Predictions of the disc instability model

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**Abstract.** Confronting the predictions of numerical calculations with observations is an important tool to progress with our understanding of the mechanism triggering the outbursts of dwarf novae and soft X-ray transients. Simultaneous multi-wavelength observations are of particular importance in this process as they contain information about the chronology of the outbursts e.g. the famous UV-delay observed in dwarf novae. We review key-predictions of the disc instability model (DIM) and confront them with the corresponding observations.

1. Introduction

Dwarf novae are a subgroup of cataclysmic variables (CVs) whose rather regular $2 - 5$ mag outbursts are thought to be driven by disc instabilities. This idea is based on the existence of a thermal-viscous instability in regions where hydrogen is partially ionized, and opacities depend strongly on temperature. Disc instabilities as the mechanism for dwarf nova outbursts have been proposed almost 30 years ago and first numerical models have been developed in the eighties. Compared to these early models the current disc instability model (DIM) has become rather complex: evaporation [Meyer & Meyer-Hofmeister 1994], irradiation [Hameury et al. 1999, Schreiber & Gansicke 2001], stream impact heating, tidal dissipation [Buat-Ménard et al. 2001a], stream overflow [Schreiber & Hessman 1998], magnetic truncation [Lasota et al. 1995], and mass transfer variations on almost every possible time scale [Schreiber et al. 2000; Buat-Ménard et al. 2001b] have been added to the “pure” disc instability. Consequently, the number of unconstrained parameter significantly increased. Confronting predictions of the model with observations requires therefore to focus on systematic dependencies of the predictions on the parameter instead of trying to “fit” the observations.

We review predictions of state-of-the-art DIM calculations in the light of recent observations. In particular, we concentrate on four topics: UV and EUV delays (Sect. 2); truncation and X-ray emission during quiescence (Sect. 3); the
triggering mechanism for superoutbursts in SU UMa systems (Sect. 4); and the absolute magnitude of SS Cyg

2. Delays: outside-in versus inside-out outbursts

Since the early days of the model, it has been known that outbursts can be triggered close to the white dwarf or in outer disc regions. If the mass transfer rate is high, the accumulation time at the outer disc edge can be shorter than the viscous diffusion time, and the instability will be triggered in the disc outer regions; the outburst is of the outside-in type. On the other hand, for low mass transfer rates, the viscous time is shorter, and the outburst will be triggered at the inner edge; it is of the inside-out type. The limit between both types of outburst therefore depends sensitively on parameters such as the mass transfer rate and the viscosity; it is therefore important to be able to determine the type of observed outbursts for constraining these parameters.

The so-called UV delay between the UV and optical rise, measured for several dwarf novae, has often been considered as a power discriminating tool between both types of outbursts. As UV radiation is emitted close to the white dwarf, one would expect that there should be a long delay in cases where the outburst is triggered in the disc outer regions, and no delay when the outburst starts at the inner disc edge. That this hypothesis can explain the observations has been stated early by Smak (1984). Shortly thereafter Pringle et al. (1986) claimed the existence of a “problem of the UV-delay” with the consequence that the following years were characterized by many attempts to find a solution for the alleged problem. Finally Smak (1998) came to the conclusion, that there is no problem if one uses the correct outer boundary condition. Here we show that Smak is right in that there is no problem but in contrast to his findings this has nothing to do with the outburst type.

Figure 1 shows predicted optical, UV, EUV, and X-ray light curves assuming the orbital parameter of SS Cyg. These light curves are calculated using the DIM-code described in detail in Hameury et al. (1998) in which tidal dissipation and stream impact heating have been included (Buat-Ménard et al. 2001a). The emission from the boundary layer is approximated as described in Schreiber et al. (2003): the boundary layer is optically thin and emits X-rays for low accretion rates, but becomes optically thick when the accretion rate exceeds the critical value $M_c = 10^{16} \text{gs}^{-1}$.

Apparently, the calculated UV and EUV delays are longer in the case of an inside-out outburst - just the opposite to what one would naively expect. To understand this result one has to take into account that the UV emission is rising when inner disc regions reach high accretion rates which is not identical to the moment at which the heating front arrives. The same holds for the EUV rise: to get a significant increase of EUV emission, the accretion rate onto the white dwarf has to increase and this does not necessarily happen when the heating front is reaching the boundary layer.

\[1\] Please note, our general conclusions are independent of this effects
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Figure 1. The predicted normalized optical (solid line) and UV flux (dashed–dotted) as well as the normalized boundary layer emission, i.e. X-rays (dotted) and EUV (long dashed) for inside-out (left) and outside-in (right) outbursts. The intermediate panel shows a detailed view of the outburst rise. The bottom panels show the heating front velocity corresponding to the rise of the outbursts. The ignition radius is marked by the vertical dashed–dotted line (see also Schreiber et al. 2003).

One has to consider another difference of outside-in and inside-out heating fronts than their propagation direction to understand the light curves. Inside-out heating fronts must propagate “uphill” against the surface-density and angular-momentum gradients. This makes the propagation difficult and such fronts can be subject to dying before reaching the outer disc (see, e.g. Lasota 2001). In contrast, an outside–in heating front starts in high surface density regions and has an easy way “downhill” sliding down along the gradients. They never die before fulfilling their task. Thus, for an outside–in front the accretion rate in the inner regions of the disc as well as the accretion rate onto the white dwarf increase much more rapidly than in the case of an inside–out heating front. As a consequence, the UV and EUV delay at the onset of the optical rise are shorter than in the inside–out case but both are in agreement with the observations (Schreiber et al. 2003). The old picture is valid only for the X-ray emission from the optically thin boundary layer: in the case of an inside-out outbursts there is no delay of the X-ray rise with respect to the optical (Figure 1). When the heating front started far away from the white dwarf, the X-ray flare is delayed relative to the optical rise by 0.3 – 0.45 days, i.e. the time it takes the heating front to reach the inner edge.
Figure 2. Optical light curves and mass accretion rates when the inner region is assumed to emit X-rays ($\dot{M}_{\text{thin}}$) assuming the orbital parameters of VW Hyi. In the top panels we assumed the disc to extend down to the surface of the white dwarf whereas the disc has been truncated during quiescence in the bottom panels. In the latter case the accretion rate is higher and almost constant during quiescence. X-ray flares are predicted at the onset and end of the outbursts.

3. X-rays and truncation during quiescence

The accretion rate derived from X-ray observations of dwarf novae during quiescence is generally several orders of magnitudes larger than the one predicted by the standard DIM. Three prominent examples are SS Cyg (Wheatley et al. 2003), VW Hyi (Pandel et al. 2003), and OY Car (Ramsay et al. 2001). As it is too often ignored we want to stress here again that disc truncation by a magnetic field (Lasota et al. 1995; Hameury et al. 1997; Schreiber et al. 2003, 2004) and/or by evaporation (Meyer & Meyer-Hofmeister 1994) can bring into agreement models and observations because the disc is not stationary during quiescence. Assuming e.g. a weakly magnetic white dwarf, the inner disc radius is given by the “magnetospheric” radius, i.e. $R_{\text{in}} = R_{\text{M}} = 9.8 \times 10^{8} \dot{M}_{15}^{-2/7} M_{\text{wd}}^{-1/7} \mu_{30}^{4/7} \text{cm}$ where $\mu_{30}$ is the magnetic moment of the white dwarf in units of $10^{30}$ G cm$^{3}$ (Hameury & Lasota 2002). The postulation of such an inner hole dramatically increases the predicted X-ray flux during quiescence. Figure 2 displays this influence of truncation on the predicted X-ray emission for the parameter of VW Hyi. Instead of $10^{11} - 10^{13}$ g s$^{-1}$ without truncation we obtain $\dot{M}_{\text{acc}} \sim 3 - 5 \times 10^{14}$ g s$^{-1}$ with truncation. This increase of the expected X-ray emission during quiescence results from the fact that the DIM predicts accretion rates which increase with radius while the disc accumulates mass.
4. What triggers superoutbursts in SU UMa systems?

SU UMa stars are short-period, i.e. $P_{\text{orb}} \leq 2.2$ hr dwarf novae whose light curve consists of two types of outburst: normal dwarf nova outbursts and 5-10 times longer as well as $\sim 0.7$ mag brighter superoutbursts. Sometimes superoutbursts follow a so-called precursor outburst, i.e. a normal outburst shortly before the superoutburst.

Since the early days of the DIM it is discussed whether the particular behavior of SU UMa systems is caused by a thermal tidal instability (TTI) (e.g. Osaki 1996) or by enhanced mass transfer (EMT) from the secondary (Hameury et al. 2000). Here we focus just on one important systematic difference of the models which concerns the sensitivity of the predictions to variations of the mean mass transfer rate. In the TTI model (TTIM) a super outburst is triggered when the disc expands beyond the 3:1 resonance radius and becomes tidally unstable. Increasing the mass transfer rate has two effects: (1) the disc’s mass increases faster which makes it easier to reach the critical radius during outburst and (2) the torque exerted by the stream material increases which makes it more difficult to reach $R_{\text{crit}}$. Both effects cancel out to some extent and the predictions of the TTIM are rather insensitive to fluctuations of the mass transfer rate. In the EMT model (EMTM) the triggering condition for superoutbursts is independent of the outer radius reached during the expansion. Instead it depends on the maximum accretion rate during outburst which increases with the mass of the disc. So the disc mass must exceed a critical value to trigger a superoutburst. The time scale on which a superoutburst is triggered depends therefore only on the mean mass transfer rate.

Figure 3 shows light curves calculated with the TTIM and the EMTM for different values of the mass transfer rate. While the mass transfer rate has been changed drastically in the case of the TTIM (Figure 3, right), we just slightly increased it for the EMTM (Figure 3, left). The predictions of the EMTM are much more sensitive to mass transfer variations as e.g. the number of normal outbursts decreased from five to three and the precursor outburst disappeared. The burning question now is, how does this difference relate to observations?

The answer is obvious. Observed light curves of SU UMa stars do not only differ from system to system, there are also strong variations in the light curves of single systems. For example, in VW Hyi neither the single outbursts nor the outburst cycles are strictly periodic. Bateson (1977) divided the superoutbursts of VW Hyi in two classes: those with a single superoutburst and those where a precursor outburst is separated from the superoutburst. In addition, the number of normal outbursts observed between two superoutbursts varies from three to seven and the supercycle duration ranges from $\sim 100$ to $\sim 250$ days (e.g. Mohanty & Schlegel 1995). Such variations of the supercycle length and the frequency of normal outbursts can be considered as typical for ordinary SU UMa stars. They are natural outcome of the EMTM while the TTIM fails to explain them.
Figure 3. The response of the TTIM (right) and the EMTM (left) to strong (right) and small (left) changes of the mean mass transfer rate. Concerning the outburst cycle, the number of normal outbursts per supercycle as well as the precursor phenomenon, the predictions of the EMTM depend sensitively depend on the mean mass transfer rate (for more details see also Schreiber et al. 2004).

5. The DIM and the distance of SS Cyg

The HST/FGS parallax of SS Cyg revealed a distance of \(166 \pm 12\) pc (Harrison et al. 1999) and it has been shown that the required absolute magnitude during outburst cannot be reproduced by the current DIM (Schreiber & Gänsicke 2002). If the extreme “new” distance were confirmed, two distinct problems would appear. First, one would have to explain why SS Cyg has behaved for more than 100 years as a bona fide U Gem dwarf nova, but is on the average brighter than Z Cam and two other DN of the same type EM Cyg and AH Her, which are at the same orbital period, and presumably have a larger disc due to a less massive primary. Second, even if this observational problem could be solved by e.g. reevaluating distances to all CVs, one would still have to (at least) drastically revise the DIM as the critical temperature above which the disc is stable is one of the few predictions of the model which does not depend on any free parameter; this would imply decoupling the change of viscosity from the “original” instability due to partial ionization of hydrogen – a frightening hypothesis as the existence of the “natural” instability is one of the key-strengths of the model.

References

Bateson, F. M. 1977, New Zealand Journal of Science, 20, 73
Buat-Ménard, V., Hameury, J.-M., & Lasota, J.-P. 2001a, A&A, 366, 612
—. 2001b, A&A, 369, 925
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Hameury, J., Menou, K., Dubus, G., Lasota, J., & Hure, J. 1998, MNRAS, 298, 1048
Hameury, J.-M. & Lasota, J.-P. 2002, A&A, 394, 231
Hameury, J. M., Lasota, J. P., & Dubus, G. 1999, MNRAS, 303, 39
Hameury, J. M., Lasota, J. P., & Huré, J. M. 1997, MNRAS, 287, 937
Hameury, J. M., Lasota, J. P., & Warner, B. 2000, A&A, 353, 244
Harrison, T. E., McNamara, B. J., Szkody, P., MCArthur, B. E., Benedict, G. F., Klemola, A. R., & Gilliland, R. L. 1999, ApJ Lett., 515, L93
Lasota, J.-P. 2001, New Astronomy Review, 45, 449
Lasota, J. P., Hameury, J. M., & Hure, J. M. 1995, A&A, 302, L29+
Meyer, F. & Meyer-Hofmeister, E. 1994, A&A, 288, 175
Mohanty, P. & Schlegel, E. M. 1995, ApJ, 449, 330
Osaki, Y. 1996, PASP, 108, 39
Pandel, D., Córdova, F. A., & Howell, S. B. 2003, MNRAS, 346, 1231
Pringle, J. E., Verbunt, F., & Wade, R. A. 1986, MNRAS, 221, 169
Ramsay, G., Córdova, F., Cottam, J., Mason, K., Much, R., Osborne, J., Pandel, D., Poole, T., & Wheatley, P. 2001, A&A, 365, L294
Schreiber, M. R. & Gänscicke, B. T. 2002, A&A, 382, 124
Schreiber, M. R. & Gänscicke, B. T. 2001, A&A, 375, 937
Schreiber, M. R., Gänscicke, B. T., & Hessman, F. V. 2000, A&A, 358, 221
Schreiber, M. R., Hameury, J.-M., & Lasota, J.-P. 2003, A&A, 410, 239
—. 2004, A&A, in press (astroph/0408179)
Schreiber, M. R. & Hessman, F. V. 1998, MNRAS, 301, 626
Smak, J. 1984, Acta Astron., 34, 317
—. 1998, Acta Astron., 48, 677
Wheatley, P. J., Mauche, C. W., & Mattei, J. A. 2003, MNRAS, 345, 49