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Transient Processes in a Binary System with a White Dwarf.

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Abstract

Using the results of 3D gas dynamic numerical simulations we propose a mechanism that can explain the quiescent multi-humped shape of light curves of WZ Sge short-period cataclysmic variable stars. Analysis of the obtained solutions shows that in the modeled system an accretion disk forms. In the outer regions of the disk four shock waves occur: two arms of the spiral tidal shock; "hot line", a shock wave caused by the interaction of the circum-disk halo and the stream from the inner Lagrangian point; and the bow-shock forming due to the supersonic motion of the accretor and disk in the gas of the circum-binary envelope. In addition, in our solutions we observe a spiral precessional density wave in the disk. This wave propagates from inside the disk down to its outer regions and almost rests in the laboratory frame in one orbital period. As a results every next orbital period each shock wave passes through the outer part of the density wave. Supplying these shocks with extra-density the precessional density wave amplifies them, which leads to enhanced energy release at each shock and may be observed as a brightening (or hump) in the light curve. Since the velocity of the retrograde precession is a little lower that the orbital velocity of the system, the same shock wave at every next orbital cycle interacts with the density wave later than at the previous cycle. This causes the observed shift of the humps over binary phases. The number of the shock waves, interacting with the density wave determines the largest number of humps that may be observed in one orbital period of a WZ Sge type star.

Keywords: cataclysmic variables - dwarf novae - optical - spectroscopy - photometry - numerical simulations - individual: SS Cyg ≡ BD+42° 4189a.

1 Introduction

WZ Sge stars (subclass of SU Uma stars) are deeply evolved close binary systems with very short orbital periods ($\sim$ 80) min and low mass ratios of the components ($q < 0.1$). As a rule these objects are very faint (fainter than 15^m). The most remarkable observational feature of these stars in quiescence are their multi-humped orbital light curves. Usually astronomers call them double-humped.There are a number of models proposed to explain a double-humped shape of the light curves of WZ Sge stars. One of them, advocated by Aviles et al. (2010), explains the formation of the humps by visibility conditions of two arms of the tidal spiral shock caused by the action of the 2:1 tidal resonance. Another model, mentioned, for instance, by Wolf (1998) and Silvestri et al., (2012) supposes that the stream from the inner Lagrangian point may overflow the disk after it ricochets on the disk rim and forms an additional hot spot at the opposite side of the disk, i.e. two hot spots give two humps in the light curve.

These two models would have worked perfectly had not there been a number of observational facts that cannot be explained by them. We, above, deliberately called the light curves of WZ Sge stars "multi-humped" instead of commonly used "double-humped", since there are a number of works where observers report from one to four humps in one orbital period (see, e.g., Araujo-Betancor et al. (2005), Katysheva & Shugarov (2009), Kitsionas et al. (2005), and Pavlenko (2009)). Besides, as shown in the mentioned papers, even in the same system the number of the humps varies depending on the epoch of observations. Thus, only two bright sources, implied by the models, described above, are not enough to explain more than two humps.

One more feature of the humps that cannot be explained by, say, the visibility conditions of the arms of the tidal shock is that they tend to shift over binary phase when observed in time-distant nights. The point is that the positions of the tidal shock arms in an accretion disk are determined by the Roche potential and fixed in the coordinate frame, rotating along with the binary. Thus, their contributions must always be observed at the same binary phases in every night.

It is commonly accepted that the most important observational manifestations of CVs and, in particular, WZ Sge stars, come from gas dynamical processes initiated by the mass transfer between the components.

Therefore, in order to understand what happens in WZ Sge stars and what structures and processes contribute to their observational manifestations one needs to study gas dynamics of these objects. In this paper we, by means of 3D gas dynamic simulations, aim to investigate the flow structure in a representative of WZ Sge stars and propose a physical model, capable to explain the multi-humped nature of their light curves.

In Section 2 we describe the simulations and show their results. In Section 3, based on the results of gas dynamic simulations we consider a physical model of the formation of the humps in orbital light curves of WZ Sge stars. In Section "Conclusions" we summarize our results and discuss further studies.

2 Numerical Simulations

To investigate flow structure in WZ Sge stars we have performed gas dynamic simulations of a close binary system having the parameters of V455 And. This system is one of the brightest representatives of the class and has well defined parameters (Araujo-Betancor et al. (2005)) that are as follows. The secondary mass is $M_{sec} = 0.07M_{\odot}$, and the primary mass (white dwarf) is $M_{wd} = 0.6M_{\odot}$. The binary separation of the system is $A = 0.56R_{\odot}$. The mass transfer rate in the system is estimated as $\dot{M} = 10^{-11}M_{\odot}/year$. The orbital period of the system is $P_{orb} = 81.08$ min.

To model the flow structure in the V455 And system we use a numerical HD/MHD code "NURGUSH" (Zhilkin & Bisikalo (2009)). When modeling, we set the magnetic field of the accretor equal to zero, so this is a pure gas dynamic case. The simulations are conducted until the system enters a quasi-stationary regime, i.e. the total mass of the disk varies by less than 2% in one orbital period. Approaching this regime takes approximately 30 orbital periods.

The results of the calculations are shown in Fig. 1. In its panels we show density distributions in the equatorial plane of the system for two time moments $\tau = 33.53P_{orb}$ and $\tau = 34.13P_{orb}$. Analysis of the obtained results shows that an elliptic accretion disk forms in the system. One also can see that in the disk a spiral density wave occurs. Its approximate location is denoted by the white dashed lines. This precessional density wave, first described by Bisikalo et al. (2004), occurs due to the retrograde precession (apsidal motion) of elliptic flow lines, caused by the tidal action of the secondary. The angular velocity of the retrograde precession of this wave (its absolute value) is only a few precent lower than the orbital angular velocity of the system. This means that in the observer's frame in one orbital period this wave almost rests and, in the frame, rotating with the binary, it makes almost a round during the same period. This effect is well-seen in Fig. 1 where at two time moments, separated by approximately $0.6P_{orb}$, the outer part of the wave occupies almost opposite locations.

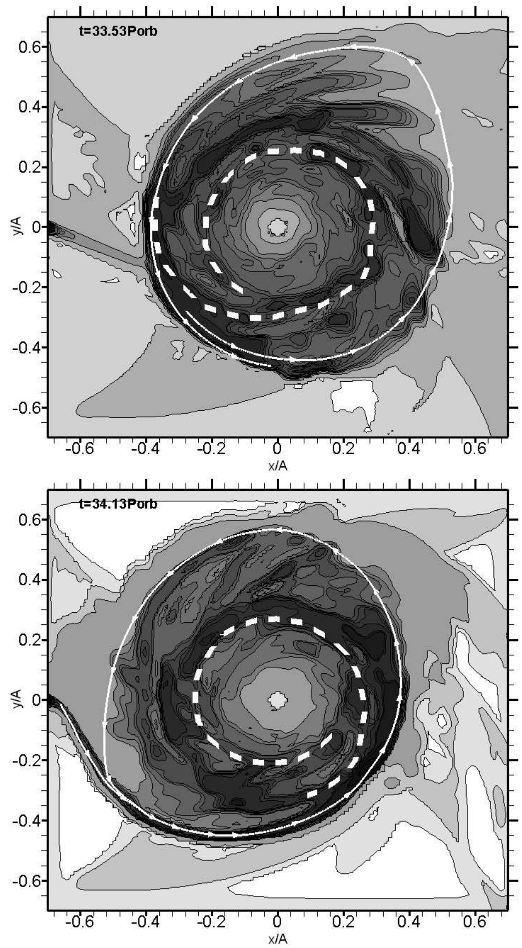

Figure 1: Density distributions in the equatorial plane of the system for two time moments $\tau = 33.53P_{orb}$ (top panel) and $\tau = 34.13P_{orb}$ (bottom panel). The white dashed line denotes the position of the precessional density wave.

3 Model of the Multi-Humped Light Curve

In Fig. 1 one can clearly see that the precessional spiral density wave in our solution propagates down to the outer regions of the accretion disk. From our previous studies (see, e.g., Bisikalo & Kononov (2010), Kononov et al. (2012)) we know that in the outer regions of the disk four most powerfull shock waves should form. These are: two arms of the spiral tidal shock; "hot line", a shock wave caused by the interaction of the circumdisk halo and the stream from the inner Lagrangian point; and the bow-shock forming due to the supersonic motion of the accretor and disk in the gas of the circum-binary envelope. Since, as we noted above, the precessional density wave rests in the observer's frame and propagates down to the outer regions of the disk, the latter four shocks must pass through its outer part in every next orbital period.

When a shock wave passes through the outer part of the density wave it is supplied with extra-density. This must cause amplification of the shock wave. Indeed in Fig. 2, where we plot pressure distributions for the time moments, corresponding to those of Fig. 1, we can see that in the location of the outer part of the density wave pressure increases. The cases shown in Fig.2 correspond to time moments when the density wave interacts with the arms of the tidal shock. In the upper panel of Fig. 2 the density wave interacts with the closer-to-donor arm of the tidal shock.

Note that at this moment the pressure in the location of the opposite arm is remarkably lower. In the lower panel the farther-from-donor arm of the tidal shock is more pronounced, while the opposite arm is "inactive".

Summarizing the above behavior, we can propose the following model that can explain the formation of the humps in quiescent orbital light curves of WZ Sge stars. In a system an elliptic accretion disk forms. Under the tidal action of the secondary, in this disk, a precessional density wave develops. This wave propagates down to the outer regions of the disk. Since the angular velocity of the retrograde precession of the wave is only a few percent lower than the orbital angular velocity of the system, the density wave almost rests in the observers frame. Thus the four main shock waves also located in the outer regions of the disk consecutively pass through the outer part of the density wave every next orbital period. When the shock wave interacts with the density wave it is supplied with extra-density and, hence, amplified. The amplification of the shock wave must increase the energy release at the shock that should be seen as a hump in the light curve of the system.

We should note that our model can explain not only the origin of the humps but, as well, their behavior. In particular, in the frame of our model, we can easily explain why the humps shift over binary phases from night to night. The point is that the angular velocity of the retrograde precession is not exactly the same as the orbital velocity of the system, it is a little lower. Thus, at the next round a shock wave approaches the outer part of the density wave a little later than at the previous one and the interaction between the two waves starts later. The corresponding humps, hence, must shift forward over the binary phase.

One more feature of the WZ Sge light curves that should be explained is the varying number of the humps. We show above that in principle one can observe not two but up to four humps in the light curve, since the density wave may interact with four most powerful shock waves located in the outer regions of the disk. However, the number of seen humps may depend on the visibility conditions of the amplified shock. For example, if a shock is amplified when it is situated at the moment of observations at the opposite from the observer side of the disk, radiation from the shock must pass through the disk and, in principle, may be reduced. Besides, the shocks may be of different power. In order to have a clear answer to this question we need to have more observations.

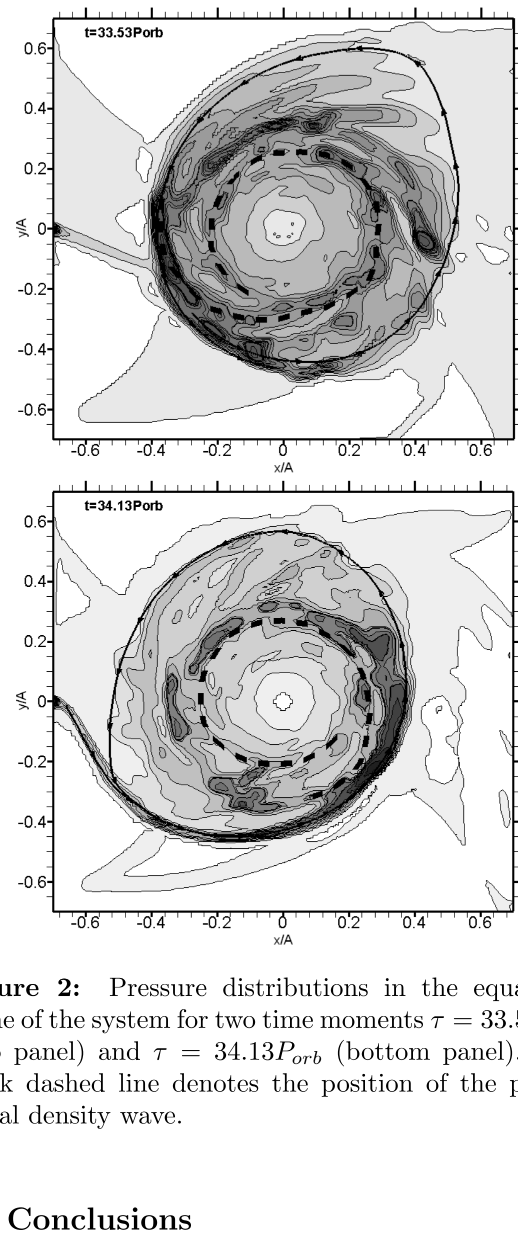

Figure 2: Pressure distributions in the equatorial plane of the system for two time moments $\tau = 33.53P_{orb}$ (top panel) and $\tau = 34.13P_{orb}$ (bottom panel). The black dashed line denotes the position of the precessional density wave.

4 Conclusions

We have performed 3D gas dynamic simulations of the flow structure in a short-period cataclysmic variable star of WZ Sge type. Analysis of the results has shown that in the system an elliptic accretion disk forms. In the disk a precessional density wave develops. The wave propagates down to the outer regions of the disk. Bisikalo et al. (2004) showed that the angular velocity of the retrograde precession of this wave is only a few percent lower than the orbital velocity of the system. Thus, the precessional density wave almost rests in the observer's frame. From our previous studies we know that in the outer regions of the disk four shock waves form. Every next orbital cycle these shocks consecutively pass through the outer part of the density wave. As a result every shock is supplied with extra-density and amplified. The amplification of a shock causes enhanced energy release and may be seen in the light curve as a hump.

Since the density wave retrogradely precess with the velocity that is a little lower than the orbital velocity, at every next round the same shock passes through the outer part of the density wave a little later. Thus the corresponding hump in the light curve at every next round occurs at a later binary phase. This, in the frame of our model, allows us to explain the observational fact that the humps shift over binary phases when observed at different nights. The variable number of the humps may be explained by the visibility conditions of the amplified shock wave.

Our studies of WZ Sge stars continue and with further accumulation of observational results we expect to have a more detailed model of the formation of light curves in these cataclysmic variable stars.

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