The standstill luminosity in Z Cam systems

R. Stehle, A. King, C. Rudge

Astronomy Group, University of Leicester, Leicester, LE1 7RH, UK

ABSTRACT

We consider accretion discs in close binary systems. We show that heating of a disc at the impact point of the accretion stream contributes significantly to the local energy budget at its outer edge. As a result the thermal balance relation between local accretion rate and surface density (the ‘S-curve’) changes; the critical mass transfer rate above which no dwarf nova outbursts occur can be up to 40% smaller than without impact heating. Standstills in Z Cam systems thus occur at smaller mass transfer rates than otherwise expected, and are rather fainter than the peak luminosity during the dwarf nova phase as a result.

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

1 INTRODUCTION

Dwarf novae are a subset of cataclysmic variables (CVs), close binary systems in which a white dwarf accretes from a low-mass secondary (see Warner, 1995). Their defining feature is outbursts lasting a few days, which recur at intervals of weeks. The thermal–viscous disc instability model is generally accepted as the most successful explanation for these outbursts (see Cannizzo 1993 or Warner 1995 for recent reviews). The outbursts are thought to result from a thermal instability of the disc when hydrogen is partially ionized. Hence accretion cannot be steady for a certain range of mass transfer rates $-\dot{M}_2$ from the secondary such that dissipation at local accretion rates $\dot{M}_{\text{acc}} = -\dot{M}_2$ implies partial ionization somewhere in the disc. We can write this condition as $\dot{M}_B < -\dot{M}_2 \leq \dot{M}_A$, where $\dot{M}_A$ and $\dot{M}_B$ are the critical local accretion rates for low and high ionization at a given point of the disc (see Fig. 1).

If this condition holds, the disc goes through a limit cycle with alternating high ($\dot{M}_{\text{out}}$) and low ($\dot{M}_{\text{qui}}$) mass accretion rates. If the mass transfer rate is higher than $\dot{M}_A(r)$ everywhere in the disc, the accretion disc is in permanent outburst and $\dot{M}_{\text{acc}} = -\dot{M}_2$ is steady. As the critical mass accretion rates increase with radius this condition is equivalent in saying that accretion discs are stable and the whole disc is permanently in outburst as long as

$$-\dot{M}_2 > \dot{M}_A(r_{\text{disc}})$$

where $r_{\text{disc}}$ is the radius of the outer disc edge. (A second stable regime exists if $-\dot{M}_2 < \dot{M}_B(r_{\text{in}})$, where $r_{\text{in}}$ is the radius of the inner edge of the accretion disc. This in practice, however, requires unrealistically low mass transfer rates.)

To lowest order $\dot{M}_{\text{out}}$ and $\dot{M}_{\text{qui}}$ are independent of $-\dot{M}_2$. Thus one can approximately divide systems into steady ( nova-like) systems or dwarf novae according as (1) holds or not, with $\dot{M}_A(r_{\text{disc}})$ a universal function of outer disc radius.

Z Cam systems are a subset of the dwarf novae which occasionally show standstills, i.e. epochs where the luminosity is constant for several days, at a value intermediate between the outburst and quiescent states (e.g. Warner, 1995, Oppenheimer, Kenyon & Mattei 1998, Section 3.4), and a mean brightness during standstills exceeding the time averaged brightness during the dwarf nova phase (Honeycutt et al. 1998). One can qualitatively understand these as systems where the mass transfer rate $-\dot{M}_2$ is close to the critical value $\dot{M}_A(r_{\text{disc}})$, but is somewhat time-variable. Thus when $-\dot{M}_2 > \dot{M}_A(r_{\text{disc}})$ the accretion disc is permanently in outburst, corresponding to a standstill, while at times when $-\dot{M}_2 < \dot{M}_A(r_{\text{disc}})$ the system undergoes a limit cycle as a normal dwarf nova system. Cannizzo & King (1998) sug-
gested this type of picture, with the required variations in −M₂ resulting from a varying population of starspots near the L₁ point on the secondary.

Although this picture is attractive, Esin et al. (2000) point out a quantitative shortcoming; it appears to predict standstill luminosities which are as bright as (or brighter than) the peak luminosity during dwarf outbursts. For an outbursting disc behaves as if steady, i.e. the accretion rate is almost constant through it. At the peak of the outburst, just before the cooling wave propagates inwards, the accretion rate at the outer edge of the hot disc region (which may be the outer edge of the whole disc) is by definition very close to the value \( \dot{M}_A (r_{\text{disc}}) \). Hence we expect that \( \dot{M}_{\text{out}} \simeq \dot{M}_A (r_{\text{disc}}) \). However, standstills occur only when \( \dot{M}_{\text{standstill}} \gtrsim \dot{M}_A (r_{\text{disc}}) \). Thus one might expect that \( \dot{M}_{\text{standstill}} \gtrsim \dot{M}_{\text{out}} \) resulting in a comparable or greater disc brightness during standstills. This is in direct contradiction to observations which always show that the disc brightness during standstills is lower than the peak of any outburst.

It is clear that the derivation of the discordant inequality (2) relies on the assumption that the critical mass transfer rate \( \dot{M}_A (r_{\text{disc}}) \) is essentially independent of −M₂. We show here that this is not correct, since the disc is heated at a local rate \( Q_{\text{HS}} \) by the impact of the gas stream from the secondary, and this heating effect increases as −M₂ increases. \( \dot{M}_A \) therefore depends not only on the the disc radius, but also on the mass transfer rate, i.e.

\[
\dot{M}_A (r_{\text{disc}}) \dot{M}_A (r_{\text{disc}}, \dot{M}_2).
\]

The critical mass transfer rate is then given by the solution of the implicit equation

\[
\dot{M}_2 = \dot{M}_A (r_{\text{disc}}, \dot{M}_2).
\]

We show explicitly in the next section that \( \partial \dot{M}_A (r_{\text{disc}})/\partial Q_{\text{HS}} < 0 \). Taking this extra heating by the hot spot into account, the condition for the accretion disc to be permanently in outburst is already fulfilled at much smaller values than indicated by the unperturbed value of \( \dot{M}_A \). Outbursts for mass transfer rates smaller than the hot spot heating condition are not dramatically altered by the new outer boundary condition, so we conclude that \( \dot{M}_{\text{standstill}} \) is considerably lower than \( \dot{M}_{\text{out}} \), and hence that standstills should be fainter than outbursts.

2 THE F–Σ RELATION WITH IMPACT HEATING

The so-called \( f–\Sigma \) relation for a disc is defined as the locus in the \( \dot{M}_{\text{acc}}–\Sigma \) plane where the local heating by small-scale viscous processes, i.e.

\[
Q_{\text{visc}}^+ = \frac{3GMWD}{4\pi r_{\text{WD}}^2} f
\]

is in equilibrium with radiative cooling of both surfaces of the accretion disc, given by

\[
Q_{\text{rad}}^+ = 2\sigma T_{\text{eff}}^4.
\]

Thus we have \( \dot{M}_{\text{acc}} = 3\pi f \), with \( f = 2/3c_0 H_{\text{eq}} \Sigma \) (cf. Ludwig & Meyer 1998, among others).

The thermal equilibrium curve \( Q_{\text{visc}}^+ = Q_{\text{rad}}^- \) is determined by the vertical temperature structure in the accretion disc through the requirement \( T_{\text{eff}} = T_{\text{eff}} (T_c) \) at a given surface density \( \Sigma \). We show Ludwig & Meyer (1998) and assume that the relation between \( T_{\text{eff}} \) and \( T_c \) is independent of the actual heating mechanism. In Fig. 2 we show the \( f–\Sigma \) relation for the parts of the accretion disc where the energy impact from the ballistically falling accretion stream particles contribute significantly to the local energy budget, i.e. where

\[
Q_{\text{visc}}^+ + Q_{\text{HS}}^+ = Q_{\text{rad}}^-.
\]

Here the impact heating is given by

\[
Q_{\text{HS}}^+ = -\frac{\eta_{\text{heat}} e_{\text{kin},r} \dot{M}_2}{2\pi \sigma \delta r} = \text{const.}
\]

where \( e_{\text{kin},r} \) is the kinetic energy of the ballistically infalling mass thermalized at the impact of the accretion stream. We assume that only the radial velocity component of the transferred material is thermalized, with efficiency \( \eta_{\text{heat}} \); for a strong impact shock \( \eta_{\text{heat}} \) is close to unity. Thus \( Q_{\text{HS}}^+ \) is of order a few times \( 10^{15} \text{erg g}^{-1} \) for typical binary and disc parameters (see Fig. 3). The impact point is stationary in the corotating binary frame, and heats a ring \( 2\pi r_{\text{disc}} \delta r \) of disc material at the outer edge, where \( \delta r \) is the radial extent of the impact point, typically of the order of a few percent of \( r \).

For typical binary and disc parameters we find

\[
Q_{\text{HS}}^+ \simeq 1.5 \times 10^{10} \eta_{\text{heat}} \dot{M}_{\text{HS}} \text{erg s}^{-1} \text{cm}^{-2},
\]

where \( \dot{M}_{\text{HS}} = -\dot{M}_2/10^6 \text{g s}^{-1} \). Fig. 2 shows \( \dot{M}_{\text{acc}} \) as a function of \( Q_{\text{HS}}^+ \) at a disc radius of \( 2.7 \times 10^9 \text{cm} \) for a 1.15\( M_\odot \) white dwarf. Using the parameterization of \( Q_{\text{HS}}^+ \) of Eq. (2) we derive a critical mass transfer rate from

\[
\dot{M}_c = \frac{\dot{M}_A (r_{\text{disc}})}{M_\odot \text{yr}^{-1}} \simeq -8.48 - 0.013 \frac{Q_{\text{HS}}^+}{10^{15} \text{erg s}^{-1} \text{cm}^{-2}}
\]

for \( Q_{\text{HS}}^+ < 17 \times 10^{15} \text{erg cm}^{-2} \text{s}^{-1} \). The S-curve is straightened out for impact energies greater than \( 17 \times 10^{15} \text{erg cm}^{-2} \).  

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s\(^{-1}\) and no thermal–viscous instability occurs close to the outer disc edge.

We see that including heating by the accretion stream lowers the threshold mass transfer rate preventing a return to quiescence by about 40%. Put another way, a significant rise in the mass transfer rate will produce a 40% decrease in \(M_A(r_{\text{disc}})\) because of heating by the accretion stream. We expect standstill luminosities about 40% fainter than the peak of an outburst.

3 CONCLUSION

We have shown that inclusion of impact heating of an accretion disc by the mass transfer stream from the secondary star has a significant effect on the critical mass transfer rate required for stable accretion. Accordingly, models attributing Z Cam standstills to slight increases of the mass transfer rate above this critical value do predict that the standstills should occur at lower disc brightness than the peak of the dwarf nova outbursts, as observed.

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