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Accretion disk evolution in dwarf novae through outbursts: disk instability and mass-transfer instability cases

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Abstract. I discuss a set of observations of eclipsing dwarf novae through outbursts which allow fundamental tests of the predictions of the two models proposed to explain their outbursts. The observational picture which emerges from these tests indicate that there are two distinct groups of dwarf novae. While the outbursts of one group can be understood in the framework of the thermal-viscous disc instability model, those of the other group can only be explained in terms of the mass-transfer instability model. I also show that morphological differences in the orbital light curves of eclipsing dwarf novae can be useful to distinguish members of each group.

Key words. accretion, accretion discs — stars: dwarf novae — stars: imaging — novae, cataclysmic variables — binaries: eclipsing

1. Introduction

In dwarf novae, a late-type star overfills its Roche lobe and transfers mass to a non-magnetic ($B \leq 10^{5-6}\,G$) white dwarf (WD) via an accretion disc. They show recurrent outbursts on timescales of days-months, in which the disc brightens by factors 10-100 for $\simeq$ 1-15 days as a result of a sudden increase in mass accretion. Two models were proposed to explain these outbursts. In the mass transfer instability model (MTIM, e.g., Bath 1975), the outburst is the time dependent response of a viscous accretion disc to a burst of mass transfer from the donor star. In the thermal-viscous disc-instability model (DIM, e.g., Lasota 2001), matter is transferred at a roughly constant rate to a low viscosity disc and accumulates until a critical surface density is reached at a given radius, causing a heating wave to switch the disc to a high viscosity regime allowing the gas to diffuse rapidly inwards and onto the white dwarf. Below I list a set of distinct predictions from these models that might be tested observationally:

1. *The disc viscosity in quiescence:* The disc viscosity parameter at outburst is observationally constrained by the rise and decline timescales to be $\alpha_o \sim 10^{-1}$. Within the MTIM framework, the same value holds during quiescence $\alpha_q = \alpha_o$. However, in order to match the observed duration and amplitude of dwarf nova outbursts, DIM requires that the disc viscosity in quiescence be an order of magnitude lower

Send offprint requests to: R. Baptista than in outburst, $\alpha_q \sim 0.1\alpha_o \sim 10^{-2}$ (Lasota 2001). Therefore, DIM predicts low-brightness, non-steady state quiescent discs with a slow response to changes in mass transfer rate, $\dot{\mathrm{M}}$, while MTIM predicts higher brightness, steady-state quiescent discs which reacts to changes in $\dot{\mathrm{M}}$ at the same short timescale as in outburst.

2. *Changes at outburst onset:* As a consequence of the burst of mass transfer, MTIM predicts gas stream overflow and enhanced emission along the stream trajectory beyond the disc rim at outburst onset. Furthermore, the disc reacts to the sudden addition of matter with low specific angular momentum by first shrinking (and then expanding because of redistribution of angular momentum). Within the DIM framework no enhanced gas stream emission nor disc shrinking at outburst onset are expected (the disc just expands towards outburst maximum).
3. *Disc temperatures along outburst cycle:* Because the thermal limit-cycle relies on the partial ionization of hydrogen, disc temperatures are strongly constrained in the DIM framework, with quiescent discs bound to $T < T_{\rm crit1} \simeq 6000\,K$ and hotter outbursting discs with $T > T_{\rm crit2} = (10000 - 7000)\,K$ for $R = (0.02 - 0.5)\,R_\odot$. There are no temperature restrictions for discs in the MTIM.
4. *Speed of cooling wave:* DIM predicts the cooling wave that switches the disc back to its low-viscosity state should decelerate at it moves inwards (Menou et al. 1999). In MTIM the cooling wave may either accelerate or decelerate, depending on the radial run of the disc viscosity parameter.

Eclipsing dwarf novae provide the opportunity to study the time evolution of their accretion discs and to critically test the above set of predictions with the aid of eclipse mapping techniques (Horne 1985). From the shape of the eclipse it is possible to infer the disc radius by measuring the ingress/egress phases of the WD and of the bright spot (BS) where the in-falling gas hits the edge of the disc and to test whether the disc shrinks at outburst onset (Baptista et al. 2007). Time-resolved eclipse mapping through outburst can be used to (i) detect enhanced gas stream emission at early outburst stages, (ii) follow the time evolution of the disc temperature distribution $T_b(R)$ and compare them with $T_{\rm crit1}$ and $T_{\rm crit2}$, (iii) test whether $T_b(R)$ of a quiescent disc is consistent with that of an opaque, steady-state disc, and (iv) trace possible acceleration/deceleration of the cooling wave by measuring its speed at different stages along outburst decline (Baptista & Catalán 2001). Flickering mapping has been useful to separate the stream-related and disc-related flickering sources (Baptista & Bortoletto 2004) and, if the disc-related flickering is caused by magneto-hydrodynamic (MHD) turbulence (Geertsema & Achterberg 1992), it is possible to infer the radial run of the disc viscosity parameter from the radial distribution of the flickering relative amplitude.

2. Where DIM works

The light curve of Z Cha shows the double-stepped sequential eclipse of the WD at disc centre and of the BS at disc edge, plus a conspicuous orbital hump caused by anisotropic emission from the BS (Fig. 2). This indicates that its optical light is largely dominated by emission from the WD and the BS, with a small contribution from a relatively faint accretion disc (Wood et al. 1986). The ratio of the disc to the BS luminosity is,

$$\frac{L_{\rm disc}}{L_{\rm bs}} = \frac{\dot{\mathrm{M}}(wd)}{\dot{\mathrm{M}}(bs)} \frac{R_{bs}}{R_{wd}}\,, \tag{1}$$

where $\dot{\mathrm{M}}(wd)$ and $\dot{\mathrm{M}}(bs)$ are, respectively, the mass accretion onto the WD and the mass inflow in the outer disc (at the BS), and R_{wd} and R_{bs} are the WD and the BS radii, respectively. Because $L_{\rm bs} > L_{\rm disc}$ and $R_{bs} \gg R_{wd}$, one is forced to conclude that $\dot{\mathrm{M}}(wd) \ll \dot{\mathrm{M}}(bs)$, indicating that matter is accumulating in an unsteady, low-viscosity disc in quiescence – in agreement with DIM predictions. Eclipse mapping of the Z Cha accretion disc underscores this conclusion. The radial temperature distribution in outburst closely follows the $T \propto$

$R^{-3/4}$ law expected for an opaque steady-state disc (Horne & Cook 1985), while that in quiescence is essentially flat with $T \leq T_{\rm crit1}$ everywhere (Wood et al. 1986). This indicates that the accretion disc viscosity is much lower in quiescence than in outburst and that the quiescent disc is far from being in a steady-state – lending further support to the DIM. Similar light curve morphology and results are found for OY Car (Rutten et al. 1992) and IP Peg (Wood & Crawford 1986; Bobinger et al. 1997). While in U Gem and WZ Sge the lower inclination does not lead to eclipses of the WD and eclipse mapping studies cannot be properly made, the fact that their light curves in quiescence are also dominated by strong anisotropic emission from the BS suggests that they also belong to the group of eclipsing dwarf novae the outbursts of which can be explained by the DIM.

3. Where DIM fails (and MTIM works)

Time-resolved eclipse mapping of EX Dra along outbursts shows that the temperatures of the outbursting disc are $T > T_{\rm crit2}$, and that the cooling front decelerates as it travels inwards (Baptista & Catalán 2001). As these results are consistent with both DIM and MTIM, they offer no power to discriminate between these models. However, the same eclipse mapping study reveals that the radial temperature distribution of EX Dra in quiescence follows the $T \propto R^{-3/4}$ law of opaque steady-state discs (Fig. 1), and that this quiescent state is reached only 2 d after the end of the outburst. Both results indicate that the viscosity of its quiescent disc is as large as in outburst – in contradiction with DIM and in agreement with predictions of the MTIM. In addition, the early rise map shows evidence of enhanced gas stream emission, indicative of an enhanced mass transfer rate at this early outburst stage (Fig. 1). The integrated disc luminosity at early rise ($1.4 \pm 0.3\,L_\odot$) is comparable to that in quiescence ($1.2 \pm 0.1\,L_\odot$), and is not enough to support the idea that the enhanced mass transfer could be triggered by an increased irradiation of the mass donor by the accretion disc. Thus, one is lead to the conclusion that the observed enhanced mass transfer at early rise is not a consequence of an ongoing outburst, but its cause. The outbursts of EX Dra seems powered by bursts of mass transfer – as predicted by the MTIM.

A similar time-lapse eclipse mapping study of the dwarf nova V2051 Oph yields a compelling set of results in favour of the MTIM (Baptista et al. 2007). It is found that (i) the disc shrinks at outburst onset, (ii) the cooling wave accelerates as it travels towards disc center, and (iii) during outburst the disc brightness temperatures remain below $T_{\rm crit2}$ everywhere for an assumed distance of 92 pc. In addition, the disc viscosity parameter inferred from its flickering mapping in quiescence is large and comparable to that measured in outburst, $\alpha_q \simeq \alpha_o \simeq 0.1 - 0.2$ (Baptista & Bortoletto 2004). The results of a combined time-lapse and flickering mapping study of HT Cas in quiescence also favors the MTIM. The fast response of the WD and of the disc to an increase in $\dot{\rm M}$ and the relative amplitude of the disc-related flickering indicate that the quiescent disc of HT Has has high viscosity, $\alpha_q \simeq 0.3 - 0.7$ (Baptista et al. 2011). This is in clear disagreement with DIM and implies that the outbursts of HT Cas are caused by bursts of enhanced mass-transfer from its donor star – in agreement with predictions by the MTIM. Similar results are found for V4140 Sgr (Baptista et al. 2012).

Although it is not an eclipsing system, SS Cyg might also be included in the group of dwarf novae with MTIM-driven outbursts. At a distance of ($166 \pm 12\,pc$) its accretion disc is hot enough to be always on the stable branch of the thermal-limit cycle and, therefore, no dwarf nova outbursts would be possible within the DIM framework (Schreiber & Lasota 2007).

4. Discussion and conclusions

The picture that emerges from the observational evidence presented in the previous sections indicates there are two distinct groups of dwarf novae. While the outbursts of one group can be understood in the DIM framework, those of the other group can only be explained in terms of the MTIM. The basic question seems no longer which model is right.

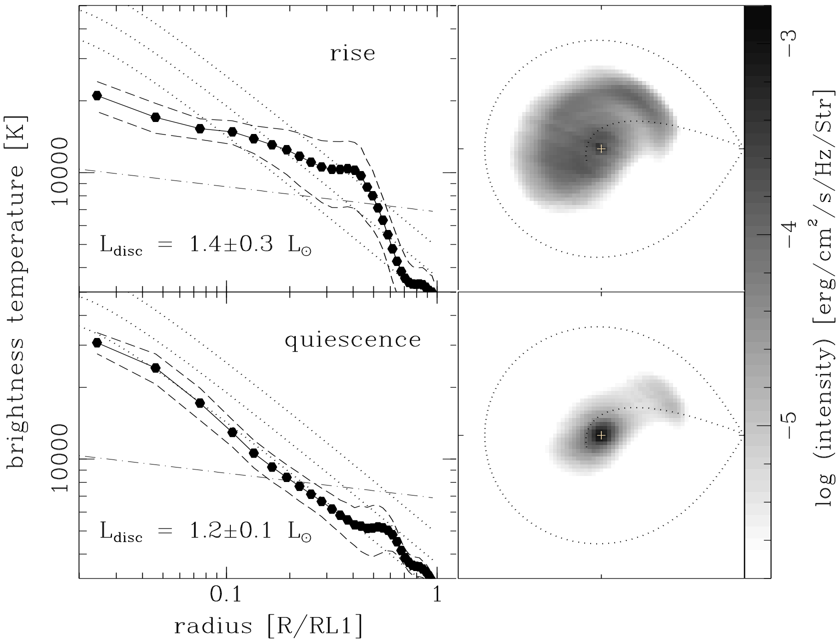

Fig. 1. Left: average radial temperature distributions for the accretion disc of EX Dra in quiescence (bottom) and rise to outburst maximum (top). Dashed lines show the 1-σ limits on the average temperature, while dotted lines show the $T \propto R^{-3/4}$ law of opaque steady-state discs for mass accretion rates of 10^{-8}, $10^{-8.5}$ and 10^{-9} $M_{\odot} yr^{-1}$. Integrated disc luminosities (in $L_{\odot}$) are indicated in each panel. Right: corresponding eclipse maps in a logarithmic grayscale. Dotted lines show the primary Roche lobe and the ballistic stream trajectory.

Instead, one could now properly ask: which mechanism applies to which object?

Alternatively, is there an observational criterion one could use to identify membership to each group? Dwarf novae with DIM-driven outbursts (DDNs) have low-viscosity quiescent discs, while those with MTIM-driven outbursts (MDNs) have high-viscosity quiescent disc. This leads to clear morphological differences in the light curves of eclipsing systems (Fig. 2). Because there is little accretion onto the WD in DDNs, their quiescent light curves are dominated by emission from the BS and shows strong orbital hump plus a double-stepped eclipse shape. In contrast, the viscous quiescent discs of MDNs outshine the BS emission and their light curves show weak or absent orbital hump and smooth eclipses that resemble those of nova-like systems.

The idea that dwarf nova outbursts can be powered by two distinct mechanisms needs to be explored from the theoretical point of view and tested in more detail from the observational point of view. Given the key role of the quiescent disc viscosity in discriminating between the two models, important studies to be performed concern the flickering mapping of quiescent DDNs to see whether one finds $\alpha_q \sim 10^{-2}$ (as expected from DIM) and independent of radius (as usually assumed by DIM theoreticians). Additionally, more eclipse mapping studies are needed to increase the (so far poor) statistics about the two groups. In the theoretical side, there are important questions that will need to be addressed: Why (and how) mass transfer from the donor star is unstable? What is the influence of the WD magnetic field on the time behavior of $\dot{M}_2$ (e.g., why is $\dot{M}_2(t)$

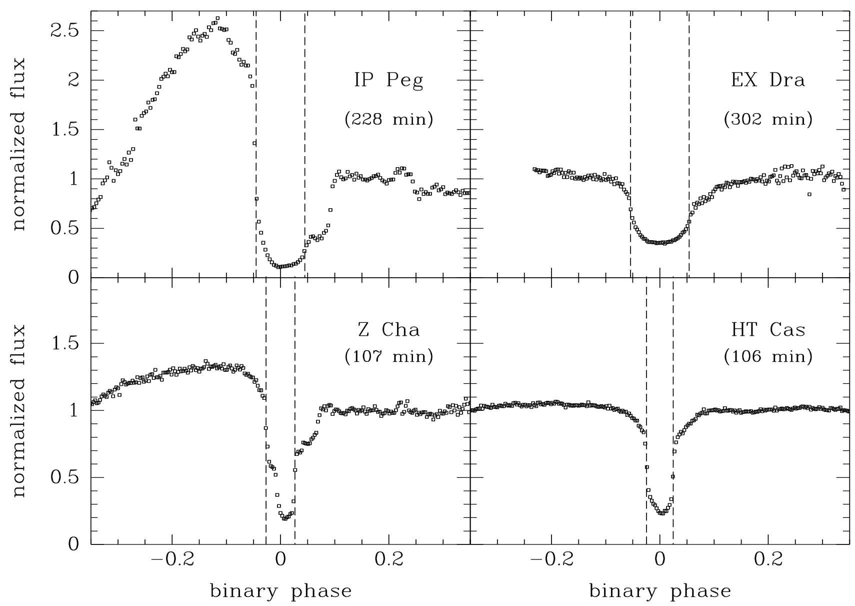

Fig. 2. Comparison of average quiescent optical light curves of dwarf novae with DIM-driven outbursts (left) and MTIM-driven outbursts (right), with examples above (top) and below (bottom) the CV period gap. Vertical dashed lines mark the ingress/egress phases of the WD at disc centre. The light curves were normalized to show unit flux outside of eclipse and away from the orbital hump.

of AM Her so different from that of SS Cyg)? Why is the disc viscosity of MDNs always high and, apparently, independent from $\dot{M}$ (and from the resulting physical conditions in the accretion disc)?

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