodic nature and is characterized by small magnitude and short timescale. On the other hand, besides sporadic short-period oscillations light curves in CVs demonstrate periodic or quasi-periodic photometric modulations with typical period ~ \(0.1 \div 0.2P_{\text{orb}}\). Various models were suggested to explain these modulations of light curves: from intrinsic disk instabilities up to modulations of the rate of mass transfer from the mass-donating star (Warner 1995). Based on the results of 3D gasdynamical simulations we concluded in (Bisikalo et al. 2001, hereinafter Paper I) that if spiral shocks are presented in the accretion disk then any disturbance of the disk would result in the appearance a new dense formation in the disk – a blob, the latter moving through the disk with variable velocity. A significant density contrast between the blob and the disk (up to 1.5 times) as well as the variable velocity of the blob (but with constant period of revolution ~ \(0.1 \div 0.2P_{\text{orb}}\)) permit us to consider the
appearance of this formation as a possible reason for observable quasi-periodic oscillations on the light curves in CVs. If the emissivity of the blob is larger than that for the accretion disk (e.g., for the case of recombination radiation which is proportional to the square of density) the oscillations on the light curve can be caused by the occultation the blob by optically thick disk. And if the blob emissivity is less than that for the disk the oscillations can be caused by occultation of the disk by optically thick blob.

The main aim of this work is more detailed (as compared to Paper I) investigation of the blob formation as well as a determination of the dependence of its features on the parameters of the model. We also analyze observations of eclipsed binaries with spiral shocks (IP Peg and EX Dra) in the context of applicability of proposed mechanism for explanation of oscillations on light curves in these binaries.

## 2 Results of numerical simulations in CVs with variable mass transfer rate

In Paper I we have presented the results of 3D gasdynamical simulations of flow structure in semidetached binaries after the mass transfer termination. The investigation of the residual accretion disk shows that as early as at the time \( t = t_0 + 0.2P_{\text{orb}} \) (where \( t_0 \) is time when mass transfer has been ceased) the flow structure is changed significantly. The stream from \( L_1 \) doesn’t dominate anymore, and the shape of accretion disk changes from quasi-elliptical to circular. The second arm of tidally induced spiral shock is formed while earlier (before the termination of mass transfer) it was suppressed by the stream from \( L_1 \). The results of numerical simulations presented in Paper I show that a dense blob is formed in the residual disk, the velocity of the blob motion through the disk being variable. The blob is a dense formation which in steady-state solution coincides with a post-shock zone of the spiral shock. After mass transfer termination when the nourishment of the disk from the stream is ceased and equilibria of the disk is disturbed the blob comes off from the front of spiral shock and begins to move.

Two factors can force the blob to smear out as it moves through the accretion disk – dissipation and differential rotation of the disk. Dissipation smearing occurs in viscous timescale which can be evaluated as tens — hundreds orbital periods for \( \alpha \sim 0.01 \div 0.1 \) which is typical for CVs. We would like to stress that the viscosity timescale of smearing out of the blob gives the lower estimation of its lifetime, since this time is so large that the recurrent mass transfer rate variation and the subsequent disturbance of the disk is very probable. It means that the new disturbance of the disk due to mass transfer rate variation can occur earlier than the dissipative smearing out of the blob.

Smearing out (or mixing) of the blob due to differential rotation of the disk is virtually more important since this process occurs in dynamical timescale and one may suppose that the blob disappears during few orbital periods. Nevertheless, 3D gasdynamical calculations of Paper I show that existence of a spiral shock prevents dynamical mixing of the blob. Passing through the front of spiral shock the blob becomes denser and more compact, this effect being presented up to the moment when spiral shock disappears. The density contrast between the blob and the disk begins to decrease after the disappearing of the spiral shock as well.

We understand that the situation of complete termination of mass transfer from donor-star is rather rare, so we should consider the possibility of the blob formation when the variable parameter of the model. We also analyze observations of eclipsed binaries with spiral shocks (IP Peg and EX Dra) in the context of applicability of proposed mechanism for explanation of oscillations on light curves in these binaries.

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\[ \tau_{\nu} = \frac{R_d^2}{\nu} = \frac{R_d^2 \nu}{acH} = \frac{R_d \nu V_K}{ac^2} \approx \frac{1}{\alpha \beta^2 \Omega_K}, \]

where \( R_d \) – the radius of accretion disk; \( \nu \) – kinematic viscosity; \( c \) – sound speed; \( \alpha \) – Shakura-Sunyaev parameter; \( H \) – height scale of the disk; \( \beta = H/R_d = c/V_K \); \( \Omega_K \) and \( V_K \) – angular and linear rotational velocities of Keplerian disk. Transform the last expression to obtain

\[ \tau_{\nu} = \frac{\Omega_{\text{orb}}}{2\pi\alpha^2 \Omega_K} = \sqrt{\frac{q}{2\pi \alpha^2}} \left( \frac{R_d}{A} \right)^{3/2}, \]

where \( P_{\text{orb}} \) – orbital period; \( q \) – mass ratio (the ratio of donor-star mass to accretor mass); \( A \) – the separation of binary. In our calculations the typical values of parameters are: \( \beta \sim 0.1 \div 0.15 \) and \( R_d/A \sim 0.3 \div 0.4 \), so for \( \alpha \sim 0.1 \) we have \( \tau_{\nu} \sim 25P_{\text{orb}} \) while for \( \alpha \sim 0.01 \) we have \( \tau_{\nu} \sim 250P_{\text{orb}} \). In Paper I we have obtained the lifetimes of accretion disk for various values of \( \alpha \) which give a little bit less but comparable values of \( \tau_{\nu} \).
ation of the mass transfer rate is relatively small. In this paper we present the results of investigation of the flow structure in semidetached binary after the mass transfer becomes weaker twice and 10 times.

Note, that in the case of complete termination of mass transfer our calculations have been stopped after the disk vanishes, while in case of the reduced rate of mass transfer we have observed the flow structure went out to a new quasi-steady-state solution. In general, to reach an ultimate steady-state solution we should conduct our simulations over time interval comparable to viscous timescale of the disk. Nevertheless, we have restricted this time to few tens of orbital periods bearing in mind the typical timescale of outburst activity in CVs resulting in the formation of spiral shocks.

The full description of the 3D gasdynamical model can be found in Paper I. Here we pay attention only to the main features of the model. To describe the gas flow in the binary we used the 3D system of Euler equations for Cartesian coordinate system. To close the system of equations, we used the equation of state of ideal gas with adiabatic index \( \gamma \sim 1 \), that corresponds to the case close to the isothermal one. Other dimensionless parameters which determine the solution were adopted as follows: mass ratio is \( q = 1 \), the ratio of sound speed in \( L_1 \) to orbital velocity is \( \epsilon = c(L_1)/\Omega A \). The gas flow was simulated over a parallelepipedon \( [\frac{1}{2}A \ldots \frac{3}{2}A] \times [-\frac{1}{2}A \ldots \frac{1}{2}A] \times [0 \ldots \frac{1}{4}A] \) without a sphere with a radius of \( \frac{1}{100}A \) representing the accretor. The calculations were conducted on the grid \( 61 \times 61 \times 17 \), in terms of the \( \alpha \)-disk the numerical viscosity approximately corresponded to \( \alpha \sim 0.05 \). To obtain the numerical solution of the system of equations we used the Roe–Osher TVD scheme of a high approximation order (Roe 1986, Chakravarthy & Osher 1985). We used quasi-steady-state solution for constant rate of mass transfer as initial condition. At the moment of time \( t = t_0 \) we decreased the density of the injected matter twice (run “A”) and 10 times (run “B”).

The Figure 1 presents time variation of the mean density of matter passing through a semi-plane \( XZ \) \((Y = 0, X > A)\) slicing the disk. Along with a general density fall we can see here periodic oscillations called forth by passing the blob. The analysis of curves in Fig. 1 shows that after changing (decreasing) the mass transfer rate a dense formation – blob – arises. The period of blob revolution is \( \sim 0.15P_{orb} \) for run “A” and \( \sim 0.18P_{orb} \) for run “B”. After recurrent reaching of quasi-steady-state solution (i.e. for \( t > t_0 + 3P_{orb} \) for run “A” and \( t > t_0 + 13P_{orb} \) for run “B”) the period of the blob revolution increases and becomes \( \sim 0.16P_{orb} \) for run “A” and \( \sim 0.20P_{orb} \) for run “B”. The new quasi-steady-state solution is characterized by long-period oscillations (Fig. 1) with period \( \sim 5.1P_{orb} \) for run “A” and \( \sim 2.5P_{orb} \) for run “B”. The Figure 2 presents the Fourier analysis of curves from Fig. 1. It is seen that for run “A” dominating harmonics are \( 0.155P_{orb} \) and \( 0.165P_{orb} \) (Fig. 2a). The beating of these two gives long-period oscillations with period \( \sim 5.1P_{orb} \). For run “B” dominating harmonics are \( 0.18P_{orb} \) and \( 0.21P_{orb} \) (Fig. 2b), and their beating gives long-period oscillations with the period \( \sim 2.5P_{orb} \).

Let us consider how does the disk structure change after the rate of mass transfer decreases. The Figure 3 presents the results of run “A” and shows the density distributions over the equatorial plane for 6 moments of time \( t_0 + 0.44P_{orb}, 0.47P_{orb}, 0.49P_{orb}, 0.52P_{orb}, 0.54P_{orb}, 0.57P_{orb} \), covering the full period of the blob revolution. The maximal density in Fig. 3 corresponds to \( \rho \sim \)
These results are relevant to the transient stage when dense stream from \( L_1 \) vanishes at the moment of time \( t = t_0 \) and the flow structure is determined by the relatively dense disk while the matter of rarefied stream (with density twice less than the initial density) plays a minor role. This stage begins after the last portions of matter of the old stream come to the disk, i.e. at \( t = t_0 + 0.2P_{orb} \), and finishes when a new quasi-steady-state solution will be reached. The main features of this stage are: the dense residual disk dominates; its shape changes from quasi-elliptical to near circular; the second arm of spiral shock forms.

The Figure 4 also presents the results of run “A” and shows the density distributions over the equatorial plane for other 6 moments of time \( t_0 + 17.64P_{orb}, 17.67P_{orb}, 17.70P_{orb}, 17.73P_{orb}, 17.76P_{orb}, 17.79P_{orb} \), covering the full period of the blob revolution for the stage when the new quasi-steady-state solution is established. The maximal density in Fig. 3 corresponds to \( \rho \simeq 0.02\rho(L_1) \). The analysis of these drawings shows that obtained flow structure is similar to the solution for the case of constant rate of mass transfer (see, e.g., Bisikalo et al. 1998, 2000, Paper I). It is seen that the stream from \( L_1 \) dominates. It is also seen that the uniform morphology of the system stream–disk results in quasi-elliptical shape of the disk and the absence of ‘hot spot’ in zone of stream–disk interaction (\( X \simeq 0.8A, Y \simeq -0.1A \)). At the same time the interaction of the gas of circumbinary envelope with the stream results in the formation of an extended shock wave located along the stream edge (‘hot line’). The Figure 4 also manifests the formation of only one arm of tidally induced spiral shock located in I and II quadrants of coordinate plane. The flow structure in the place where the second arm should be is defined by the stream from \( L_1 \) which appears to suppress the formation of another arm of the tidally induced spiral shock.

Nevertheless, opposite to the case of constant rate of mass transfer the blob remains to live and gives the periodic changes of disk structure. The Figure 4 shows that the blob tends to spread uniformly but passing through the arm of spiral shock it is retarded, this leads to the formation/sustaining of compact blob. This also leads to periodic changes of disk structure in a new quasi-steady-state solution. The Fourier analysis shows (see Fig. 2a) that for run “A” dominating harmonics are \( 0.155P_{orb} \) and \( 0.165P_{orb} \). The beating of these two gives long-period oscillations with period \( \sim 5.1P_{orb} \). First (short-period) harmonic appears to be due to interaction of the blob with the arm of spiral shock and the second harmonic is due to interaction of peripherical parts of the blob with the stream of matter from \( L_1 \), the period of latter harmonic being larger. The larger period is result of differential rotation of the disk – peripherical parts of the blob locate at larger radii and rotate slower. After interaction with the stream this lag decreases and the blob becomes compact.

Comparative analysis of Figs 1–4 shows that the mean period of the blob rotation is the same both for transient stage when two arms of spiral shock exist and for new quasi-steady-state solution with one arm of spiral shock. At the same time the density contrast between the disk and the blob changes significantly due to long-period modulations (Fig. 5). It is seen that on the transient stage when the dense disk dominates the contrast is \( \sim 1.5 \). Later, after reaching the recurrent quasi-steady-state solution with two dominating harmonics and long-
Figure 3: Density distribution over the equatorial plane for run “A”. Results are presented for the moments of time $t_0 + 0.44P_{\text{orb}}$, $0.47P_{\text{orb}}$, $0.49P_{\text{orb}}$, $0.52P_{\text{orb}}$, $0.54P_{\text{orb}}$, $0.57P_{\text{orb}}$, covering the full period of the blob revolution for the transient stage. The maximal density corresponds to $\rho \simeq 0.035\rho(L_1)$. 
Figure 4: The same as in Fig. 3 for other six moments of time: $t_0 + 17.64 P_{\text{orb}}$, $17.67 P_{\text{orb}}$, $17.70 P_{\text{orb}}$, $17.73 P_{\text{orb}}$, $17.76 P_{\text{orb}}$, $17.79 P_{\text{orb}}$, covering the full period of the blob revolution for the stage when the new quasi-steady-state solution is established. The maximal density corresponds to $\rho \simeq 0.02 \rho(L_1)$. 
Figure 5: The density contrast between the disk and the blob versus time.

period modulations the density contrast varies from $\sim 1.1$ to $\sim 1.8$.

Resuming the results of run “A”, we can conclude that the solution at the recurrent quasi-steady-state stage is defined by the stream from $L_1$ and the presence of the blob manifests in periodic variations of the disk structure.

Let us consider now the results of run “B” when the mass transfer rate was decreased 10 times and the gas of the stream has significantly less density. Similar to run “A” on the transient stage the dense disk and the blob dominate. But opposite to run “A” the blob continues to dominate even at the recurrent quasi-steady-state stage. Opposite to run “A” the blob changes the general flow structure, in particular, the blob ‘blows off’ the stream when reaching it. This is seen from Fig. 6 where the density distributions over the equatorial plane for moments of time $t_0 + 22.45P_{\text{orb}}, 22.48P_{\text{orb}}, 22.51P_{\text{orb}}, 22.54P_{\text{orb}}, 22.57P_{\text{orb}}, 22.61P_{\text{orb}}$, covering the full period of the blob revolution for the new quasi-steady-state stage of run “B”.

The maximal density in Fig. 6 corresponds to $\rho \simeq 0.0035\rho(L_1)$. The small value of density confirms the significant influence of the blob on the flow structure on all stages of run “B”. The Fourier analysis of results of the run “B” shows (see Fig. 2b) that dominating harmonics are $0.18P_{\text{orb}}$ and $0.21P_{\text{orb}}$. The beating of these two gives long-period oscillations with period $\sim 2.5P_{\text{orb}}$. Similar to run “A” these harmonics appears to be due to interaction of the blob with the arm of spiral shock and with the stream of matter from $L_1$.

The analysis of these results as well as the results of Paper I shows that for binaries with spiral shocks small disturbances resulting from variations of mass transfer rate lead to formation of the blob. Moreover, on the dynamical timescale the blob is supported by the presence of spiral shocks and this mechanism is independent on the variations of mass transfer rate. Thus, we can conjecture that not only mass transfer rate variation but every disturbance of disk structure will transform into the blob. The lifetime of the blob is determined by the lifetime of spiral shock which prevents the blob spreading in dynamical timescale, and dissipation which governs the blob spreading in viscous timescale.

3 The blob parameters and the variability of light curves of CVs with spiral shocks

Spiral shocks or, more exactly, the dense post-shock regions attached to the arms of the spiral shock were often considered as probable source of variability of astrophysical objects (see, e.g., Chakrabarti & Wiita 1993a, 1993b). Recently we argued in Paper I that the dense blob can detach from the front of spiral shock and further travel through the disk. In Paper I as well as in the present work the blob is formed as a result of disturbance of the disk structure due to variation of mass transfer rate. Once forming blob tends to distribute uniformly along the disk due to differential rotation but retards after passing trough spiral shock so the compactness of the blob retains/resumes. Later the increasing density contrast between the blob and the disk as well as growths of pressure gradient will force the standstilled blob to move. When reaching again the front of spiral shock the process of formation/retainment of the blob is repeated. Results of 3D gasdynamical calculations show that the blob travels through the disk during tens of orbital periods, its main characteristics being conserved. The blob ought spread under the action of dissipation but the vis-
Figure 6: Density distribution over the equatorial plane for run “B”. Results are presented for the moments of time $t_0 + 22.45P_{\text{orb}}, 22.48P_{\text{orb}}, 22.51P_{\text{orb}}, 22.54P_{\text{orb}}, 22.57P_{\text{orb}}, 22.61P_{\text{orb}}$, covering the full period of the blob revolution for the new quasi-steady-state stage of run “B”. The maximal density corresponds to $\rho \approx 0.0035\rho(L_1)$. 
cous timescale is much greater than the time of our calculations so we can neglect the viscous spreading of the blob. We should like to stress that the we have chosen the duration of our calculations (up to \( \sim 25P\text{orb} \)) not arbitrary but in agreement with typical length of the outburst decline (tens of \( P\text{orb} \)). It is on the stage of outburst decline the decreasing of mass transfer rate is possible, and, besides, on this stage the spiral shocks are observable (or, more exactly, the most reasonable assumptions on their existence can be made here).

To determine the typical features of the blob in CVs it is necessary to conduct a set of calculations covering all the range of parameters which are relevant to CVs. Nevertheless, based on the results of Paper I as well as on the results of this work we can conclude that generally the period of the blob revolution depends on the value of viscosity: it equals to \( 0.15 \div 0.20P\text{orb} \) for \( \alpha \sim 0.05 \), and to \( 0.10 \div 0.15P\text{orb} \) for \( \alpha \sim 0.01 \). This means that for typical accretion disk with \( \alpha \sim 0.01 \div 0.1 \) the period of the blob revolution should be in range \( 0.10 \div 0.25P\text{orb} \). Another important property of the blob is the density contrast w.r.t. the rest of the disk since this parameter determines the observational evidences of the blob. As it was shown above the value of density contrast is independent on the rate of mass transfer and changes periodically around the mean value of \( \sim 1.5 \). The nature of mechanism of formation/sustaining of the blob permits us to believe that this value is typical for different CVs.

Let us consider the virtual observation evidences of the blob and compare it with the real observations. The existence of the blob is maintained by spiral shocks, so we have chosen the observation of IP Peg which was gave the first evidences of the spiral shocks (Steeghs, Harlaftis & Horne 1997\(^1\); Harlaftis et al. 1999\(^1\)) and EX Dra where the existence of spiral shocks is also probable (Baptista, Catalán & Costa 1999\(^2\); 2000\(^3\); Joergens et al. 2000\(^4\); Joergens, Spruit & Rutten 2000\(^5\)).

Since the blob is preserved from the spreading by the existence of spiral shock let us consider the link between the light curve variations and the appearance/disappearance of spiral shocks. The standard treating of IP Peg and EX Dra suggests the extension of the accretion disk and formation of spiral shocks in it at some stage. After the outburst ends and the quiescence state establishes the radius decreases so tidal interaction can't induce spiral shocks anymore. Thus, the light curves should manifest quasi-periodic variations only during outburst and, possible, some time after it. Observations show variations of un eclipsed parts of the light curves for both systems during outburst and immediately after it. The width of these variations is \( \sim 0.1 \div 0.2 \) for EX Dra (Baptista, Catalán & Costa 2000\(^3\)) and for IP Peg (Marsh & Horne 1990\(^2\); Webb et al. 1999\(^6\)), the amplitude of variations sufficiently decreasing when the quiescence state establishes. These observations confirm the proposed model on the qualitative level: it is seen that variations of uneclipsed parts of light curves correlate with the presence of spiral shocks, and the width of variations corresponds to the theoretical one.

As another test for the suggested model let us consider the quantitative evidences of the blob existence. The analysis of light curves shows that the disk deposits the major fraction of luminosity during outburst (up to \( 5/6 \) for IP Peg, see, e.g., Khruzina et al. 2001\(^7\)), so the amplitude of light curve variations should be approximately equal to the density contrast. Our calculations give the mean value of density contrast as 1.5 so taking into account the relative luminosity of the disk we can expect the amplitude of variations on light curves as \( \sim 40\% \). Observations show the amplitude of variations of the flux on uneclipsed parts of light curves as \( \sim 30\% \) for IP Peg (see, e.g., Steeghs et al. 1996\(^8\); Morales-Rueda, Marsh & Billington 2000\(^9\)) and \( \sim 15\% \) for EX Dra (Baptista, Catalán & Costa 2000\(^3\)). Unfortunately, the analysis of light curve variations in quiescence is inconvenient due to both decreasing of density contrast and relative luminosity of the disk (\( 1/5 \) for IP Peg, see, e.g., Khruzina et al. 2001\(^7\)), so we restrict ourself by consideration of quantitative estimations for outburst only. The comparison of these estimations confirms the proposed model on the quantitative level as well.

As an additional test of the model applica-

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\(^1\)Note that if the viscosity in the disk is small then the dissipative spreading is negligible and the blob can exist even when the spiral shocks vanish. Correspondingly, the light curve variations can be observable after that while decreasing magnitude.
bility we would like to stress its relevance to the explanation of variation of emission lines profiles in CVs. For example, the observations of $H_\alpha$ profiles in the disk of binary SS Cyg (Martínez-Pais et al. 1994[16]) show its essentially asymmetrical nature, the distance between peaks being significantly variable. The presence of spiral shocks permits to explain the asymmetry of line profiles (Chakrabarti & Wiita 1993a[7]), but the spiral shocks by itself can’t give the mechanism resulting in variable distance between peaks. The mechanism suggested in this work do explain both the asymmetry of line profiles (in the same manner as above) and the variability of the distance between peaks (by the variability of the projection of blob velocity). Note also that the sporadic low-magnitude variations on the light curve (flickering) can also be a consequence of the presence of the blob in the disk. Disturbances of the disk structure due to periodic travelling of the blob as well as due to stream/blob interaction can result in low-amplitude oscillations manifesting as sporadic variations on the light curve.

4 Conclusions

Light curves of CVs show periodic or quasi-periodic photometric modulations with typical width $\sim 0.1 \div 0.2$. The 3D gasdynamical simulations of flow structure in binaries disturbed by the mass transfer rate variation prove the appearing a new dense formation – blob, the latter moving through the disk with variable velocity. Long lifetime of the blob, significant density contrast between the blob and the rest of accretion disk (the mean value is $\sim 1.5$), and characteristic period of its revolution $\sim 0.1 \div 0.2 P_{\text{orb}}$ permit us to consider this formation as a possible reason for observable quasi-periodic variations of light curves of CVs. Note that if suggested mechanism is valid then the variations of light curves of CVs give an additional proof for the spiral shocks existence.

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