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Jean-Marie Hameury, Jean-Pierre Lasota

► **To cite this version:**

Jean-Marie Hameury, Jean-Pierre Lasota. Disc radius variations in binaries. Spectra and timing of compact X-ray binaries, 2005, Mumbai, India. hal-00005346

HAL Id: hal-00005346

<https://hal.science/hal-00005346v1>

Submitted on 13 Jun 2005

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Accretion–disc radius variations in close binaries

Jean-Marie Hameury ^a, Jean-Pierre Lasota ^b

^a*Observatoire de Strasbourg, 67000 Strasbourg, France*

^b*Institut d'Astrophysique de Paris–UMR 7095 du CNRS, 75014 Paris, France*

Abstract

Outer radius variations play an important role disc structure and evolution. We consider theoretical and observational consequences of such variations in cataclysmic binaries and low-mass X-ray binaries. We find that the action of tidal torques must be important well inside the tidal radius. We also conclude that it is doubtful that the tidal-thermal instability is responsible for the superoutburst/superhump phenomena.

Key words: accretion, accretion discs, binaries: close, cataclysmic variables, X-ray binaries

PACS: 97.10.Gz, 97.30.Qt, 97.80.Gm, 97.80.Jp

1 Introduction

Dwarf novae are a subclass of cataclysmic variables undergoing outbursts lasting (at least) a few days during which their brightness increases by several magnitudes (see e.g. Warner, 1995, for a review). These outbursts are widely believed to be due to a thermal/viscous disc instability (see Lasota, 2001, for a review). The weakest point of this model – aside from the assumption that angular momentum transport is due to viscosity (i.e. is a local phenomenon accompanied by energy dissipation) described by the α -prescription, is the approximate treatment of 2D effects at the disc edge.

There is in particular a debate about the outcome of the disc reaching the radius at which the 3:1 resonance occurs (this may happen for low secondary

Email addresses: hameury@astro.u-strasbg.fr (Jean-Marie Hameury), lasota@iap.fr (Jean-Pierre Lasota).

to primary mass-ratios). SPH models (see e.g. Whitehurst, 1988) treat accurately the dynamics of the disc and are in principle quite appropriate to deal with these effects; they predict that when the 3:1 resonance radius is reached, the disc becomes tidally unstable, eccentric and precesses. SPH models are, however, limited in that it is difficult to include in them detailed microphysics; the energy equation is often replaced by isothermal or adiabatic approximations; this significantly affects the results as showed by Kornet & Różyńska (2000). Nevertheless, the tidal instability, coupled with the standard thermal instability is also believed (Osaki, 1989) to be the reason for the long duration of superoutbursts during which superhumps are seen.

Another point of debate is the amplitude of the torque T_{tid} due to the tidal forces, even far from the resonance. In a steady state, the radius of the accretion disc is determined by T_{tid} . One often uses the prescription of Smak (1984), derived from the linear analysis of Papaloizou & Pringle (1977) confirmed by numerical simulations by Ichikawa & Osaki (1994) (at least for radii not too close to the tidal truncation radius r_{tid} , at which the trajectories of test particle orbiting around the white dwarf intersect, leading to high dissipation Paczyński, 1977). This torque reads:

$$T_{\text{tid}} = \check{c} \frac{2\pi}{P} r \nu \Sigma \left(\frac{r}{a} \right)^n \quad (1)$$

where P is the orbital period, a the orbital separation and \check{c} a numerical constant. ν and Σ are respectively the kinematic viscosity coefficient and the surface density. The index n was found to be close to 5. In the particular case of U Gem, Ichikawa & Osaki (1994) obtained a value for \check{c} smaller by almost two orders of magnitude than that required for the disc to be truncated at the tidal radius in steady state. They concluded that the tidal torque is very small everywhere except very close to the tidal radius r_{tid} where T_{tid} diverges. If true, the tidal removal of the angular momentum would occur only at the disk's outer edge within a negligibly small radial extent (Smak, 2002).

We consider here various aspects of outer disc radius variations. We first concentrate on disc sizes observed in eclipsing VY Scl systems. (see Harrop-Allin & Warner, 1996). We then turn to SU UMa stars and Soft X-ray Transients (SXTs) and examine for these systems the consequences of assuming that superhumps and superoutbursts are due to a tidal instability.

2 The tidal torque and VY Scl stars

VY Scl stars are a subgroup of cataclysmic variables which are usually in a bright state, and have occasionally low states during which their luminosity

drops by more than one magnitude, bringing them into the dwarf-nova instability strip. Yet, they do not have dwarf-nova outburst, even though the decline can be very gradual and prolonged, longer than the disc's viscous time. It had been suggested that the apparent stability of these systems could be due to the irradiation of the inner disc edge (Leach et al., 1999), but Hameury & Lasota (2002) showed that outbursts are unavoidable unless the disc disappears completely during quiescence, most probably truncated by the white-dwarf's magnetic field. This translates into a requirement on the magnetic field strength that must be sufficient for the magnetospheric radius to be roughly equal to the circularization radius when the accretion rate is just equal to the critical rate below which instabilities would appear.

Recently, Stanishev et al. (2004) observed the eclipsing VY Scl star DW UMa in a state intermediate between minimum and maximum. Eclipse mapping techniques allowing to reconstruct the disc luminosity profile, they found that the luminosity difference between the high and intermediate states is almost entirely due to a change in the accretion disc radius, from ~ 0.5 to ~ 0.75 times R_{L_1} , the distance from the white dwarf to L_1 . It is observed that in the intermediate state, the disc is entirely eclipsed by the secondary, while its outer parts are visible during the high state. A possible explanation of this could be that the disc is not in equilibrium (i.e. \dot{M} is not constant within the disc), so that radius variations are a consequence of mass redistribution inside the disc. This, however, cannot be the case, since, as noted by Stanishev et al. (2004), the recovery from the low state takes ~ 4 months; the disc has enough time to readjust its structure to changes of the mass-transfer rate. The disc should then be quasi steady, and its radius close to the tidal radius if tidal torques were exerted only in very small annulus at $r \sim r_{\text{tid}}$. Observations show, however, a disc radius $\sim 50\%$ smaller than r_{tid} (Stanishev et al., 2004). We used our disc-instability model code (Buat-Ménard et al., 2001) to simulate the accretion-disc properties of DW UMa. We used Eq. (1) with a large \check{c} .

Figure 1 shows the evolution of a system with parameters similar to those of DW UMa, in which the white dwarf is magnetized strongly enough to prevent dwarf nova outbursts during intermediate and low states. There are still some small oscillations left but these could be suppressed if the field were slightly stronger, and are probably not detectable. We have assumed a slow decrease of the mass transfer rate \dot{M}_{tr} until the disc almost disappears, followed by a rapid (essentially for numerical reasons) increase of \dot{M}_{tr} . The second panel shows that the disc is always close to equilibrium ($\dot{M} \approx \dot{M}_{\text{tr}}$). It can be seen that significant variations of the outer disc radius are obtained. When the disc is still fainter by 1 magnitude than the maximum, the disc is 20% smaller than its maximal extension. This is not quite the 50% variations that are claimed by Stanishev et al. (2004), but is acceptable in view of the fact that we define the disc outer edge as the place where the surface density vanishes, whereas Stanishev et al. (2004) use a photometric definition.

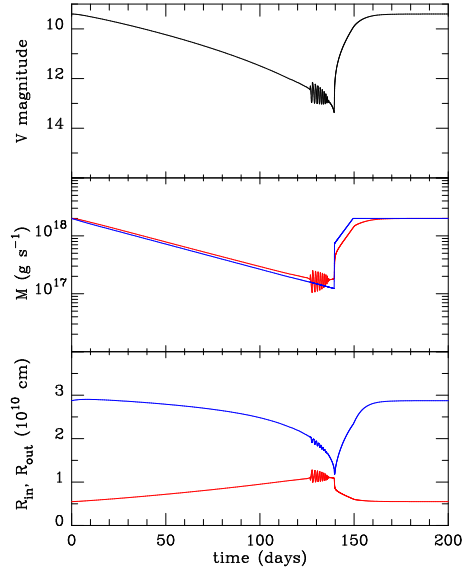


Fig. 1. Evolution of a system with the parameters of DW UMa resulting from changes of the mass transfer from the secondary. The top panel shows the visual magnitude of the system, the intermediate one the mass transfer from the secondary (blue curve) and the mass accretion rate onto the white dwarf (red curve, slightly below the previous one), and the bottom panel the inner and outer disc radius. The magnetic moment is $8 \cdot 10^{32} \text{ G cm}^3$, and the primary mass $0.7 M_{\odot}$

These results show that the tidal coupling cannot be negligible in the intermediate state, even at radii quite a bit smaller than the tidal truncation radius.

3 SU UMa systems

As mentioned earlier, the popular explanation for superoutbursts combines the thermal instability with a tidal instability that is supposed to arise when the disc reaches the 3:1 resonance radius (see e.g. Osaki, 1989). At this point, the disc would become eccentric and precess, allegedly causing the superhumps. The tidal torque T_{tid} is supposed to increase by at least one order of magnitude, resulting in a corresponding enhancement of dissipation and angular momentum transport. According to this scenario the disc shrinks until the radius has decreased to an (arbitrarily chosen) critical value of the order of 0.35 times the orbital separation, and the superoutburst stops. A sequence of several normal outbursts, during which the disc grows on average then follows until the next superoutburst.

This model is essentially based on SPH simulations indicating that the disc does become eccentric and precesses when the 3:1 resonance radius is reached (Murray, 2000; Truss et al., 2001), and on the fact that SU UMa systems are found below the period gap, for systems in which the mass ratio q is less than

$1/3$ – the condition for the 3:1 resonance–radius to be smaller than the tidal truncation radius. According to simulations by Truss et al. (2001) the critical value of q above which no superoutburst occur is in fact rather $1/4$.

However, two elements seem to have seriously put in doubt the viability of the thermal-tidal model of super-humps and outbursts. First, Kornet & Różyczka (2000) found that the outcome of numerical simulations depends on the equation of state that has been used; they found that eulerian models gave the same results as the SPH codes in the isothermal approximation, but found very different results (no superhumps) when using the full thermal equation. More recently Smak & Waagen (2005) discovered superhumps in the famous U Gem 1985–superoutburst. The component masses of this prototypical binary are rather well constrained giving a rather large value of $q = 0.364 \pm 0.017$. Clearly the tidal instability cannot apply to this system. In addition, a permanent superhump was detected in TV Col (Retter et al., 2003) a binary with an estimated mass-ratio between $q = 0.62$ and 0.93 (Hellier, 1993), consistent with its 5.39 hour orbital period. One could try to save the tidal model by arguing that U Gem and TV Col superhumps are phenomena different from those observed in SU UMa stars but such an argument would have to explain why, as remarked by Smak & Waagen (2005), when plotted on superhump excess-period vs orbital period (logarithmic) plane, U Gem and TV Col fall on the linear extension of the relations defined by shorter period dwarf novae and permanent superhumpers (see Patterson et al., 2003, Fig. 20).

Clearly a new model for SU UMa stars is needed. Irradiation and enhanced mass transfer probably play a significant role (Hameury et al., 2000), but one must find an explanation for the superhump and superoutburst phenomena keeping in mind that none of them seems to require the action of tidal forces.

4 Soft X-ray transients

In SXTs, the mass ratio is usually very small, and one would expect to find superhumps in these systems, if indeed the explanation of this effect is related to the tidal instability. Indeed there is observational evidence of modulations at periods slightly longer than the orbital period (Zurita et al., 2002, see also Charles, these proceedings). There are, however, several important differences between SXTs and SU UMa's: first, because the mass ratios are extremely small, the disc should remain permanently eccentric, and second, the outer parts of the disc can remain unaffected by the thermal instability in systems where the disc is large. Finally, in SXTs superhumps would arise from a modulation of the reprocessed flux by the changing disc area and not from an increase of viscous dissipation as in SU UMa stars (Haswell et al., 2001).

As an example, for $q = 0.05$, the circularization radius is $0.42a$, where a is the orbital separation, larger than the critical radius below which the tidal instability cannot be maintained (typically $0.35a$, see e.g. Osaki, 1989). The disc can therefore never shrink enough for the tidal instability to stop, and it should remain in a permanently eccentric state. This conclusion holds for values of q below 0.10, i.e. for most SXTs. Therefore the tidal instability cannot be the cause of SXT outbursts.

4.1 Short period systems

For systems with periods P less than ~ 1 day, such as A 0620-00, the whole disc is affected by the outburst. One therefore expects that the superhump modulation, if related to the 3:1 tidal instability, should be visible in these systems. Systems for which a superorbital modulation has been claimed (XTE J1118+480, Nova Musca 1991, GRO J0422+32 and GS 2000+25; Zurita et al., 2002; O’Donoghue & Charles, 1996) all have $P \leq 1$ d. However, the disc is *always* larger than the 3:1 resonance radius as confirmed by the presence of the superhump in quiescence (Zurita et al., 2002), hence outbursts in SXTs cannot be due to tidal interactions. Interestingly superhumps in quiescence have been also observed in SU UMa stars (Patterson et al., 1995).

4.2 Long period systems

In systems with long orbital periods, the outer disc will not be affected by the outburst, except possibly by illumination effects. If the tidal instability sets in, it will therefore always remain present, and superhumps are expected to be present both in quiescence or in outburst. It turns out however that in quiescence, the outer disc is too cold to radiate efficiently even in the infrared: most of the luminosity originates from the central regions, despite the reduced emitting area. Figure 2 shows the structure of a disc in a system with the orbital parameters of black-hole X-ray transient V404 Cyg (M_1 : $12 M_\odot$; M_2 : $0.7 M_\odot$; P : 78 hr); the mass transfer rate was taken to be 10^{16} g s^{-1} .

In quiescence, the effective temperature is of order of 1000 K, and less than 0.1 % of the total luminosity is emitted by the outer parts of the disc; any modulation of the light emitted by these cool regions would therefore be undetectable.

In outburst, the disc heats up as a result of irradiation from the primary (we assumed here the same prescription for irradiation as in Dubus et al. (1999, 2001)). A significant fraction of the disc luminosity in the infrared band should therefore be emitted by regions of the disc possibly affected by the tidal

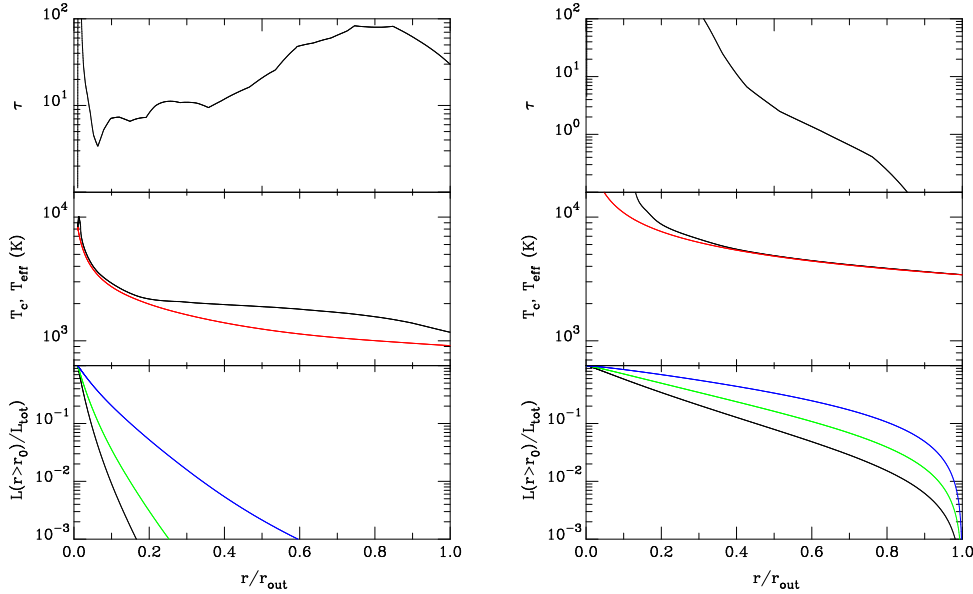


Fig. 2. Structure of the accretion disc in a system with the orbital parameters of V 404 Cyg, in quiescence (left), and in outburst (right). The top panel shows the optical depth of the disc as a function of radius, the intermediate one the central (upper curve) and effective (lower curve) temperatures, and the bottom panel gives the fraction of the total luminosity emitted above a given radius in the I (upper curve), V (intermediate), and B (lower) bands

instability. However, the opacity is minimum for temperatures of the order of 3,000 K, typical in these regions that are affected by illumination, and it turns out that the optical depth is very small. As a consequence, the assumption of blackbody emission does no longer hold, and the colour temperature will be significantly higher than the effective temperature; light will be shifted in the optical or blue band, and will again be diluted in the total light emitted by the inner disc.

We therefore do not expect to detect any superorbital modulation in these systems, in the hypothesis that it would originate from the outer parts of the accretion disc (whether it is caused by a tidal instability or not).

5 Conclusion

The effects of the companion on the accretion disc are still unclear. Even in the simple case where no strong resonance is present, observations of intermediate states of VY Scl stars indicate that the tidal torques must be strong enough to truncate the disc at radii much smaller than the so called tidal truncation radius. The presence of superhumps during the superoutburst of U Gem casts doubt on the validity of the tidal-thermal model of these phenomena. This

conclusion is strengthened by theory and observations of superhumps in TV Col. If we make the assumption that superhumps are in some way related to the 3:1 resonance, we predict that superhumps should be observed in short period SXTs in quiescence and in outburst, but not in long period systems. The outburst mechanism should then be unrelated to this resonance, and the tidal-thermal instability model does not apply to these systems.

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