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MODERN MODELS DESCRIBING THE FLOW OF MATTER IN CATACLYSMIC VARIABLES

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Abstract. Light curve synthesis for cataclysmic variables is discussed in a framework of a general model in which a normal star (red dwarf) fills its Roche lobe, while another component – a spherical star (white dwarf), is surrounded by an elliptical geometrically thick accretion disk. The comparison of four models is performed using the base program simulating an extended shock wave located along the edge of the gas flow near the outer disk edge (hot line). These models take into account the presence in the system 1) of the classical hot spot on the outer side of the disk, 2) of the hot line situated outside of the disk, 3) of both hot line and classical hot spot, and 4) of the hot line and a hot region towering over the outer side of the disk respectively. Results of light curve interpretation for some cataclysmic variables in different phases of their activity with these models are given.

1. INTRODUCTION

Study of light curves of close binary systems in late stages of evolution gives a large volume of information about the parameters of gas flows, streams, disks and other structures, forming as a result of mass transfer to the later-type component.

For the last four decades, the hot spot model suggested by Gorbatskii (1967) and Smak (1970) in the late 1960s has been used to interpret the light curves of cataclysmic variables (CV). In this model, the interaction between a stream of matter and the accretion disk leads to formation of a shock wave, and a region of energy release is formed where the stream comes into contact with the disk. The region is usually called a "hot spot". This model can explain the formation of a hump in the light curves of cataclysmic variables close to orbital phases $\varphi \sim 0.7 - 0.85$. However, as the amount of observational data grew deviations from this model were revealed.

During the last two decades, we developed light curve synthesis for low-mass X-ray binary systems, as well as for cataclysmic variables using various models.

The first of them is the program for computation of light curves in the classical model of a hot spot situated on the outer edge of the accretion disk. In the second "hot line" model, the presence of an extended shock wave along the gas stream towards the inner Lagrangian point was taken into account. This model is based on the three-dimensional gas-dynamical computations of mass flows in close binary systems (see e.g. Bisikalo et al. 1987, Makita et al. 2000). In our third "unified" model the region of energy release represents a superposition of two components – a hot line situated on surfaces of gas flow with maximum flux near the external edge of the disk and a hot spot on the leeward part of the disk itself. Finally, the above numerical simulations show that as a result of interactions of gaseous flow and the accretion disk the temperature and density inside the disk increase. This leads to an expansion of the disk material perpendicularly to the orbital plane of the system in the regions of hot line and hot spot. Our fourth model, called "advanced unified" model, takes this effect into account.

2. BASIC MODEL OF THE SYSTEM

In the process of synthesis of light curves, we suppose that the binary system consists of the secondary star (this star has a late spectral type), filling its Roche lobe, and the primary star – a spherical star of small size with radius R_1. The primary is a white dwarf in the case of CVs. For low-mass X-ray systems we choose very small value for the radius of the primary to imitate the dimension of the compact object. The primary is surrounded by a geometrically thick elliptical accretion disk with a complex shape, which is geometrically thin near the white dwarf and thick at the edge of the disk (for details see Khruzina 2000). The primary is situated in one of the foci of the elliptical disk. The disk is represented as an intersection of an ellipsoid with semiaxes a, b and c with two paraboloids. The value of the ellipticity of the disk ellipsoid in the orbital plane is $e = \sqrt{(1 - b^2/a^2)}$. The value of the paraboloids constant changes depending upon the angle of turn of the radius-vector around the axis perpendicular to the orbital plane. The ellipsoid defines the shape of the disk's external surface. The paraboloids define the shape of the internal (upper and lower) surfaces of the elliptical accretion disk. The disk orientation is defined by an angle α_e between the radius-vector, connecting the spherical star's center with the point of the disk's periastron, and the axis OX of the system (see Fig. 1).

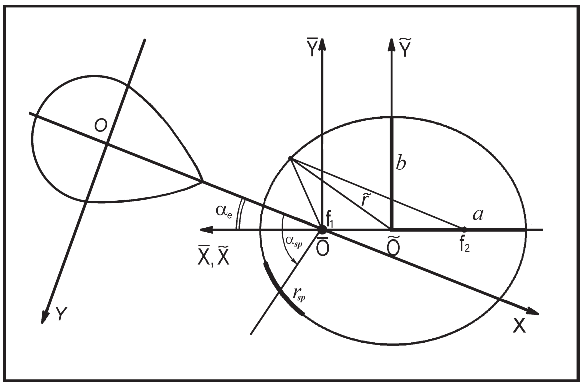

Figure 1: The schematic view of the system in the orbital plane. f_1, f_2 are the foci of disk's ellipsoid with semiaxes a and b. Thick solid line in the disk oval represents the hot spot region.

The temperature of an area element on the disk depends on the distance r between its center and the surface of the spherical star. The disk is also heated by radiation of both components. The value of the additional heating is given by the temperature increase ΔT. So the disk temperature follows the dependence $T \sim T_{in} \cdot r^{-\alpha_g} + \Delta T$. Here T_{in} is the temperature in the inner region of the disk near the surface of the primary; α_g is a parameter, its theoretical value is $\alpha_g = 0.75$, assuming that each point on the disk surface radiates as a blackbody. In practice, its value is usually smaller, $\alpha_g \sim 0.3 - 0.75$. Fig. 2 demonstrates the shape of the accretion disk in the described models. The left figure (Fig. 2a) represents the disk with a very thick external edge, one can see ellipsoidal surface of external edge of the disk, and paraboloidal surface of its internal regions. The right figure (Fig. 2b) shows the disk with real thickness in the system OY Car.

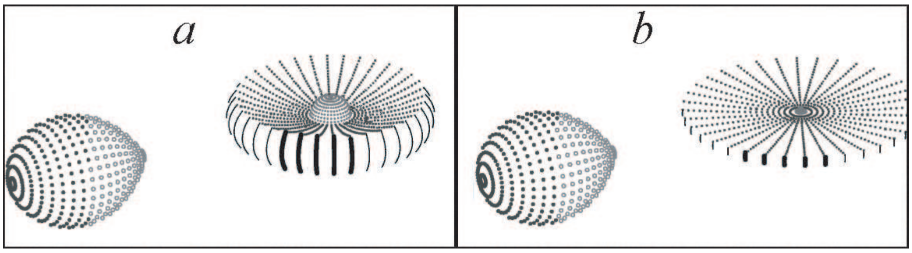

Figure 2: The model of the system in the orbital phase $\varphi = 0.85$. a – a disk with a very thick external edge for clearer view of the disk shape, b – a disk with real parameters corresponding to those of the system OY Car. The dark region on the ellipsoidal part of the disk represents the hot spot.

3. MODELS OF CATACLYSMIC VARIABLES

We consider four versions of the computer program described in (Khruzina 1998, 2000, 2001, 2009) for a geometrically thick disk. The disk is either axisymmetric (relatively OX axis, see Fig. 1) or asymmetric in the regions of the energy release. This programs is suitable for the analysis of the light curves of CVs in various stage of activity.

3. 1. THE CLASSICAL MODEL OF HOT SPOT

In the classical, generally accepted model of a CV the “hot spot” hypothesis is used for the description of particularities of light curves. This hot spot is forming as a result of shock interaction of the gas stream with the external border of the accretion disk (see Gorbatskii 1967; Smak 1970). So the hot spot in our first model is situated only in the ellipsoidal part of the disk and does not touch the inner (paraboloidal) regions of the disk (see Fig. 2, hot spot is the dark region on external edge of the disk). The parameters of the hot spot are its azimuth α_{sp}, the radius r_{sp} and the temperature of disk's element j in hot spot region $T_{sp}(j) = T_d(j)(f_{sp} + 1)$. Here f_{sp} is the ratio of the temperature increase ΔT_{sp} to the temperature of matter in the same elementary area j in the absence of a gas stream $T_d(j)$. The parameter ΔT_{sp} has constant value in the spot region. The spot radius r_{sp} is the radius of a sphere centered at the center of the spot (see Fig. 1).

Such a model, on the qualitative level, describes a typical light curve of a cataclysmic variable in quiescence sufficiently well, especially in cases of small orbital inclinations. Within the framework of this model, it is possible to obtain reasonable

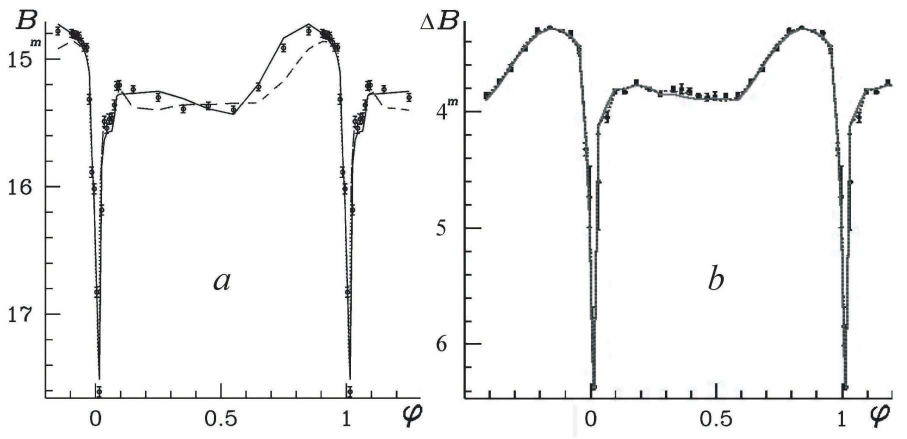

Figure 3: The light curve of CV OY Car in B-filter in quiescence: a theoretical light curves computed with the hot line and hot spot models are shown by solid and dashed curves respectively; b theoretical light curves computed with the advanced unified and the hot line models are shown by solid and dashed curves.

characteristics of the system, including parameters of the hot spot – its dimensions, luminosity, and position angle. This model can also successfully reproduce the shape of the primary minimum and the height and position of the hump on the light curve (see Fig. 3a), but fails to reproduce the out-of-eclipse brightness variations, often observed in CVs.

However, in the process of the accumulation of observational information, a great number of CVs revealed problems when their light curves were computed within the framework of the hot spot model. The presence of a powerful radiating structure in a binary system, outside the accretion disk, will contribute to significant distortion in light curves of such systems. They are not explained within the framework of models with the classical hot spot. For example, in the light curve of some variables, sometimes one can see not only the usual hump at the orbital phase 0.8 – 0.9 but, episodically, a second anomalous hump. On the light curves of other variables, the eclipse has been observed not on the fall-down branch, as the classical model requires, but on the rising branch of the hump. As a result, the classical hot spot is situated at such position angles, that disagree with physical laws. Such light curves are called abnormal. The examples of both such anomalies can be seen in Fig. 4.

3. 2. THE MODEL OF HOT LINE

Three-dimensional numerical simulations of the flow of matter in non-magnetic semi-contact binaries, carried out by Bisikalo et al. (1997), have indicated the absence of the shock interaction, called the hot spot, between the stream of matter flowing from the inner Lagrangian point to the accretion disk. The interaction between the stream and the common envelope of the system forms an extended shock wave along the edge of the stream, whose observational properties are roughly equivalent to those of a hot spot in the disk. Even if a newly formed stream collides with a previously formed disk

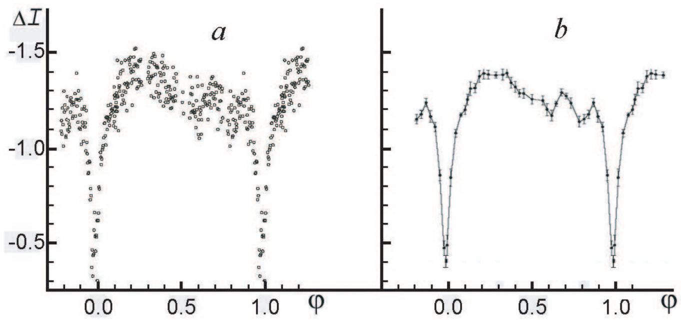

Figure 4: The individual (a) and mean (b) light curves of the cataclysmic system UX UMa in I-filter during intermediate state (Khruzina et al. 2007).

initially, the gas-flow morphology will be rearranged after several orbital periods, so that the interaction between the stream and disk will become shockless. At the same time, an extended shock wave, whose observational manifestations are equivalent to those of a hot spot on the disk, will be formed along the edge of the stream. Later this result was confirmed by Makita et al. (2000). They enter a notion "hot line" as opposite to the "hot spot".

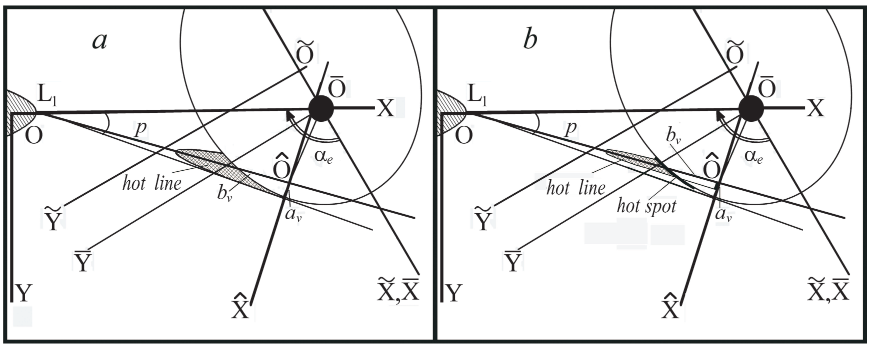

Figure 5: Schemes of the system in orbital plane with hot line ellipsoid (a) and hot line ellipsoid submerged in the hot spot on the external edge of the disk (b).

Our second hot line model can be used to construct both standard and abnormal light curves of CVs, and can reproduce some out-of-eclipse features in the light curves, such as small humps or dips.

In the process of modelling we will assume that the shock can radiate energy at the surface of the stream, both from the side of the inflowing matter and from the opposite side, depending on the physical parameters of the interacting flows (velocity, density, etc.). To model the shape of this optically thick region of energy release (the hot line), we assume that it can be represented as a part of an ellipsoid extended towards the inner Lagrangian point L_1 (see Fig. 5a). The semiaxes of this "hot line" ellipsoid are a_v, b_v and c_v. Here a_v is the distance between the disk edge and the center of hot line ellipsoid located at point $\widehat{O}$ in the orbital plane inside the elliptical disk. The semi-major axis b_v is restricted by the distance p between the L_1 and the center of the hot line ellipsoid.

The hot line model is able to describe the light curve shapes better than the hot spot model, and does not lose any of the advantages of the latter. Depending on the adopted parameters, the hot line can have various shapes, from an optically thick formation elongated along the gas-stream axis to a small bulge at the lateral surface of the accretion disk, with properties close to those of a hot spot (see Fig. 6).

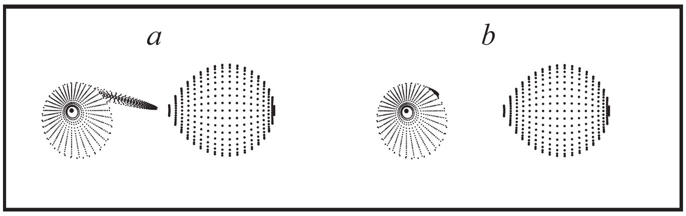

Figure 6: The view of the system in the orbital plane for hot line lengths $b_v = 0.9p$ (a) and $b_v = 0.25p$ (b). The parameters of the system are $q = M_1/M_2 = 0.3$, $R_d = 0.235a_0$ in apoastron, $e = 0.3$, $R_1 = 0.0067a_0$, $a_v = 0.036a_0$, a_0 – the distance between the centers of the mass of the components.

Our interpretation of eclipsing light curves of many cataclysmic variable in quiescence using two alternative models (hot line and hot spot) indicates that the hot line model describes the observed light curves much better than the hot spot model. The hot line model better reproduces the width of the peaks in the light curves, the shape of the eclipse, and the details of out-of-eclipse brightness variations. The comparison of these two models can be seen in Fig. 3a that shows the light curve of the system OY Car in B-filter. Theoretical light curves computed with the hot line and hot spot models are shown by solid and dashed lines respectively. Observational data were taken from Wood et al. (1989).

The model of the hot line has some defects. The main one is too high model value of thickness of gas flow in the region of its interaction with disk in situations when the radius of the accretion disk is sufficiently closely approaching Roche lobe borders of the white dwarf, since the leeward part of the hot line is located on the tangent to disk edge in this model. Actually, in the fitting process, we got a very large value of the semi-minor axis a_v of the ellipsoid, describing the shape of the hot line. The reduction of the thickness of the hot line to more realistic values gives, first, a large angle between the axis of the gas flow and the OX axis, connecting the centers of the mass of the components of the system. This angle exceeds values given by physical laws. Second, the heated part of the hot line on its windward region, as a rule, was covered by the disk edge eclipsing hot radiation from the flow on phases $\varphi \sim 0.2$. This fact decreases the capacity of the model in the description of light curves.

3. 3. THE UNIFIED MODEL OF ENERGY RELEASE REGION

In the third model we have taken into account the results of recent numerical simulation of the flow of matter in semi-contact binaries (Bisikalo et al. 2003). They have shown that alongside with the noncollisional interaction between the stream and the disk due to gas motion in the disk the matter heated by the shock wave is displaced in direction of the rotation of the disk creating an analogue of a hot spot on the leeward part of the external edge of the accretion disk. In this unified model, the region of energy release represents a combination of two components - a hot line situated on surfaces of gas stream with maximum flux near the external edge of the disk and a hot spot on the leeward part of the disk itself. The schematic view of this model in the orbital plane is shown in Fig. 5b. In this model, the semi-thickness of the hot line in the orbital plane a_v and its azimuth are independent parameters. So in the process of search for best parameters which can reproduce the light curve, there is no need to search for a compromise between the disk radius, thickness of the hot line and its azimuth like in the hot line model. A schematic view of the unified model with a very thick external edge of the accretion disk is shown in Fig. 7. Real CVs have smaller thickness of external edge of the disk. The typical value is about three or four degrees.

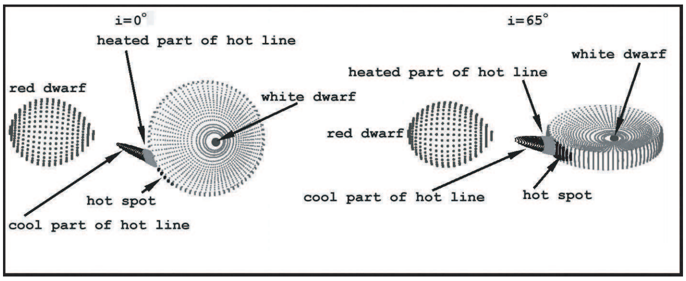

Figure 7: The schematic view of the system in the orbital plane (left) and for the orbit inclination $i = 65°$ (right) obtained for a system with parameters of OY Car.

3. 4. THE ADVANCED UNIFIED MODEL OF ENERGY RELEASE REGION

Three-dimensional numerical modelling (see Bisikalo et al. 2004) demonstrates also a thickening of the halo above the disk. In the gas-dynamical flow pattern described with the “hot line” model, a considerable fraction of the matter is accelerated in the vertical direction during the flows interaction with the disk surrounding the halo. The vertical motion of the gas due to the presence of the z component of the velocity leads to a gradual thickening of the disk. The computations reveal the strongest thickening of the halo above the outer edge of the disk at phases $\varphi \sim 0.7$, in agreement with observations of stationary-disk CVs.

Our advanced unified model is a modification of the unified model. In this model increase of the vertical thickness of the disk in regions of interaction with gas flow is correctly taken into account. In preceding three models it is supposed that the height of the hot line or hot spot does not exceed the thickness of the disk on its edge.

Fig. 8 shows the view of the thickened edge of the disk in the fourth model at two orbital phases ($\varphi = 0.64$ and 0.74). In the region of such thickening the structure of the inner parts of the disk is changed due to the local increasing of the parameter A of disk’s paraboloid.

A comparison of light curves obtained in the hot line and the advanced unified models shows that using both models it is possible to reproduce the shape of the light curves of CVs in inactive state, both classical and abnormal, with sufficiently good

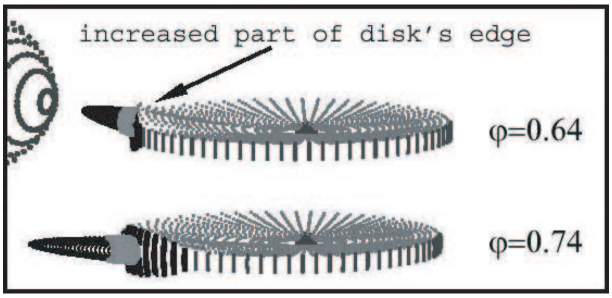

Figure 8: The view of the thickened edge of disk constructed in the framework of the advanced unified model.

accuracy. For example, Fig. 3b shows the light curves of OY Car in quiescence computed in both models. Observational data were taken from Schoembs et al. (1987). One can see that both curves agree with each other. Basic parameters of model curves such as the mass ratio $q = M_1/M_2$, the orbital inclination i, the temperature of the secondary T_2, the temperature in the inner regions of the disk near the equator of the white dwarf T_{in} (in the boundary layer), do not change. The second group of parameters – the eccentricity e and the major axis a of the weakly elliptical disk, the parameter α_g determining the radial variations of the disk temperature, the azimuth of the disk periastron α_e, the thickness of the outer edge of the disk β_d – differ by several percent. The difference between parameters that represent the shape of the hot line are more significant – this is a consequence of different conditions of the models.

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