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VARIATION OF THE MASS TRANSFER RATE DURING DWARF NOVAE AND SOFT X-RAY TRANSIENTS OUTBURSTS

M. Viallet[1] and J.-M. Hameury[1]

Abstract. We discuss a possible heating of the Lagrangian point, which is screened from irradiation by the accretion disc, during dwarf novae and soft X-ray transients outbursts. An efficient heating of L_1 could lead to an increase the mass transfer rate and this could turn to be an important ingredient to explain the outburst cycle. We first show that heat can not be effectively transported from the irradiated regions on the secondary towards the L_1 point. However, we find that in some cases the L_1 point could be heated by the edge of the accretion disc disc and by a fraction of the accretion luminosity scattered by optically thin material above the disc.

1 Introduction

Dwarf novae (DN) and soft X-ray transients (SXT, also called X-ray novae) are close binary systems that undergo regular outbursts, which are a sudden increase of their luminosity (see Warner 1995 and Tanaka & Shibazaki 1996 for reviews). In both types of systems, a compact object (namely a white dwarf in DN and a neutron star or a black hole in SXT) harboring an accretion disc accretes from a late type secondary star which overfills its Roche lobe. The standard explanation for dwarf nova and soft X-ray transient outbursts is based on the thermal/viscous instability of the accretion disc triggered when hydrogen becomes partially ionized (see e.g. Lasota 2001). It is usually assumed that the mass transfer rate from the secondary is constant on the time scale of an outburst. This seems natural since the L_1 point remains shielded by the accretion disc and thus is not under the direct influence of the accretion luminosity.

However, if for some reason the L_1 point could be heated, an increase of the mass transfer rate would result. Numerical investigations showed that enhanced mass transfer episodes could explain the outburst bimodality (Smak 1999) or that it could lead to long outburst similar to superoutbursts of the SU UMa stars (a subtype of DN, see Hameury 2000). However, in these works either an empirical relationship between the mass transfer rate and the mass accretion rate was assumed or mass transfer burst episodes were arbitrarily imposed.

We discuss here various effects that could be responsible for a heating of the L_1 point.

2 Direct irradiation of the secondary star

For a more detailed discussion of this effect, we refer the reader to the proceeding of the PNPS session "Hydrodynamic simulations of irradiated secondaries in dwarf novae". Here we summarize our results and discuss the case of SXT at the end of this section.

It has been often argued that enhancement of the mass transfer rate could result from the irradiation of the secondary. Heating of L_1 requires a way to transport heat from irradiated regions to the L_1 point. To check this possibility, we compute numerically the surface flow on the secondary star during an outburst. Instead of using the full Roche geometry, we consider a spherical secondary star on which we apply a map of the Coriolis force computed from the Roche geometry. We use a finite difference scheme to solve the Euler equations with inclusion of the Coriolis force and heating/cooling terms. Due to screening by the accretion disc, only a fraction of the stellar hemispheres facing the primary are heated by irradiation. The shadow boundaries are located $\pm 20°$ above/below the equator on the main meridian. We assume that the outburst lasts for 60 orbital periods

[1] Observatoire de Strasbourg, Université Louis Pasteur/CNRS, 11 rue de l'Université, 67000 Strasbourg

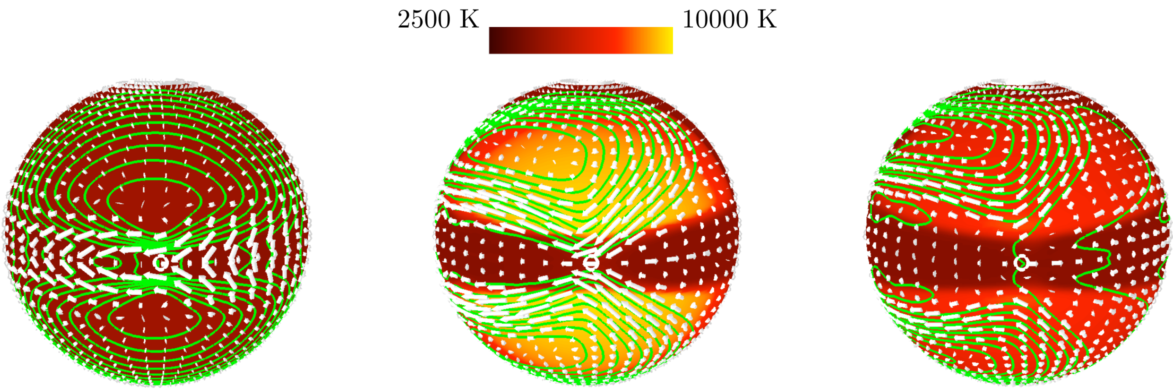

Fig. 1. Snapshots at $t = 0.7, 30, 45\ P_{\rm orb}$. Each snapshot shows the surface temperature (see the color legend), isobars and the velocity field. The L_1 region is marked by a circle whose surface is equal to the stream cross section. For the sake of figure readability, the magnitude of the velocity field has been multiplied by 6 at $t = 0.7\ P_{\rm orb}$.

(i.e. a few days) and that, at the outburst maximum, the irradiation flux impinging the secondary corresponds to an effective temperature of 10^4 K.

Figure 1 shows three snapshots of the secondary viewed face on at the beginning of the outburst ($t = 0.7\ P_{\rm orb}$), at outburst maximum ($t = 30\ P_{\rm orb}$) and during the outburst decay ($t = 45\ P_{\rm orb}$). One can see that a circulation flow crossing the L_1 region forms during the initial stage of the outburst. This circulation flow is part of a bigger clockwise circulation associated with a high pressure region. This "anti-cyclonic" perturbation results from the irradiation and the associated circulation flow is "geostrophic", i.e. the Coriolis force balances the pressure gradient. During the outburst, the anti-cyclonic perturbation drifts westward thus quenching the flow through L_1 before the end of the outburst.

However, the temperature field remains unperturbed by the velocity flow. This shows that no heat advection occurs in our simulation. This is due to a rapid cooling of the hot gas as it enters the shadowed region. Our simulations show that the time needed to cross the shadowed region is of order of a few orbital periods. In our model we assumed that gas cools as a blackbody ; the cooling time scale is then $\tau_{\rm cool} = \Sigma c_v T/\sigma T^4 \propto \Sigma T^{-3}$ (Σ is surface density of the gas, T its temperature). As the gas crosses the shadow boundary, its temperature is $T \sim 10^4$K. The surface density of the layer affected by irradiation is of the order of ~ 100 g.cm^{-2}. This yields a cooling time scale < 0.1 orbital periods, much smaller than the crossing time scale. As a consequence, there is no efficient heating of the L_1 point.

In SXT the main difference is that irradiation is much stronger, the irradiation flux impinging the secondary has an effective temperature of the order of 5.10^4K. As a result, pressure gradients are much stronger and velocities could possibly outreach the sound speed, which makes the problem numerically difficult. An investigation of this case therefore requires a more robust numerical code.

3 Heating of L_1 by the edge of the accretion disc

During an outburst, the disc grows as a consequence of an effective outward transport of angular momentum. The mean maximal radius of the disc is determined by tidal interactions with the secondary which truncate the disc at a radius $\sim 0.85 R_{L_1}$ (see Smak 2002; Ichikawa & Osaki 1994), where R_{L_1} is the size of the primary Roche lobe. During an outburst, the disc likely reaches this maximal radius, for SU UMa systems this could be true only during a superoutburst (see Osaki 1996), and tidal dissipation heats up the outer region of the disc. Smak (2002) argued that tidal dissipation occurs in a very narrow region at the disc rim and suggested that this energy is radiated away by the disc edge, whereas heat generated by viscous dissipation is radiated by the surface of the disc.

Following Smak's hypothesis, we first determine the tidal torque $\dot{J}_{\rm tid}$ applied to the disc. The work done by this torque is radiated as a "tidal luminosity" $L_{\rm tid} = \dot{J}_{\rm tid}\Omega$, where Ω is the angular velocity at the disc edge. Since $L_{\rm tid}$ is radiated by the disc edge, we define an effective temperature T_{edge}:

$$L_{\rm tid} = \sigma T_{\rm edge}^4 2\pi R_d^2 \frac{H}{R}\Big|_{R_d} \quad (3.1)$$

where R_d is the disc outer radius and the ratio H/R at the outer radius appears explicitly. Smak (2002) used the steady state state balance of the disc total angular momentum to determine $\dot{J}_{\rm tid}$. Here we instead consider the local balance of angular momentum at the disc edge: once the disc has reached its maximal radius, the angular momentum transported to the disc edge has to be removed by the tidal torque. This yields:

$$\dot{J}_{\rm tidal} \sim 3\pi\nu\Sigma j|_{R_d} \quad (3.2)$$

where the first term is the viscous torque, i.e. the rate at which angular momentum is transported outwards by viscous process (j is the specific angular momentum assuming Keplerian rotation). We have not included the contribution from the incoming stream, which is negligible during outburst. We estimate $\dot{J}_{\rm tidal}$ from Eq. (3.2) by using the numerical code described in Hameury et al. (1998) and we compute $T_{\rm edge}$ from Eq. (3.1) with relevant parameters for DN and SXT ; this yields an effective temperature of the order of 10^4 K.

The L_1 point is then subject to an incoming thermal flux from the edge of the disc. The specific intensity of the radiation (integrated over frequency) at the edge is given by:

$$I = \sigma T_{\rm edge}^4/\pi \quad (3.3)$$

The radiation is isotropic and, neglecting limb darkening, the flux falling on L_1 is:

$$F = I\omega \quad (3.4)$$

where ω is the solid angle subtended by the edge of the disc as viewed from L_1. The determination of ω is a geometrical problem. Our computations show that $\omega = 2.10^{-2} - 3.10^{-2}$ for DN and $\omega = 6.10^{-2}$ for SXT (due to larger H/R ratio at the disc edge). The influence of the incoming flux is given by the corresponding effective temperature:

$$T_{\rm eff} = T_{\rm edge}(\omega/\pi)^{1/4} \quad (3.5)$$

which can then be compared with the effective temperature of the secondary star. Eq. (3.5) yields $T_{\rm eff} \sim 3700$ K for SXT and $T_{\rm eff} \sim 3000$ K for DN. DN below the period gap of cataclysmic variables have very cool secondary stars with effective temperature ~ 2500 K, whereas SXT and DN above the period gap have hotter secondaries with effective temperature $\sim 3500-4500$ K. Heating by the disc edge could play a role for DN under the period gap (due to cooler secondaries) and for SXT (due to a larger disc edge), but is not a major effect.

4 Heating of L_1 by scattering of the accretion luminosity

There are observational evidences supporting the presence of outflows in dwarf novae during their outbursts (see Warner 1995). The mass loss rate is not likely to be larger than a few percent of the mass accretion rate. We investigate here the possibility that a fraction of the accretion luminosity is scattered towards the L_1 point by the outflowing matter. In SXT, the scattering medium is more likely a corona above the whole disc ; however as no reliable model of corona exists we shall apply the outflow model to SXT as a first approximation.

We consider that 5% of the accretion rate is lost in a spherically symmetric wind. The mass conservation law yields:

$$4\pi r^2\rho(r)v(r) = \alpha\dot{M}_{\rm acc} \quad (4.1)$$

where $\dot{M}_{\rm acc}$ is the accretion rate onto the compact object during an outburst, $\alpha = 0.05$ is the 5% mass loss and r is the distance to the primary center of mass. It follows that $\rho \propto r^{-3/2}$. We consider for simplicity an uniform and isotropic opacity $\kappa = 0.4$ (corresponding to Thomson scattering by free electrons) to compute the optical depth of the wind:

$$\tau = \Sigma\kappa \quad (4.2)$$

where Σ is the total column density of the wind. This yields:

$$\tau = 2\rho_1 r_1 \kappa \tag{4.3}$$

where r_1 is the radius of the primary star and ρ_1 is the gas density near the surface of the compact object, computed from Eq. (4.1) with $v = v_{\rm esc}(r_1)$ ($v_{\rm esc}$ is the escape velocity). With relevant parameters, τ is of order of $\sim 10^{-2}$ in DN and $\sim 10^{-1}$ in SXT. As expected, τ is low and the wind is optically thin. Only a very small fraction of the accretion luminosity will be scattered toward L_1. To compute this fraction, we suppose that no "double scattering" occurs and we neglect the radial decrease of the accretion luminosity due to scattering losses. Scattering is handled as an emissivity ϵ equals to:

$$\epsilon(r) = \frac{L_{\rm acc}}{16\pi^2 r^2}\rho(r)\kappa \tag{4.4}$$

where r is the distance to the primary center of mass. The flux arriving at L_1 is then:

$$F = \int_V \frac{\epsilon(\vec{r})dV}{d^2} \tag{4.5}$$

where d is the distance between L_1 and the running point $\vec{r}$, V (the integration volume) accounts approximatively for the shielding of the inner part of the outflow by the disc. This can be written as:

$$F = \frac{L_{\rm acc}}{4\pi D^2}\tau f \tag{4.6}$$

where f is a geometrical factor and D is the distance from L_1 to the primary center of mass. $L_{\rm acc}/(4\pi D^2)$ is the flux L_1 would receive if no screening from the disc were present, τf is therefore the fraction of this flux "reflected" by the surrounding medium. Not surprisingly, we found that this fraction is very low, of the order of 10^{-4} both in DN and SXT.

Here again we can estimate the importance of the incoming flux by computing its effective temperature. This yields $T_{\rm eff} \sim 10^4$ K for SXT (due to their high luminosity) and $T_{\rm eff} \sim 2000 - 3000$ K for DN. The effect is therefore negligible in DN but could be significant in SXT.

5 Conclusion: implication for $\dot{M}_{tr}$

We have shown that in dwarf novae below the period gap (with very cool secondary stars) the L_1 point receives a non-negligible heating flux from the edge of the accretion disc. In SXT, the same effect exists but L_1 receives a much larger flux due to the reflection of the accretion luminosity by material surrounding the disc.

We expect the vertical structure in the L_1 region to be modified by the incoming radiation and this could result in an enhancement of the mass transfer rate. However, the details depend on the nature of the incoming radiation. For example, the radiation falling on L_1 as a result of the scattering by the surrounding medium in SXT will consist mainly of soft X-ray photons. These are absorbed at low column density by neutral hydrogen and a hot ionized shell structure forms, which means that the bulk of the incoming radiation does not affect the atmosphere very deeply. On the other hand, the radiation emitted by the edge of the disc is radiated as a black-body of temperature 10^4 K. The radiation is therefore mainly in the near-UV and most photons cannot ionize hydrogen. In this case we can expect the radiation to penetrate more deeply and change the vertical structure of the secondary.

A precise determination of the mass transfer enhancement is a difficult task ; it depends both on the nature of the secondary and on the nature of the incoming radiation. This problem needs further investigations, to be developed in a forthcoming paper.

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