Hot white dwarfs and the UV delay in dwarf novae

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ABSTRACT
We calculate the effect of illumination of dwarf nova accretion discs by radiation from a hot, central, white dwarf. We show that only for very hot white dwarfs (\(T_{\text{eff}} \approx 40000\) K) the inner region of quiescent dwarf nova discs are partially depleted so that the delay between the rise to outburst of the optical and UV fluxes would be increased as suggested recently by King (1997). This depletion, however, must create several small outbursts between main outbursts, contrary to observations. Lower white dwarf temperatures may cause the outbursts to be of the ‘inside-out’ type removing the UV delay. We conclude that white dwarf irradiation of dwarf nova discs is not very efficient for example because the UV radiation from the hot white dwarf does not penetrate deep enough in the disc atmosphere. The total ablation of the inner disc by e.g. evaporation (possibly related to illumination) appears to be a very promising possibility, accounting for both the EUV delay and the general lightcurves properties.

Key words: accretion, accretion discs – instabilities – novae, cataclysmic variables – binaries : close

1 INTRODUCTION

Dwarf novae (DN) are cataclysmic variables which exhibit large amplitude outbursts that are commonly attributed to a thermal/viscous instability occuring in the accretion disc around the white dwarf (primary) component of the binary system (see e.g. Cannizzo (1993) for a review). In this picture, a stable disc has a bimodal behaviour: it can be either in a hot, ionized, state, corresponding to large mass transfer rates, or in a cool, neutral state, with a very low mass transfer rate. Systems in which the mass transfer rate from the secondary is in the intermediate range cannot be steady. The disc becomes unstable when partial ionization of hydrogen sets in; this may occur either in the innermost parts of the disc, in which case the outburst is of the inside-out type, or in the outer disc (outside-in outburst). In both cases, a heat front forms and rapidly propagates across the disc, bringing it entirely (or almost entirely) to a hot state, in which the local mass transfer rate is larger that the rate at which matter is provided by the secondary. The disc thus empties until a cooling wave starts from the outer edge of the disc, and brings it entirely to the cool (and unsteady) state.

Whereas the disc instability picture accounts for the general observational properties of DNs, it still has to face a number of contradictions, both internal and external. Models suffer from a number of drawbacks and inconsistencies (Lasota & Hameury, 1998, Hameury et al., 1998). The description of viscosity which drives accretion onto the white dwarf is purely phenomenological (and often \textit{ad hoc}), so that it may be difficult to determine if failures to reproduce some observational properties of dwarf nova outburst are due just to the approximate treatment of the disc structure, or to some more fundamental physical problems (see e.g. Gammie & Menou 1998).

During some DN outbursts one observes a so called ‘UV-delay’ - the rise to outburst in the optical wavelength precedes the UV rise by as much as 0.5 to 0.75 day (Hassall et al., 1983, Warner, 1995); the delay between the optical and EUV can be as long as 1 day (Mauche, 1996). Such delays are observed during outbursts which start at the outer disc regions - the ‘outside-in’ outbursts and are usually assumed to be the propagation time of a heating front across the disc. Whereas this interpretation can be questioned in the case of 1000 – 2000 Å UV, since the spectral modelling of the disc must be accurately done (Cannizzo, 1998), the E.UV rise clearly marks the arrival of the heating wave at the white dwarf surface. The presence of the UV-delay has been a serious difficulty for all disc models, since according to them, the heating front propagates too rapidly across the disc - the disc becomes too fast for an appreciable delay between UV and optical to appear (see Fig. 1). Attempts to solve this problem by modifying the local physical properties of the disc (e.g. increasing the thermal scale – Mineshige, 1988)
or involving convection—Duschl (1989)—have not been successful. A much more promising possibility was suggested by Meyer (1990); he proposed that the innermost regions of the disc are ablated by a coronal siphon flow in quiescence, so that UV emission, originating from the immediate vicinity of the white dwarf, can occur only after the central disc has been reconstructed, which is happening in a viscous time (see Hameury et al., 1997b for the description of the same phenomenon in low mass X-ray binary systems).

Although the inability of DN models to reproduce observed UV-delays has been attributed to the simplified way disc radiation is treated in time-dependent calculations (see e.g. Cannizzo 1998) the EUV delay represents the real heating-front propagation time because EUV radiation is not emitted by the disc but by a boundary layer between the disc and the white dwarf.

The precise physical mechanism causing the truncation of the disc is still a matter of debate. In addition to the evaporation of the inner disc by siphon flow described by Meyer & Meyer-Hofmeister (1994), Livio & Pringle (1993) suggested that the inner hole is due to the presence of a weak (∼10⁴ G) magnetic field. It is interesting that Patterson et al., (1998) found that the white dwarf in WZ Sge may have a magnetic field (1 – 5) × 10⁴ G and that the presence of a truncated disc in this system had been proposed before by Lasota, Hameury & Hure (1995) and Hameury, Lasota & Huré (1997a).

In a recent paper, King (1997) argues that irradiation by the white dwarf also leads to the truncation of the disc. According to King (1997) disc regions close to a hot enough white dwarf cannot be brought to a cool state at the end of a DN outburst, so that matter is transferred rapidly onto the white dwarf, leading to the formation of a very low density, hot flow.

The effect of disc irradiation in the context of soft X-ray transients was studied by Tuchman, Mineshige & Wheeler (1990), and may play an important role in low-mass X-ray binaries in general (van Paradijs, 1996; Dubus et al., 1998).

In this paper, we study the effect of the illumination of the disc by the white dwarf, leading to the formation of a very low density, hot flow. We have solved the disc vertical structure in the optically thick approximation, as described in Hameury et al. (1995) and Hameury, Lasota & Huré (1997a).

The main effect of disc irradiation from the outside is to change the surface temperature. A fraction 1 – β of the incident flux is absorbed in optically thick regions, thermalized and reemitted as photospheric radiation. The remaining is either scattered, or absorbed in optically thin regions, possibly forming a warm corona (Idan & Shaviv, 1996). Because the white dwarf temperature is not very different from that of the disc surface, King (1997) assumed that the albedo β is not close to unity - in this case effects of irradiation on the inner disc structure can indeed be important.

In the case of a geometrically thin disc surrounding a white dwarf whose radius is larger than the disc thickness, the illumination temperature $T_{\text{ill}}$ defined as

$$\sigma T_{\text{ill}}^4 = F_{\text{ill}}$$

where $F_{\text{ill}}$ is the radiative flux illuminating each side of the disc is given by (Friedjung 1985; Smak 1989; Hubeny 1991):

$$T_{\text{ill}} = (1 - \beta) T_c^4 \frac{1}{\pi} \arcsin \rho - \rho (1 - \rho^2)^{1/2}$$

where $\rho = R_c/r$, $R_c$ and $T_c$ are the white dwarf radius and temperature, and $r$ is the radial coordinate in the disc.

We have solved the disc vertical structure in the optically thick approximation, as described in Hameury et al. (1998), having modified the disc outer boundary condition according to:

$$\sigma T_{\text{ill}}^4 = F_{\text{ill}} + \sigma T_{\text{eff}}^4$$

where $T_{\text{ill}}$ is the disc photospheric temperature and $F_{\text{ill}}$ is the energy flux due to viscous dissipation. Examples of the resulting $\Sigma - T_{\text{eff}}$ curves are given in Fig. 1, where $\sigma T_{\text{eff}}^4 \equiv F_{\text{ill}}$ (see e.g. Dubus et al., 1998), which is proportional to the mass transfer rate in steady state. We have assumed a bimodal behaviour of the Shakura-Sunyaev parameter $\alpha$, taken as:

$$\log(\alpha) = \log(\alpha_{\text{cold}}) + \left[ \log(\alpha_{\text{hot}}) - \log(\alpha_{\text{cold}}) \right] \left[ 1 + \left( \frac{2.5 \times 10^4}{(T_c^2 + 5 T_{\text{ill}}^2)^{1/2}} \right)^8 \right]$$

where $T_c$ is the central disc temperature, and $\alpha_{\text{cold}}$ and $\alpha_{\text{hot}}$ are constants, here taken to be 0.04 and 0.2 respectively. Note the presence of a $T_{\text{ill}}$ term, that did not appear in

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Figure 2. Maximum value of $\Sigma$ on the lower stable branch of the $\Sigma - T_{\text{eff}}$ curve. The primary is a 0.6 $M_\odot$, $8.5 \times 10^8$ cm white dwarf, with effective temperature 25,000 K (lower solid curve), or 15,000 K (upper solid curve). The unilluminated case (dashed curve) is also shown for comparison.

Hameury et al. (1998), and which is needed to have $\alpha = \alpha_{\text{hot}}$ on the hot branch for moderate $T_c$. Fig. 1 shows the 'effective S-curves' used in time-dependent calculations and not the constant-$\alpha$ S-curves that are usually found in the literature (see also Hameury et al. (1998)).

As can be seen, regions in the immediate vicinity of the white dwarf are stabilized by irradiation from the white dwarf when the central disc temperature is pushed above the hydrogen ionization range. The condition for this to happen is close to that given by King (1997), i.e. $T_s > 6500$ K as in unilluminated discs, but with $T_s$ now given by Eq. 3; this condition slightly overestimates the effect of illumination, as the relation between $T_s$ and the central disc temperature is altered. This is however not the sole effect of irradiation. Figure 2 shows the corresponding maximum value of surface density on the cool branch, $\Sigma_{\text{max}}$, as a function of radius, $\alpha$ being given by (4). On Fig. 2 the curves describing maximum allowed $\Sigma$ for cold, stable, disc equilibria end at radii where the disc become stable (there are no more 'S-curves' for smaller radii). At larger radii, however, irradiation has a strong destabilising effect as seen in Fig. 2 where $\Sigma_{\text{max}}$ is reduced by more than an order of magnitude compared to the non-irradiated case. In these regions, irradiation increases the midplane temperature, bringing it close to the hydrogen partial ionization regime. Equivalently, the maximum mass transfer rate on the lower branch is severely reduced. This, as we will see in the next section, has an important influence on the properties of dwarf nova outbursts when they are affected by irradiation from the white dwarf.

3 LIGHT CURVES AND DISC IRRADIATION

We calculated a grid of vertical structures modified by irradiation. Such a grid provides the cooling term as a function of the central temperature and surface density and we used it in the numerical code described in Hameury et al. (1998) to determine the time evolution of the outbursts. Figures 3 and 4 show the general light curve of a system with

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Figure 3. Visual light curves of the accretion disc with a 0.6 $M_\odot$, $8.5 \times 10^8$ cm radius white dwarf, $\dot{M} = 10^{16}$ g s$^{-1}$ with $\beta = 1$, $T_s = 25,000$ K (upper panel), 15,000 K (intermediate panel), and no illumination (lower panel). The contribution of the primary or the secondary is not taken into account.

Figure 4. Same as Fig. 3, but for $\dot{M} = 10^{17}$ g s$^{-1}$. Note that the scale of the time axis are quite different.

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The first visible effect of illumination is the appearance of intermediate, smaller outbursts that are always of the inside-out type; these appear because of the destabilization of the inner edge of the disc by irradiation as seen on Fig. 3. They are at least one magnitude fainter than the main outbursts. During these small outbursts, the heat front is not able to propagate across the entire disc, but dies out at rather small radii (typically less that one half of the disc radius). The characteristics of the main outbursts are not drastically changed, with one exception. With $\dot{M} = 10^{17}$ g s$^{-1}$ and no illumination, the out-
bursts are of the outside-in type, as noted above. With $T_\star = 25,000$ K, the major outbursts are still of the outside-in type, while the smaller ones are inside-out. There is a transition regime when $T_\star = 15,000$ K where only large inside-out outbursts are seen. For this intermediate regime, the surface density is everywhere close to $\Sigma_{\text{max}}$ in the cold state (as in the non-illuminated case) but illumination is strong enough to destabilize regions close to the white dwarf. Heat fronts created in the inner regions of the disc can thus propagate throughout the disc and not only in a limited region. In other words, for these parameters the ‘small’ inside-out outbursts become major outbursts. These light curves are very similar to those obtained with higher primary masses, and hence much shorter inner disc radii, in which small inside-out outbursts are also seen (Cannizzo, 1993; Hameury et al., 1998).

A second effect is the reduction of the outbursts amplitude. They are only slightly fainter at maximum, but the main contribution to the reduced amplitude comes from the increased brightness during quiescence, that results from the brightening of the inner parts of the disc due to the reprocessing of light from the white dwarf.

As suggested by King (1997), illumination does reduce the surface density in the inner parts of the disc. Fig. 4 shows the radial disc structure in a system with a $0.6 \, M_\odot$, $8.5 \times 10^8$ cm white dwarf, $M = 10^{16}$ g s$^{-1}$, and $(1 - \beta)^{1/4} T_\star = 25,000$ K just prior to a major outburst. $\Sigma$ is much reduced in the region where illumination is important, i.e. up to about 2 white dwarf radii, but not to the point making the disc optically thin. For the value of $M$ considered here, the outburst will be of the inside-out type, as can be seen from the relative position of the $\Sigma$ and $\Sigma_{\text{max}}$ curves. For higher mass transfer rates, outside-in outbursts are possible. Fig. 5 shows the time behaviour of the onset of the bursts of both the disc visual magnitude, and the “accretion rate magnitude”, defined as $m_\alpha = 27 - \log M_{\text{wd}}$, where $M_{\text{wd}}$ is the accretion rate onto the white dwarf in g s$^{-1}$, which represents the EUV flux. As expected, the delay between the start of the rise of the disc brightness and the rise of mass accretion rate onto the white dwarf increases when illumination is important. The increase is however not very large; for the parameters assumed here, the total delay amounts to about 5.3 hr, of which about 1.5 hr is attributable to the depletion of the inner disc; longer values are possible for higher white dwarf temperatures, or lower values of $\alpha$.

It is also interesting to note that illumination makes the rise of the mass accretion rate onto the white dwarf much less sudden than in the unilluminated case. This is due to the fact that close to the white dwarf, the heat front propagates now in a hot disc, with a constant value of $\alpha$. This reduces the non-linearities which are responsible for the presence of sharply defined heat fronts.

4 THE CASE OF SS CYG

SS Cyg is a well studied system in which a 1 day EUV delay has been observed (Mauche, 1996) that contains a hot, massive white dwarf, whose temperature is estimated to be in the range 34 – 40,000 K (Warner, 1995) for a mass of about $1.2 \, M_\odot$ (Ritter & Kolb, 1998). In such a system, the efficiency of accretion is large, and illumination by the disc itself and by the boundary layer between the disc and the surface of the white dwarf could be important. The geometrical extent of the hottest parts of the system is not well known; as a simplifying assumption, and in order to maximize the effect of accretion related irradiation, one can assume that the source of illumination is the white dwarf surface, so that Eq. (2) still applies if the constant temperature $T_\star$ is replaced by $T_\alpha$ given by:

$$\sigma T_\alpha^4 = \sigma T_\star^4 + \frac{GM_1 \dot{M}}{4\pi R_\alpha^2}$$ (5)

where $M_1$ is the primary mass. The cooling term $T_{\text{eff}}$ has been calculated for several illumination temperatures, and a cubic spline interpolation is performed, as described in Dubus et al. (1998).

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**Figure 5.** Radial profiles of temperature $T$ (in $10^5$ K), surface density $\Sigma$ and critical surface density $\Sigma_{\text{max}}$ (in g cm$^{-2}$) and local mass transfer rate (in units of $10^{15}$ g s$^{-1}$) just prior to one of the major outbursts shown in Fig. 3 for $(1 - \beta)^{1/4} T_\star = 25,000$ K.

**Figure 6.** Time dependence of the $V$ magnitude (left two curves) and the “accretion rate magnitude” (right two curves, see text) at the onset of an outside-in outburst under the effect of illumination (solid curve, $(1 - \beta)^{1/4} T_\star^4 = 25,000$ K) and without illumination (dashed curve). The primary mass is $0.6 \, M_\odot$, and the mass transfer rate is $10^{17}$ g s$^{-1}$.
which has a similar form to the rate used in Hameury et al. (1997b) (but not the same numerical coefficients). $R_{10}$ is the radius in units of $10^{10}$ cm. In the present case, the radius of the inner edge of the disc is taken to be about $3.5 \times 10^{9}$ cm in quiescence, i.e. 7 white dwarf radii; it has been taken such as to produce a one day delay between the onset of the outburst in optical and the time at which the disc reaches the white dwarf surface. One should note that the radius of the inner edge of the disc in quiescence is very similar to that required to account for the long recurrence time of WZ Sge if standard values of $\alpha$ are assumed (Hameury, Lasota & Huré, 1997a). It should finally be mentioned that Eq. (6) is largely empirical, and should be supported by models. Such models exist (Meyer & Meyer-Hofmeister, 1994; Liu, Meyer & Meyer-Hofmeister, 1992), but the uncertainties are large.

As one can see, illumination by the white dwarf and/or by the boundary layer also produce light curves which show many small outbursts in between major ones, and cannot therefore account for the observed light curves. The situation is slightly better when the boundary layer is included, but is far from being satisfactory. Similarly, the predicted EUV delays are too short, since too small a fraction of the disc is affected by illumination.

By contrast, both the light curves and the EUV delay obtained when one assumes that the disc is truncated are in good agreement with observations. The very significant difference between the case of a hole in the disc and a depletion of the inner regions is precisely the existence, in the latter case, of a hot, optically thick, central region that is able to interact with the outer disc and destabilize it.

One should finally note that the alternation of various types of outbursts in SS Cyg cannot be explained if no parameter (e.g. $\dot{M}$) is allowed to vary with time. Cannizzo (1993) found that regular sequences of short and long outbursts were a natural outcome of the disc instability model for low values of the disc inner radius; one should however keep in mind that all his outbursts were of the inside-out type (because the outer disc radius was fixed at a given distance), which is very difficult to reconcile with the existence of UV and EUV delays. We do also obtain such sequences, even with alternating inside-out and outside-in outbursts (see e.g. fig. [3]), but the small outbursts are much fainter than the major ones, in contradiction with observations. The long term light curve of SS Cyg shows large variations of the mass transfer rate from the secondary on timescales of years (Cannizzo & Mattei, 1992); these variations must be taken into account when trying to interpret the alternation of outside-in and inside-out outbursts, and we know that changes in $\dot{M}$ induce changes of the outburst type (see Figs. [3] and [4]).

5 CONCLUSION

We have shown that efficient illumination of the accretion disc by a hot white dwarf affects the dwarf novae outbursts in several ways:

(i) it causes the appearance of several small outbursts in between the major ones. This conclusion is firm and does not depend on the assumed viscosity, but merely reflects the unavoidable presence in quiescence of an unstable transition region between the hot and cold regimes.
(ii) for moderate white dwarf temperatures and mass transfer rates, outside-in outbursts are replaced by inside-out outbursts

(iii) when outside-in outbursts are present, the UV delay is increased. This happens only for \( T_\star (1 - \beta) \leq \frac{1}{4} \) much above 15,000 K.

The proposition of King (1997) that illumination is responsible for the observable UV delay is therefore difficult to maintain once the UV delay is increased only for very hot white dwarfs, but then it implies the presence of small outbursts in between major ones that are not observed.

However, as pointed out by King (1997), such hot white dwarfs are present in some DNs, and their radiation does illuminate the innermost parts of the accretion disc. We suggest that the fraction 1 - \( \beta \) of the illumination flux that affects the vertical structure of the disc might be smaller than previously estimated, as (i) the opacities are a very sensitive function of temperature when hydrogen is partly ionized (factors of the order of 2 in the Rosseland opacity for a temperature difference of only 20%), and (ii) the grazing angle is quite small; both effects reduce penetration depth of the UV photons, which could be absorbed in regions which are not optically thick and would not modify the photospheric boundary condition but instead lead to the formation of a corona above the cool disc. The determination of the albedo is, however, much more complex than in the case of illumination by hard X-rays, where electron scattering contributes significantly to the opacities.

A much more promising explanation is that the inner parts of the disc that would be affected by illumination do not exist, precisely because of the formation of a corona that evaporates the central regions of the disc. Irradiation would indeed accelerate the evaporation process itself, but the coupling between evaporation and illumination remains to be understood.

One should finally keep in mind the possibility that the disc instability model does not apply to dwarf nova outbursts, but then the scenario proposed by King (1997) would not apply anyway.

When this work was almost completed we learned of similar study by Stehle & King (1998).

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