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Outbursts of AM CVn stars

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Abstract AM CVn stars are very promising objects for testing accretion disk instability models. We present the most characteristic features of their complex lightcurves. We test the Disk Instability Model for the case of helium disks and compare synthetic lightcurves with observations. Our results indicate that standard DIM has to be complemented with Enhanced Mass Transfer Model in order to reproduce the observational features of AM CVn stars lightucurves.

Key words. Stars: AM CVn stars – accretion disks – outbursts – disk instability model – enhanced mass transfer rate

1. Introduction

AM CVn stars are a group of very close binaries consisting of a He or C/O white dwarf primary and, most probably, a helium white dwarf secondary. Their hydrogen-free, helium-dominated spectra and very short orbital periods (10 min – 65 min) make them unique among all others binaries. Due to their relative faintness ($m_{V,\rm min} \approx 21$ mag, $m_{V,\rm max} \approx 12$ mag) they are difficult to observe and until now only 27 objects have been classified as AM CVn stars. 11 of them show outbursts which are similar to those observed in Dwarf Novae (hereafter DN); the remaining 16 are found either in persistently high or in persistently low luminosity states.

As in DN two main types of outbursts are observed. The properties of their lightcurves may be summarized as follows: i.) superoutburst amplitudes are in the range 2.5 – 5.5 mag; the shortest superoutburst recurrence time is 14.7 days and the longest observed is 450 days; the superoutburst duration may be as short as 9 days and as long as 60 days; ii.) normal outbursts have been observed very rarely.

In particular one can distinguish 3 types of lightcurves among outbursting AM CVns:

1. Lightcurves with superoutbursts only - KL Dra.
   So far KL Dra is the only object among AM CVn stars, which has a lightcurve showing only superoutbursts. This system, with orbital period $P_{\rm orb} = 25$ min, was recently observed by Ramsay's group (Ramsay et al. 2010, 2011). They found that superoutbursts last $\sim$ 14 days, and appear every 63 days. They found that the characteristic feature of these eruptions is a 2 mag dip occurring about 2 days after a superoutburst maximum.
2. The lightcurves with superoutburts and normal outbursts - PTF 1J0719
   The Palomar Transient Factory has recently delivered one of the most detailed lightcurves of an AM CVn-type binary. It reassembles those seen in SU UMa-

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type Dwarf Novae: superoutbursts, occurring every 65 days, are intermitted by several outbursts which can be classified as normal - they are short ($\sim$ 1 day), without flat top, and have no superhump detected.

3. Superoutburst and cycling state - V803 Cen, CR Boo, SDSS J2047, etc.
   The most numerous is the group of the lightcurves showing characteristic a pattern of cycling state following the superoutburst. In this state the luminosity of the system changes by $\sim$ 1 mag within the time of $\sim$ 2 days. The cycling may last as long as the superoutburst itself. The dip during the superoutburst is also present in the lightcurves of this group.

The dip observed in the superoutbursts of AM CVn stars is similar to that observed in superoutbursts of WZ Sge-type DN (e.g. in WZ Sge itself and in AL Com). This is interesting since these Dwarf Novae are systems with orbital periods close to the minimum $P_{\rm orb} \sim 80\,\rm min$ for hydrogen dominated CVs which suggests that the size of the disk may play a role here.

2. The DIM for AM CVn stars

The Disk Instability Model (DIM) (for details see Lasota (2001)) implies that disks are unstable for accretion rates contained between the minimum and maximum values $\dot{M}^{\pm}_{\rm acc}(R)$ which depend on the chemical composition. Numerical fits by Dubus (private communication) give:

For $\rm X = 0, Y = 1, Z = 0$:

$$\dot{M}^{+}_{\rm acc} = 1.01 \times 10^{17} \alpha_{0.1}^{-0.05} R_{10}^{2.68} M_1^{-0.89}$$

$$\dot{M}^{-}_{\rm acc} = 3.17 \times 10^{16} \alpha_{0.1}^{-0.02} R_{10}^{2.66} M_1^{-0.89},$$

For $\rm X = 0, Y = 0.98, Z = 0.02$:

$$\dot{M}^{+}_{\rm acc} = 6.22 \times 10^{16} \alpha_{0.1}^{-0.05} R_{10}^{2.67} M_1^{-0.89}$$

$$\dot{M}^{-}_{\rm acc} = 2.04 \times 10^{16} \alpha_{0.1}^{-0.02} R_{10}^{2.62} M_1^{-0.87},$$

where $\alpha = 0.1\alpha_{0.1}$ is the viscosity parameter, $R = 10^{10}\rm cm\, R_{10}$ the distance from the center and M_1 the primary mass in solar units.

For $\dot{M}_{\rm tr} > \dot{M}^{+}_{\rm acc}(R_{\rm d})$ disks are hot and stable – systems will be observed as persistently bright. Similarly for $\dot{M}_{\rm tr} < \dot{M}^{-}_{\rm acc}(R_{\rm in})$ disks are cold and stable and systems are seen as persistently faint. In fact AM CVns are observed in 3 distinct luminosity states. Those with $P_{\rm orb} <$ 20min (AM CVn, HP Lib and ES Cet) are observed as persistently bright. V803 Cen, CR Boo, SDSS J0926 and SDSS J1240 are found as outbursting and their orbital periods are in the range 20min $< P_{\rm orb} <$ 40min, while faint binaries, like GP Com or V396 Hya, have 40min $< P_{\rm orb}$. The evaluated mass transfer rates for these systems are in agreement with the model prediction for critical mass transfer rates definig the stability of the system - for details see Kotko et al. (in preparation).

The DIM free parameters influence outburst amplitude, recurrence time and shape. These free parameters are: the viscosity parameters for the cold (when the matter in the disk is neutral) and hot (when the matter in the disk is ionized) states – α_c, α_h; the mass transfer rate $\dot{M}_{\rm tr}$; the primary mass M_1; the mean outer disk radius $\bar{R}_{\rm d}$ and the disk chemical composition. However, playing with the parameters results only in normal outbursts. Including additional effects such as the heating of the outer disk by the stream impact, truncation of the inner disk radius by weak magnetic field or evaporation, and irradiation of the inner disk by the primary white dwarf does not change the situation - their influence on the lightcurves is described in detail by Hameury et al. (2000). Within the framework of the standard DIM it is impossible to obtain superoutbursts with dips or superoutbursts followed by cycling state.

It is worth mentioning the effect of the change of chemical composition of the disk on the outbursts amplitude. For a solar composition disk assuming constant α ($\alpha_{\rm cold} = \alpha_{\rm hot}$) results only in $\sim$ 0.5 mag luminosity variations. This fact was the primary motivation for introducing different α's for cold and hot state of the oubursting disk (Smak 1984). Things are different for purely helium disk ($\rm X = 0, Y = 1, Z = 0$), where it is possible to get the outbursts of amplitude up to $\sim$ 2 mag without changing α. The reason for such a behaviour is the dependence of the critical surface density

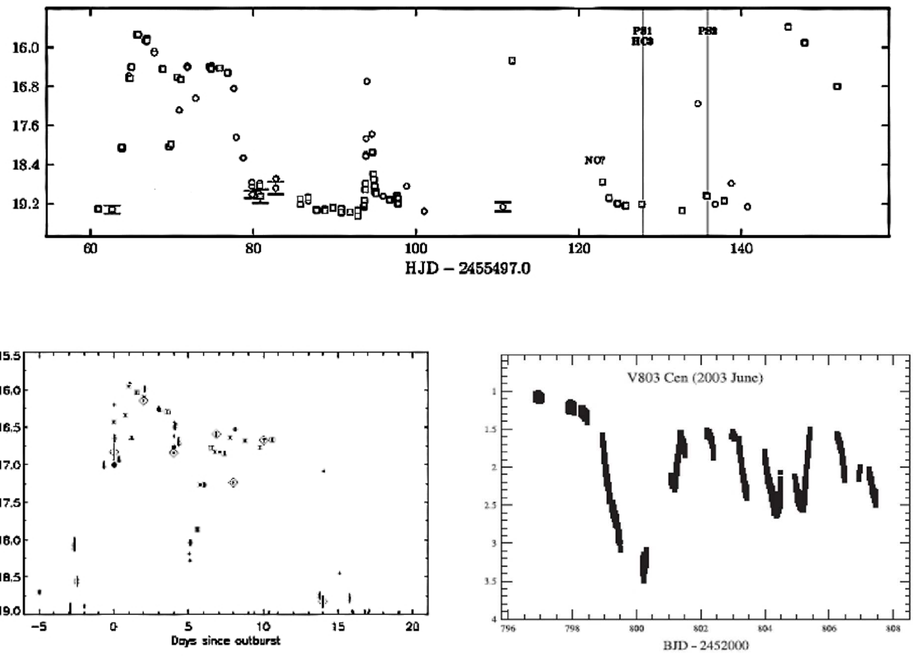

Figure 1. Examples of observational lightcurves of 3 AM CVn stars. *Top*: PTF1J0719+4858 (Levitan et al. 2011); *Bottom, Right*: V803 Cen (Kato et al. 2004); *Bottom, Left*: KL Dra (Ramsay et al. 2010, 2011)

values, $\Sigma^{\pm}_{\rm crit}$, on the disk chemical composition. $\Sigma^{+}_{\rm crit}$ and $\Sigma^{-}_{\rm crit}$ are the surface density values, when the opacity dependence on temperature changes due to the ionization/recombination of the dominant chemical element in the disk. The formulae for $\Sigma^{+}_{\rm crit}$ and $\Sigma^{-}_{\rm crit}$ depend on viscosity parameter α (α_h and α_c respectively), the radius of the disk R, at which thermal balance is considered, and a primary mass M_1 (Lasota et al. 2008).

According to the model, the outburst amplitude is directly connected to the critical surface densities ratio $\beta = \Sigma^{+}_{\rm crit}(\alpha_h)/\Sigma^{-}_{\rm crit}(\alpha_c)$ – the higher the ratio the larger the amplitude. For pure helium disk, β is large enough, even for $\alpha_h = \alpha_c$, to give an amplitude $A \sim 2$ mag. But in other cases (for example $\mathrm{X} = 0, \mathrm{Y} = 0.98, \mathrm{Z} = 0.02$), or for hydrogen-dominated disks, β is too small and to get amplitudes higher than 1 mag has to enlarge it artificially, by changing α's.

But still, even if the disks in AM CVn stars were pure helium (which according to observations is not the case), the necessity of $\alpha_c \neq \alpha_h$ would be preserved, as observed outbursts amplitudes in these systems are often higher than 2 mag.

3. Enhanced mass transfer model.

Simulations of Dwarf Nova outbursts show that enhanced mass transfer rate from the secondary produces superoutbursts (Hameury et al. 2000) In a recent series of seminal papers Smak (2009a,b,c,d) presented the observational evidence supporting such a model in SU UMa stars and showed that the supposed evidence in favour of the presence of an eccentric disk in these systems results "either from errors, or from arbitrary, incorrect assumptions". Since superoutbursts are seen in AM CVn stars it natural to check if mass-transfer enhancement works also in these binary systems.

We have tested two prescriptions for the change of $\dot{M}_{\rm tr}$:

$$\dot{M}_{\rm tr} = \max(\dot{M}_{0,\rm tr}, \gamma \dot{M}_{\rm acc}) \tag{1}$$

(Hameury et al. 2000), where $\dot{M}_{0,\rm tr}$ is the non-enhanced mass transfer rate, γ is a parameter $\in [0, 1]$ and $\dot{M}_{\rm acc}$ is the mass accretion rate on the primary.

$$\dot{M}_{\rm tr} = \max(\dot{M}_{0,\rm tr}, \dot{M}_{0,\rm tr}(1 + C \sin(\pi t/\tau))) \tag{2}$$

where t is the time variable, C and τ are the free parameters.

The physical phenomenon, which is supposed to be responsible for $\dot{M}_{\rm tr}$ enhancement in the first case, is the indirect heating of the equatorial region of a secondary by the outburst radiation. However, the efficiency of this mechanism has been questioned by Villet & Hameury (2007). According to their calculations the heated material from irradiated parts of a secondary will cool too rapidly before reaching the L_1 point to produce a significant mass transfer rate enhancement. Smak (2009d) proposed the alternative mechanism – the disk warping that unveils the L_1 point regions to the direct irradiation by a primary white dwarf. This is the inspiration for the second prescription for $\dot{M}_{\rm tr}$.

The application of the first formula results in the superoutburst – normal outburst sequence and in lightcurves with features resembling the superoutburst-cycling state pattern. But no dip appear during the superoutburst unless one uses the formula with sinusoidal variation of the mass transfer rate.

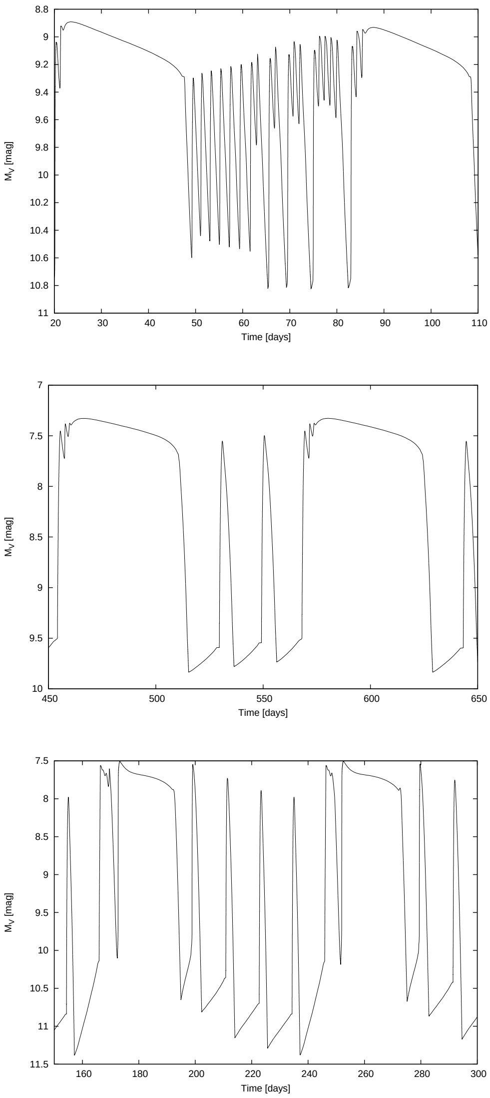

Figure 2. *Top*: X=0.0 Y=0.9997 Z=0.0003 α_c = 0.04 α_h = 0.1 $\dot{M}_{tr}$ = 2×10^{16}[g/s] γ = 0.8; *Middle*: X=0.0 Y=0.98 Z=0.02 α_c = 0.04 α_h = 0.1 $\dot{M}_{tr}$ = 3×10^{16}[g/s] γ = 0.9; *Bottom*: X=0.0 Y=0.98 Z=0.02 α_c = 0.05 α_h = 0.2 $\dot{M}_{tr}$ = 6×10^{16}[g/s], mass transfer rate changes according to 2nd prescription

4. Conclusions

The standard version of the DIM does not explain the characteristic features of AM CVn stars lightcurves. On the basis of our calculations we conclude that the necessary element which has to be included in the model is the enhancement of mass transfer rate. Even though the mechanism of this phenomenon is not well understood our preliminary results show that it is a step in the right direction.

It should be stressed that the chemical composition of the disk has a strong influence on the synthetic lightcurves and it may also have an impact on the conclusions about viscosity parameter α (Kotko et al., in preparation).

Recently, AM CVn stars have attracted attention of several groups of the observers, so with more data there will be an opportunity to test more precisely the DIM and its modifications.

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