
Disc and secondary irradiation in dwarf and X-ray novae

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Abstract

I present a short review of irradiation processes in close binary systems.

1. Introduction

Thermal-viscous instability is widely accepted as the origin of Dwarf Nova and Soft X-ray Transient (X-ray Nova) outbursts. In the ‘standard’ model, one assumes a constant mass-transfer rate, no effects of irradiation are taken into account and the accretion disc is supposed to extend down to the surface of the accreting body (or the last stable orbit in the case of accreting black holes and compact neutron stars). This version of the model, however, explains neither all the observed outburst types nor all the observed outburst properties. Generalizations of the ‘standard’ model which take into account some or all of these neglected, but obviously important, effects have been proposed and studied in various investigations. I will shortly discuss some recent results concerning irradiation (Hameury, Lasota & Huré 1997; Dubus et al. 1999; hereafter DLHC; King (1997); King & Ritter 1998).

Since in the literature of the subject most articles use incorrect equations to describe irradiated accretion discs I begin by repeating the simple derivation of the basic equations presented in DLHC.

2. A simple introduction to the vertical structure of irradiated discs

In accretion discs the vertical energy conservation equation has the form:

$$\frac{dF}{dz} = Q_{\text{vis}}(R, z) \quad (1)$$

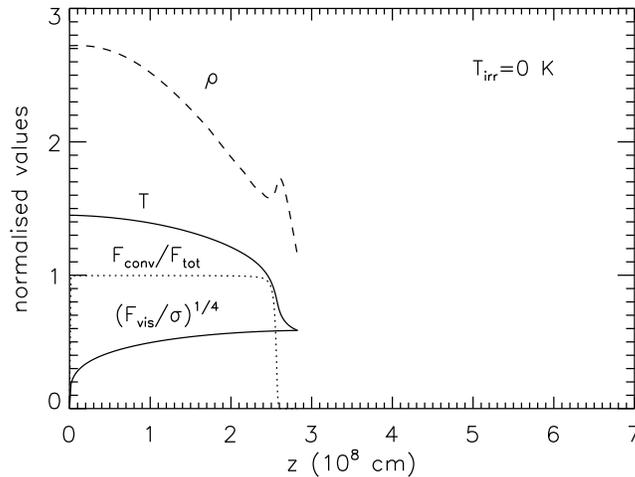


Fig. 1. Vertical structure of an accretion disc around a $M = 10M_{\odot}$ compact object at $r = 3 \times 10^{10}$ cm. $\alpha \approx 0.1$, $\dot{M} \approx 10^{16}$ g s $^{-1}$ (i.e. $T_{\text{eff}} \approx 5700$ K) and $T_{\text{irr}} = 0$. Both temperatures are normalized by 10^4 K. Since $T_{\text{irr}} = 0$, the surface temperature $T(\tau_s) = T_{\text{eff}}$. The dashed line is the density in units of $\times 10^{-7}$ g cm $^{-3}$, the dotted line the ratio of the convective to the total fluxes. Note that for these parameters, the section of the disc lays on the lower stable branch. (From DLHC)

where F is the vertical (in the z direction) radiative flux and $Q_{\text{vis}}(R, z)$ is the viscous heating rate per unit volume. Eq. (1) states that an accretion disc is not in radiative equilibrium, contrary to a stellar atmosphere. Using the “ α -viscosity” prescription (Shakura & Sunyaev 1973) $\nu = (2/3)\alpha c_s^2/\Omega_K$, where α is the viscosity parameter (≤ 1), Ω_K is the Keplerian angular frequency and $c_s = \sqrt{P/\rho}$ is the sound speed, ρ the density, and P the pressure one can write

$$Q_{\text{vis}}(R, z) = (3/2)\alpha\Omega_K P \quad (2)$$

Viscous heating of this form has important implications for the structure of optically thin layers of accretion discs and may lead to creation of coronae and winds (Shaviv & Wehrse 1986; 1991). Here, however, we are interested in the effects of irradiation on the inner structure of an optically thick disc, so our results should depend on the precise form of the viscous heating. We neglect, however, the possible presence of an X-ray irradiation generated corona and wind, described by Idan & Shaviv (1996). When integrated over z , the rhs of Eq. (1) is equal to viscous dissipation per unit surface:

$$F_{\text{vis}} = \frac{3}{2}\alpha\Omega_K \int_0^{+\infty} P dz, \quad (3)$$

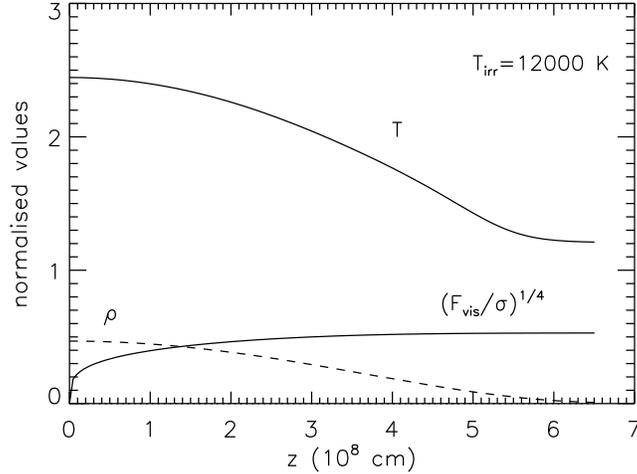


Fig. 2. Same as Fig. 1. but for $T_{\text{irr}} = 12000$ K. (From DLHC)

which is close, but not exactly equal, to the surface heating term $(9/8)\nu\Sigma\Omega_K^2$ generally used in the literature. The difference between the two expressions may be important in numerical calculation (Hameury et al. 1998) but in the present context is of no importance. One can rewrite Eq. (1) as

$$\frac{dF}{d\tau} = -f(\tau)\frac{F_{\text{vis}}}{\tau_T} \quad (4)$$

where we introduced a new variable, the optical depth $d\tau = -\kappa_R\rho dz$, κ_R being the Rosseland mean opacity and $\tau_T = \int_0^{+\infty} \kappa_R\rho dz$ is the total optical depth. As shown in DLHC, putting $f(\tau) = 1$ is a good approximation.

At the disc midplane, by symmetry, the flux must vanish: $F(\tau_T) = 0$, whereas at the surface, ($\tau = 0$)

$$F(0) \equiv \sigma T_{\text{eff}}^4 = F_{\text{vis}} \quad (5)$$

Equation (5) states that the total flux at the surface is equal to the energy dissipated by viscosity (per unit time and unit surface). The solution of Eq. (4) is thus

$$F(\tau) = F_{\text{vis}} \left(1 - \frac{\tau}{\tau_T}\right) \quad (6)$$

where τ_{tot} is the total optical depth.

To obtain the temperature stratification one has to solve the transfer equation. Here we use the diffusion approximation

$$F(\tau) = \frac{4}{3} \frac{\sigma dT^4}{d\tau}, \quad (7)$$

appropriate for the optically thick discs we are dealing with. The integration of Eq. (7) is straightforward and gives :

$$T^4(\tau) - T^4(0) = \frac{3}{4}\tau \left(1 - \frac{\tau}{2\tau_{\text{T}}}\right) T_{\text{eff}}^4 \quad (8)$$

The upper (surface) boundary condition is:

$$T^4(0) = \frac{1}{2}T_{\text{eff}}^4 + T_{\text{irr}}^4 \quad (9)$$

where T_{irr}^4 is the irradiation temperature, which depends on R , the albedo, the height at which the energy is deposited and on the shape of the disc (see Eq. 13). In Eq. (9) $T(0)$ corresponds to the *emergent* flux and, as mentioned above, T_{eff} corresponds to the *total* flux, hence the factor 1/2 in front of T_{eff}^4 . The temperature stratification is thus :

$$T^4(\tau) = \frac{3}{4}T_{\text{eff}}^4 \left[\tau \left(1 - \frac{\tau}{2\tau_{\text{T}}}\right) + \frac{2}{3} \right] + T_{\text{irr}}^4. \quad (10)$$

For $\tau_{\text{T}} \gg 1$, the temperature at the disc midplane is

$$T_c^4 \equiv T^4(\tau_{\text{T}}) = \frac{3}{8}\tau_{\text{tot}}T_{\text{eff}}^4 + T_{\text{irr}}^4 \quad (11)$$

It is clear, therefore, that for the disc inner structure to be dominated by irradiation and the disc to be isothermal one must have

$$\frac{F_{\text{irr}}}{\tau_{\text{tot}}} \equiv \frac{\sigma T_{\text{irr}}^4}{\tau_{\text{tot}}} \gg F_{\text{vis}} \quad (12)$$

and not just $F_{\text{irr}} \gg F_{\text{vis}}$ as is usually assumed. The difference between the two criteria is important in low-mass X-ra binaries since, for parameters of interest, $\tau_{\text{tot}} \sim 10^2 - 10^3$ in the outer disc regions.

The effect of disc irradiation is illustrated on Figs. 1 & 2 (DLHC). Fig. 1 shows the vertical structure of a ring which is part of an unilluminated accretion disc. This ring is on the lower, cool branch of the S-curve. The energy transport is dominated by convection. The surface temperature is equal to the effective temperature given by viscous dissipation (see Eq. 5). The vertical structure of an irradiated disc is shown on Fig. 2. Although the irradiating flux is 20 times larger than the viscous flux the disc is not isothermal. Since in the non-irradiated disc $T_c \approx 14500$ K and the surface temperature is $T_s \approx 5700$ the optical depth is ~ 100 and, obviously an irradiation temperature higher than 14500 K is required to make the disc isothermal. Note that irradiation suppressed convection and the disc now is purely radiative.

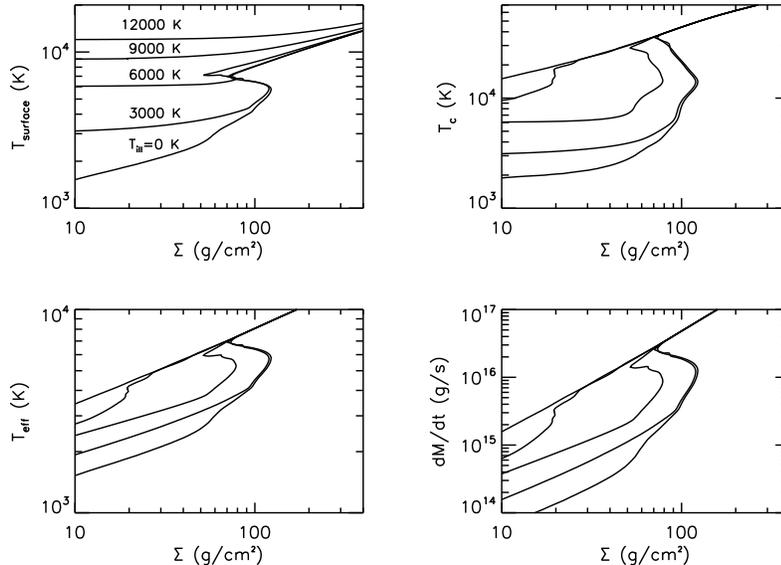


Fig. 3. $\Sigma - T_{\text{surface}}$, $\Sigma - T_c$, $\Sigma - T_{\text{eff}}$ and $\Sigma - \dot{M}$ curves for $r = 3 \cdot 10^{10}$ cm, $M = 10M_{\odot}$, $\alpha = 0.1$, and $T_{\text{irr}} = [0, 3, 6, 9, 12] \times 10^3$ K. (From DLHC)

3. Can the outer disc ‘see’ a point source located at the midplane ?

The answer is ‘no’ (see e.g. DLHC). The reason is that contrary to the frequently made assumption a ‘standard’ accretion disc is convex rather than concave. Images showing flaring discs have nothing to do with reality, at least with reality described by the standard model of planar discs.

For a point source, the irradiation temperature can be written as

$$T_{\text{irr}}^4 = \frac{\eta \dot{M} c^2 (1 - \varepsilon)}{4\pi\sigma R^2} \frac{H_{\text{irr}}}{R} \left(\frac{d \ln H_{\text{irr}}}{d \ln R} - 1 \right) \quad (13)$$

where η is the efficiency of converting accretion power into X-rays, ε is the X-ray albedo and H_{irr} is the local height at which irradiation energy is deposited, or the height of the disc “as seen by X-rays”. We use here H_{irr} and *not* H , the local pressure scale-height, as is usually written in the literature because, in general, $H_{\text{irr}} \neq H$.

Eq. (13) is usually used (at least in the recent, abundant, publications on the subject) with ‘typical’ values of $\varepsilon > 0.9$, $H/R = 0.2$ (no difference is seen between H_{irr} and H ; the fact that there is no reason for the photosphere to be at one (isothermal) scale-height seems to be largely ignored). These values are supposed to be given by ‘observations’. However, when one reads the articles quoted to support this assertion (Vrtilek et al. 1990; de Jong et al. 1996) one

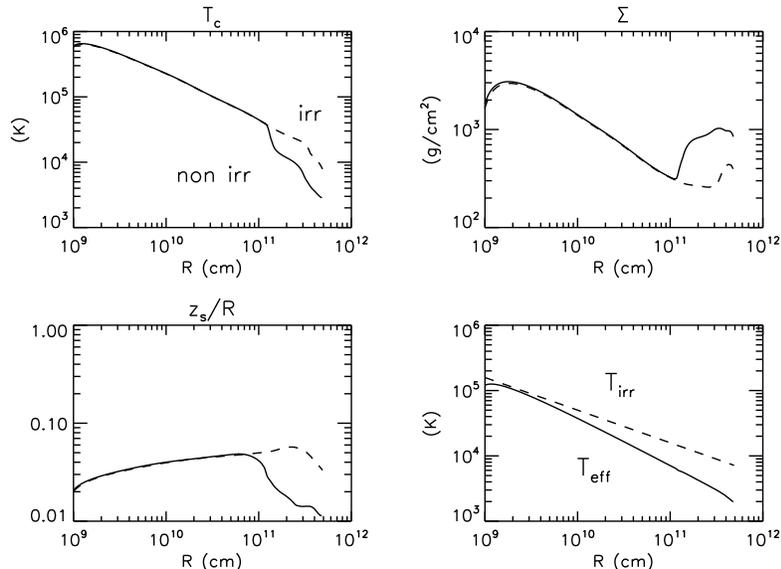


Fig. 4. Radial profiles of the midplane temperature, surface density, and photospheric height to radius ratio for an un-irradiated (continuous line) and irradiated disc (dashed line) around a $10 M_{\odot}$ compact object. In the temperature diagram the continuous line represents the effective temperature. The accretion rate is $\dot{M} = 10^{18} \text{ g s}^{-1}$, T_{irr} is taken from Eq. (15) with $\mathcal{C} = 5 \times 10^{-4}$. Regions beyond the radius at which a break in the T_c or Σ curve appears are unstable. (From DLHC)

finds nothing of the kind there. These papers *assume* that an irradiated disc is isothermal. de Jong et al. (1996) fit light-curves with the isothermal model of Vrtilik et al. (1990). Moreover, since de Jong et al. (1996) model lightcurves of neutron-star binaries the $H/R = 0.2$ cannot be applied to black-hole binaries (especially if H were the pressure scale-height): since black-holes are more massive than neutron stars, in their case H/R should be smaller at a given radius (let me add for the benefit of some readers: this is because gravity is then stronger), as seen in Fig. 6 & 7 of DLHC. In any case, for $H/R = 0.2$ the vertical hydrostatic equilibrium equation would imply high temperatures at the disc's outer rim:

$$T \sim 8 \times 10^7 \left(\frac{M}{M_{\odot}} \right) \left(\frac{R}{10^{10} \text{cm}} \right)^{-1} \left(\frac{H}{R} \right)^2 \text{ K}, \quad (14)$$

which is clearly contradicted by observations.

When one calculates self-consistent (in the sense that H_{irr} in Eq. (13) is calculated and not *assumed*) models of irradiated discs one sees that the outer disc regions whose structure could be affected by irradiation are hidden in the

shadow of the convex disc. This ‘self-screening’ results from the same physical process that is at the origin of the dwarf-nova instability: a dramatic change of opacities due to hydrogen recombination. Therefore, although irradiation could stabilize the disc, the unstable disc regions (see Fig. 3), cannot be irradiated by a point source located at the disc mid-plane. Models invoking the stabilizing effects of irradiation (van Paradijs 1996; King & Ritter 1998) have therefore to be revised (DLHC). Since outer disc regions in low mass X-ray binaries are clearly irradiated, (van Paradijs & McClintock 1995) model revisions must concern the disc-irradiating source geometry. To represent a geometry allowing the disc to see the irradiating source DLHC assumed that

$$T_{\text{irr}}^4 = C \frac{\dot{M} c^2}{4\pi\sigma R^2} \quad (15)$$

and calculated irradiated disc structure. The results are shown in Fig. 4. The continuous line represents both a non-irradiated disc and a disc irradiated according to Eq. (13) with a self-consistently calculated H_{irr} : there is no difference between the two cases.

4. Can irradiation by a hot white dwarf explain the UV-delay in dwarf novae?

As shown by Hameury, Lasota & Dubus (1999) the answer to this question asked by King (1997) is ‘no’. Irradiation of the disc by the hot white dwarf may, however, be important in a different context (see Sect. 6).

5. Can the secondary in a dwarf-nova system be irradiated during outbursts ?

The answer is ‘yes’ at least for SS Cyg (Hessman 1984) and WZ Sge (Smak 1993). In these systems it was *observed* that the secondary’s hemisphere facing the accreting white dwarf was, during the outburst, heated to 16 000 - 17000 K, which for WZ Sge implies that the irradiating flux is ~ 5000 times larger than the star’s intrinsic flux. It is hard to believe that the companion does not increase its mass transfer rate in such conditions. WZ Sge is a very special system anyway (Lasota, Kuulkers & Charles 1999).

6. Can irradiation of the disc and of the secondary determine outburst properties?

Warner (1998) suggested that outburst properties of SU UMa stars could be explained by the effects of irradiation of both the accretion disc and the sec-

ondary. Preliminary results by Hameury & Lasota (1999, in preparation; see also Hameury these proceedings) seem to confirm that properties of SU UMa (and ER UMa) stars may be explained in this way.

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