Driven-disk model for binaries with precessing donor star. Three-dimensional simulations

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Abstract—We present the results of three-dimensional numerical simulations of mass transfer in semi-detached binary with a donor star whose rotation vector precesses around the orbital rotation axis of the binary in the observer’s coordinate frame. The calculations support our previous model of flow without a ‘hot spot’. Characteristic features of the flow in this model, such as the formation of an circumbinary envelope, the absence of a ‘hot spot’ at the edge of the accretion disk, and the formation of a shock wave along the edge of the stream, are also present in the solution for a binary with precessing donor star. The parameters of accretion disk and of the structure of the near-disk regions recur with the precessional period of the rotation axis of donor star.

1 INTRODUCTION

Observations of binary systems over the past ten years indicate that in a number of close binaries, the best known being Her X-1 (HZ Her) and SS433, long-period variations are detected on characteristic timescales substantially longer than the orbital period. To explain these variations, precession of the accretion disk in the binary is widely assume (see, e.g., [1–3] and references therein).

Possible reasons for precession of an accretion disk have been analyzed in a number of studies. As early as in 1972 N.I.Shakura [4] noted that the accretion disk can precess if its plane does not coincide with the orbital plane of a binary. Among various mechanisms that can lead to formation of an accretion disk inclined to the orbital plane, two are usually considered to be most probable: influence of magnetic field of the accretor or violation of the symmetry of the donor-star outflow due to rotation of the star. The question of formation an inclined disk under the action of the accretor’s magnetic field remains open: control of
the disk orientation would require a strong magnetic field which, in turn, could inhibit the formation of the disk itself.

An inclined accretion disk is more likely to form due to a change of the position of the stream flowing from the inner Lagrangian point \( L_1 \). In particular W.Roberts [1] and A.M.Cherepashchuk [5,6] proposed a scenario in which a minor asymmetry of the explosion of a supernova (resulting in the formation of a relativistic object in the binary) can decline the orbital plane of a binary relative to the rotation axis of the normal component of the system. In this case, after the supernova explosion and the formation of a relativistic object, the rotation axis of the normal component of the system might become oriented not perpendicular to the orbital plane of the binary. For systems where mass is transfer from the normal star to the relativistic object, the disturbance of the symmetry of the outflow of matter from the donor-star might result in the formation of an accretion disk not aligned with the orbital plane. Precession of such a disk could be caused either by induced precession of the disk itself under the action of the gravitational attraction of donor-star \([7,8]\), or by the stream oscillations due to precession of the rotation vector of the donor-star (the ‘slaved disk’ model, \([1,4]\)), or by some other mechanism (see, e.g., \([9]\)).

The description of the gas dynamics of mass transfer binaries of this type calls for the use of three-dimensional models because the rotation vectors of the donor-star is not perpendicular to the orbital plane and is engaged in precession. This means that this problem cannot be reduced to a two-dimensional one. Further, there is an additional complexity in describing such systems connected with the periodic time dependence of the boundary conditions, that is with the absence of a steady-state flow of matter in the system, thus necessitating the consideration of the structure of flow over long periods of time (few times longer than maximum characteristic period of the system). Until very recently, these circumstances, together with insufficient computational resources, made numerical studies of flow structures in binary systems of this type difficult. A few attempts to consider the formation of an accretion disk in such systems were made in substantially simplified formulation \([10, 11]\).

Here we consider for the first time numerical, self-consistent solution for the three-dimensional flow structure of mass transfer in semidetached binary systems in which the donor’s rotation axis precesses. The obtained results support the model of ‘driven accretion disk’, based on the idea that the oscillations of the disk relative to the equatorial plane reflect variations of the stream of matter from the inner Lagrangian point \( L_1 \).

2 THE MODEL

In \([12]\) we presented a three-dimensional simulation of mass transfer in semidetached binaries with rotation of the donor-star. We investigated both synchronous (the rotational period of the donor-star equals to the orbital period of the system \( P_\star = P_{\text{orb}} \)) and asynchronous \( (P_\star \neq P_{\text{orb}}) \) rotation of the donor-star \([12]\). For the case of asynchronous rotation both axially aligned rotation, when the rotation vector of the donor-star is perpendicular to the orbital plane of a binary, and non-aligned, when this vector is inclined relative to the orbital plane were considered. It was also assumed in \([12]\) that the case of asynchronous non-aligned rotation implies that the rotation vector of the donor-star is in a rest in the laboratory coordinate system (i.e., relative to observer).
The existence of observational evidence for precession of rotational vector of the donor-star requires extension of the model. The model we use here assumes that the rotation vector of the donor-star precesses (in a laboratory coordinate system) about its mean position, which coincides with the vector of orbital rotation of the binary. Note that although this model has a formally more general character (rate of precession of the rotation vector in the laboratory coordinate system $\tilde{\Omega}_{\text{lab}} \neq 0$) than the model considered in [12] for the case of asynchronous non-aligned rotation (rate of precession of the rotation vector in the laboratory coordinate system $\tilde{\Omega}_{\text{lab}} = 0$), these models differ significantly in the laboratory coordinate system only. In a rotating coordinate system (adopted for our calculations), we can expect that there will be qualitatively similar solutions for both models because in this coordinate system the rotation vector of the donor-star in model of [12] also undergoes precessional motion, i.e. for both models $\tilde{\Omega}_{\text{rot}} \neq 0$. The different rates of precession in the models should lead only to quantitatively difference of the solutions leaving the general features of the flow structure in a binary unchanged.

To study in detail whether accretion disk will follow the ‘driven disk’ model, we conducted the calculations over a time exceeding the period of long-period variations of the system; this made it possible to obtain established solutions both in a laboratory and in a rotating coordinate system. To be able to compare the solutions with the results obtained in [12] we adopted the same parameters of binary system: the primary (filling its Roche lobe) parameters are $M_1 = 0.28M_\odot$, $T_1 = 10^4$ K; the secondary (compact objects) parameters are $R_2 = 0.013R_\odot$, $M_2 = 1.4M_\odot$; parameters of binary system $P_{\text{orb}} = 5^{h}56$; $A = 1.97R_\odot$. We assumed that the rotation velocity of the donor-star in the laboratory coordinate system exceeds twice the angular velocity of the system. The angle between the rotation vector of the donor star $\Omega$, and the ‘z’-axis was assumed to be $\vartheta = 15^\circ$ (in the laboratory coordinate system). The rate of precession of rotation vector of the donor-star was equal to $\tilde{\Omega}_{\text{lab}} = \frac{1}{6}\Omega$ in the laboratory coordinate system or $\tilde{\Omega}_{\text{rot}} = -\frac{5}{6}\Omega$ – in the rotating coordinate system (the minus sign indicates that the precession of the rotation vector is retrograde with respect to the orbital rotation).

Following the procedure of [12], we determined the boundary conditions on the surface of this star by solving the Riemann problem between gas parameters ($\rho_1$, $v_1$, $p_1$) on the stellar surface and the parameters in the computation gridpoint closest to the given point on the star surface. The asynchronism of rotation of the donor-star, as well as the precession of the vector of its rotation were taken into account when setting the boundary conditions for the gas velocity vector on the Roche lobe of the donor-star. All other parameters of the mathematical model including the details of numerical realization were taken the same as in [12], namely:

- We adopted the computational domain as a parallelepipedon $(-A \ldots 2A) \times (-A \ldots A) \times (-A \ldots A)$;
- A non-uniform (more fine in the zone near accretor) finite-difference grid with $91 \times 81 \times 55$ gridpoints was used;

\footnote{According to the vector transformation rule $\Omega_{\text{rot}} = \Omega_{\text{lab}} - \Omega$ the inclination angle of this vector in the rotating coordinate system is $\vartheta^* = 30^\circ$}
Figure 1: Iso-surfaces of density at level $\rho = 0.002\rho L_1$ for first four moments of time covering the full period of boundary conditions variations in the rotating coordinate system. Filled circle is the accretor. On the first panel corresponding to moment of time $t = t_0$, the basic features of the flow pattern are marked by $a, b, c, d$. The same features are also presented on all other panels: $a$ – the donor-star surface; $b$ – the gas stream from $L_1$; $c$ – the flow region near the accretor including the accretion disk; $d$ – the gas ‘clouds’ located in front of the forward edge of the stream outside of the disk formation region.

- The shape of the donor-star was determined, taking into account the asynchronicity of its rotation.

3 RESULTS OF CALCULATIONS

The results of calculations fully confirmed our assumption that, given a rotating coordinate system, the qualitative features of the flow structure are independent of the rate of precession of the rotation vector of the donor-star. Fig. 1 depicts the iso-surfaces of density at the level $\rho = 0.002\rho L_1$ for 10 moments of time which cover a full period of variation of the boundary conditions in a rotating coordinate system. Note that, in line with the assumed parameters of the system, the period of precession of the rotation vector of the donor-star in a rotating
Figure 1 (continued): Iso-surfaces of density at level $\rho = 0.002\rho_L$ for last six moments of time covering the full period of boundary conditions variations in the rotating coordinate system.
coordinate system $\tilde{P}_{\text{rot}}$ is equal to $6/5$ of the orbital period $P_{\text{orb}}$. Owing to this the results are given in Fig. 1 over the interval $6/5P_{\text{orb}}$.

Analysis of the results presented in Fig. 1 shows that the behavior of the disk $c$ and of the near-disk matter $d$ reflects the variations of the stream of matter $a$ flowing from $L_1$ (i.e. boundary conditions on the surface of the donor-star $a$). This points to the realization of the ‘slaved disk’ model in the calculations. The results show also that the unique morphology of the flow, as well as the effect of circumbinary envelope gas lead to a shock-free interaction between the stream and the outer edge of the accretion disk and, as a consequence, to the absence of a ‘hot spot’ in the disk. In the model discussed here the zone of increased energy release is located beyond the accretion disk – at the region where the gas of circumbinary envelope interacts with the stream and where the extended shock wave is formed. Similarly to the case of non-aligned asynchronous rotation described in [12], the interaction between the rarefied gas of the circumbinary envelope and the stream of matter results in the formation of gaseous ‘clouds’ located ahead of the front edge of the stream, beyond the zone of disk formation (marker $d$ in Fig. 1). The period of variation of these gaseous formations – ‘clouds’ – reflects the period of variation of the boundary conditions at the mass-losing star.

In the laboratory coordinate system the characteristic timescale of the long-period variation (precession of the rotation vector of the donor-star with period $\tilde{P}_{\text{lab}}$) is equal to $6P_{\text{orb}}$. The calculations were made over period of time exceeding $\tilde{P}_{\text{lab}}$ starting from the time when the flow was established. As expected, the comparison of results of calculations in the laboratory coordinate system confirms the periodic character of solution with the period $\tilde{P}_{\text{lab}}$. This is illustrated in Fig. 2 and 3 where iso-surfaces of density at the level $\rho = 0.002\rho_{L_1}$ are shown in the laboratory coordinate system. These plots show the 3D view of density distribution in the vicinity of $L_1$ and in the near-disk region, respectively, for six moments of time covering the period of precession in the laboratory coordinate system. Analysis of Fig. 2 indicates that in accordance with the variations of boundary conditions, the position of the stream flowing from $L_1$ varies with respect to the equatorial plane, and, after a time $\tilde{P}_{\text{lab}}$, returns to its initial position. Figure 3 shows that the accretion disk $c$ and surrounding gaseous formation (clouds $d$ and $d'$) follow the position of the stream (see Fig. 2), and their shape varies with the same period.

The presence of two characteristic periods – the precessional period of the rotation vector of the donor star in the laboratory frame $\tilde{P}_{\text{lab}}$ and orbital period of the system $P_{\text{orb}}$ – can explain the appearance of other periods of observation evidences, apart from $\tilde{P}_{\text{lab}}$. In particular, the interaction of $\tilde{P}_{\text{lab}}$ with $P_{\text{orb}}$ leads to formation of short-period beating oscillations. For example, as concerns the system SS433 ($P_{\text{orb}} = 13.1$, $\tilde{P}_{\text{rot}} = 12.1$), in additions to the period $\tilde{P}_{\text{lab}} = 162.5$, there should exist variations with the period of $6.28$. These short-period oscillations, as well as the following beating harmonic with period $5.83$ are observed in SS433 (see, e.g., [13,14] and references therein).

4 CONCLUSIONS

Our three-dimensional simulations of mass transfer in semidetached binaries with precession of rotation vector of donor star reveal the ‘driven’ nature of forming accretion disk. For
Figure 2: Iso-surfaces of density at level $\rho = 0.002\rho_{L_1}$ in the vicinity of the inner Lagrangian point for six moments of time covering the precession period in the laboratory coordinate system. The iso-surface is cut by plane 'yz' at a distance of 0.066A from $L_1$. Filled circle is the projection of the inner Lagrangian point onto the 'yz' cross-section.
Figure 3: Iso-surfaces of density at level $\rho = 0.002\rho_{L_1}$ in the vicinity of the accretor for six moments of time, covering the precession period in the laboratory coordinate system. On the first panel corresponding to moment of time $t = t_0$, the basic features of the flow pattern are marked by the same characters as in Fig. 1: $c$ – the flow region near the accretor including the accretion disk; $d$ and $d'$ – the gas ‘clouds’ located in front of the forward edge of the stream outside of the disk formation region.
typical parameters of numerical viscosity adopted for the numerical model \((\alpha \sim 0.1 \div 0.5\) in terms of \(\alpha\)-disk), the change of the flow pattern, the parameters of accretion disk, and parameters of the near-disk regions reflect the variations of boundary conditions on the donor star. In turn, the periodicity of boundary conditions is determined by the precessional velocity. Analysis of the flow pattern indicates that the basic features of the solution are qualitatively similar to those for calculations previously obtained for the cases of synchronous, aligned asynchronous, and non-aligned asynchronous rotation of the donor-star [12], and, in turn, indicates to the universal character of the model without a ‘hot spot’ proposed in [15–18].

The ‘driven’ character of the solution implies that the emission properties of the accretion disk and intercomponent gaseous structures recur with the precessional period of the rotation axis of donor-star. In binary systems where observed long-period variations can be explained by the precession of the donor-star the periodicity of the solution obtained here can be used to interpret the observational data.

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