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Soft X-ray emission from dwarf novae

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Summary. Dwarf novae are binary systems in which material is being transferred from a low mass main sequence star, via an accretion disc to a white dwarf companion. The two suggested regions of soft X-ray production are the 'hot spot' where the stream of transferred matter strikes the disc and the boundary layer where the accretion disc grazes the surface of the white dwarf. These two possibilities are investigated and it is concluded that the 'hot spot' gives rise to little or no soft X-ray emission, whereas the boundary layer can emit up to half the accretion luminosity as soft X-rays. The structure of the boundary layer delineated here is of relevance to other stellar systems which contain an accretion disc.

1 Introduction

Since the possible detection by Rappaport *et al.* (1974) of soft X-ray emission from the dwarf nova SS Cyg during outburst (luminosity $\sim 10^{33}\,\mathrm{erg\,s^{-1}}$, $kT < 0.4\,\mathrm{keV}$), there have been a number of observations of such systems in the soft X-ray band. Upper limits to the flux from U Gem and RX And are given by Henry *et al.* (1975). Further upper limits, and a marginal detection of SS Cyg during quiescence at a level 1 per cent of that reported by Rappaport *et al.* (1974) are provided by Heise *et al.* (1976). Other possible detections are listed by Warner (1974).

Warner (1974) has suggested that such emission could come from the 'hot spot' in these binary systems, where the stream of transferred material from the lobe-filling secondary interacts with the disc of gas accumulated around the accreting primary (white dwarf). We examine this possibility in Section 2 and show that although a requisite quantity of soft X-rays could be produced in the shock at the hot spot, only a very small fraction of these can possibly emerge without being absorbed in the surrounding disc and stream. Most of the energy liberated at the hot spot is thermalized and emerges as optical or ultraviolet radiation. On the other hand, Bath *et al.* (1974) have suggested that although the accretion disc in dwarf novae does not get hot enough to produce soft X-rays, a flux of soft X-rays could be expected from the boundary layer where the accretion disc grazes the surface of the white

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dwarf. In Section 3 we examine this suggestion in more detail and show that soft X-rays (defined as photons with energies $\geqslant 0.15$ keV) can indeed be emitted from this region. We emphasize that much of the analysis contained in Section 3 can be straightforwardly applied to other situations in which an accretion disc surrounds a central star.

2 Emission from the hot spot

2.1 CALCULATION

In this section we estimate the soft X-ray emission to be expected from the 'hot spot' in cataclysmic binary systems where the stream of transferred material interacts with the gas already orbiting the accreting white dwarf. We proceed initially in an optimistic manner, making those assumptions most conducive to X-ray emission: we discuss in 2.2 why such optimism is not warranted. We consider particular parameters for the binary system, although it will be apparent that our conclusions do not depend critically on the parameters chosen. We take the mass of the white dwarf primary to be $1\,M_\odot$ and of the lobe-filling secondary to be $M_2 = 0.6\,M_\odot$. Such values are fairly typical for those systems for which mass estimates have been possible (Robinson 1976). The assumption that the secondary fills its Roche lobe implies (Robinson 1973) that the binary period $P = 1.7 \times 10^4\ s = 0^d.2$ and hence that the binary separation $a = 1.16 \times 10^{11}$ cm.

We take the distance R_s of the hot spot from the primary to be that given by the assumption that the stream conserves its angular momentum with respect to the primary as it settles into a circular orbit (Flannery 1974; Lubow & Shu 1975). We assume that the radial (with respect to the primary) velocity of the incoming stream is dissipated at the hot spot and that the shock lies in a plane perpendicular to the orbital plane and normal to the radius vector from the primary. This assumes that the density of the disc is much greater than that in the stream. We take the mean molecular weight of transferred material to be 0.615. We find that $R_s = 1.25 \times 10^{10}$ cm and the shock temperature $T_s = 8.5 \times 10^6$ K ($kT_s = 0.7$ keV). The luminosity generated in the shock $L_s = 3 \times 10^{33} \dot{M}_{18}$ erg s^{-1} where $\dot{M}_{18}$ is the mass transfer rate in units of 10^{18} g s^{-1} $= 1.5 \times 10^{-8} M_\odot$ yr^{-1}. Thus, at first sight, the hot spot appears to be a good candidate for soft X-ray emission (e.g. Warner 1974). We now show, however, that the thickness x_s of the radiating region behind the shock is much less than the radius y_s of the stream at the shock and hence that only a small fraction of this luminosity can emerge without passing through cool material.

To investigate the structure of the shock we must know the incident density ρ_s of the stream. We follow the analysis of Lubow & Shu (1975) and obtain $\rho_s = 2.0 \times 10^{-8} e^{-2} \dot{M}_{18}$ g cm^{-3}. Here $e = 40\epsilon$ where ϵ is the small expansion parameter defined by Lubow & Shu which corresponds approximately to the ratio of the sound speed in the stream to the orbital velocity. We expect $e \sim 1$. Similarly we find $y_s = 3.5 \times 10^8 e$ cm. The width of the radiating region is given approximately by the product of the radial velocity of the shocked gas and its cooling timescale. Assuming cooling is due solely to bremsstrahlung we find $x_s = 1.5 \times 10^5 e^2 \dot{M}_{18}^{-1}$. The optical depth to electron scattering through the stream $\tau_{es} = 0.38\, y_s \rho_s = 2.4$ which implies that the optical depth to photoelectric absorption of the 0.7 keV photons produced is $\sim 10^6$. Thus the only X-ray photons that could conceivably be observed are those emerging from the sides of the shocked region. If the shocked region is indeed planar (an unlikely event – see below) the luminosity L_s would only appear twice per orbital period for a time $\sim x_s P/y_s \sim 7\, e \dot{M}_{18}^{-1}$ s, yielding an average soft X-ray flux of $L_{xs} = 1.3 \times 10^{30} e$ erg s^{-1} independent of $\dot{M}$. The rest of the radiation is absorbed in the gas surrounding the spot and re-radiated at longer wavelengths.

2.2 DISCUSSION

We now summarize why the oversimplified calculation we have just made is likely to give a gross overestimate of the X-ray flux emitted by the hot spot.

We have assumed the smallest reasonable size for R_s. In a steady accretion flow Lin & Pringle (1976) have shown that R_s assumes larger values – not so deep in the potential well of the primary. The stream velocity V_s prior to impact and the density ρ_s are thereby reduced: for example, halfway along the stream to the hot spot in the system discussed above, V_s is reduced by 2.0 and ρ_s by 3.2 (Lubow & Shu 1975). For a given accretion rate $L_s \propto T_s \propto V_s^2$, so that not only is the hot spot luminosity reduced, but also that fraction of the luminosity observable in a given soft X-ray band. Assuming, again, that bremsstrahlung cooling dominates, we find $x_s/y_s \propto V_s^{5/2}\rho_s^{-1/2}$ and hence $L_{xs} \propto V_s^{9/2}\rho_s^{-1/2}$. Furthermore, since for temperatures $\lesssim 3\times10^7$ K line emission dominates bremsstrahlung, the values we have obtained for x_s are all overestimates, possibly by an order of magnitude (Tucker & Koren 1971; Kato 1976).

One other failing in our analysis which has led us to overestimate the soft X-ray flux from the hot spot is the simple geometry we have assumed for the shock. The flickering of the optical light emitted by the hot spot (Warner 1976) probably indicates considerable inhomogeneities in the colliding material, and the shock is likely to have a much more complicated shape than the simple plane we have envisaged. This makes it much harder for any soft X-rays to emerge. If y_s is much smaller than the semithickness, H_s, of the disc of gas at that radius, the stream can plough into the disc so that the shocked region is completely covered by unshocked absorbing material. If, on the other hand, y_s is larger than H_s, much of the interaction takes place in oblique shocks above and below the disc, again enabling the shocked matter to be hidden.

3 Emission from the boundary layer

3.1 CALCULATION

If an accretion disc emits blackbody radiation, the characteristic temperature of the disc is

$$\theta_* = \left(\frac{GM\dot{M}}{8\pi R^3 \sigma}\right)^{1/4}$$

$$= 1.6\times10^5 \dot{M}_{18}^{1/4}\left(\frac{M}{M_\odot}\right) R_{8.7}^{-3/4}\ \text{K} \tag{3.1}$$

where M is the mass of the central object and $R_{8.7}$ its radius in units of 5×10^8 cm. If the central object is not rotating very close to break up speed the maximum temperature in the disc is $T_{max} = 0.595\theta_*$ (Shakura & Sunyaev 1973; Lynden-Bell & Pringle 1974) and, assuming corotation of disc and central star, up to half the emitted radiation comes from a boundary layer where the disc interacts with the stellar surface. The structure of the boundary layer for constant disc viscosity and zero pressure has been discussed by Lynden-Bell & Pringle (1974). For our purposes, however, a less detailed approach is necessary.

The radial component of the time-independent Euler equation is

$$u_r\frac{du_r}{dr} - \frac{u_\theta^2}{r} = -\frac{1}{\rho}\frac{dp}{dr} - \frac{GM}{r^2} \tag{3.2}$$

where u_r, u_θ are the radial and azimuthal velocity components, p the pressure and ρ the density. We assume that the only relevant stress is the (r,θ) component – that is, that the effective Reynold's number of the flow is greater than unity. Outside the boundary layer $u_\theta = V_k(r) \equiv (GM/r)^{1/2}$, $u_r \ll C_s = (p/\rho)^{1/2} \ll u_\theta$ and the gradient length scale is R. The disc semi-thickness H is given roughly by $H/R = C_s/V_k$. Let the thickness of the boundary layer be B. On the stellar surface we require $u_\theta = R\Omega$ where Ω is the star's angular velocity. We shall demand initially that $R\Omega \ll V_k(R)$, although we shall see below that this condition can be relaxed. Thus, in the boundary layer, where $u_\theta < V_k$, the term V_k^2/R on the right-hand side of (3.2) must be balanced *either* by

$$u_r \frac{du_r}{dr} \sim u_r^2/B \quad \text{or by} \quad \frac{1}{\rho}\frac{dp}{dr} \sim C_s^2/B.$$

We must, however, demand that $|u_r| < C_s$ throughout the flow: otherwise the presence of the central star cannot be communicated outwards. We find, therefore, that $B \sim H^2/R$ and, for a thin disc, $B \ll H \ll R$. If the central part of the disc is optically thick, the energy liberated in the boundary layer must diffuse outwards a distance $\sim H$ through the disc before emerging from top and bottom. If we take the emitting region to have an area $2\pi R.\,2H$, the effective temperature of the boundary layer $T_{BL} = \theta_*(R/H)^{1/4}$. Note that H must be determined self-consistently in this region and is, in general, larger here than in the most luminous parts of the disc itself. If gas pressure dominates we find

$$T_{BL} = 5 \times 10^5 \xi^{2/9} \dot{M}_{18}^{2/9} \left(\frac{M}{M_\odot}\right)^{1/3} R_{8.7}^{-7/9}\ \text{K}. \tag{3.3}$$

The boundary layer accretion luminosity is

$$L_{BL} = 1.3 \times 10^{35} \xi \dot{M}_{18} \left(\frac{M}{M_\odot}\right) R_{8.7}^{-1}\ \text{erg s}^{-1} \tag{3.4}$$

where $\xi = 1 - R^2\Omega^2/V_k^2$. We assume henceforth that $\Omega = 0$ and $\xi = 1$. Note that, if the accreted matter undergoes steady nuclear burning as it settles on to the white dwarf, we could have $\xi \gg 1$.

For the luminosities we consider, radiation pressure in the boundary layer cannot be neglected. If the semi-thickness of the disc is due to radiation pressure alone we find roughly $H_r/R = (L_{BL}/L_E)^{1/2}$. Here subscript r means 'due to radiation pressure' and $L_E = 1.3 \times 10^{38}$ $(M/M_\odot)$ erg s^{-1} is the Eddington luminosity, valid for an electron-scattering opacity. If the semi-thickness due to gas pressure alone is $H_g = RC_s/V_k$, we find $H_g = H_r$ when

$$\dot{M} = \dot{M}_{crit} = 8 \times 10^{16} \left(\frac{M}{M_\odot}\right)^{-6/7} R_{8.7}^{11/7}\ \text{g s}^{-1}. \tag{3.5}$$

To estimate the soft X-ray flux from the boundary layer (the flux from the disc is always insignificant (Bath *et al.* 1974)) we assume that the emergent spectrum is blackbody and that the boundary layer emits at a single temperature. We define soft X-ray flux, as that fraction of the radiation emerging at energies greater than 0.15 keV. The disc semi-thickness H is found self-consistently from the equation

$$\frac{H^2}{R^2} = \frac{L_{BL}}{L} + \frac{C_s^2}{V_k^2}. \tag{3.6}$$

In Fig. 1 the resultant values of T_{BL} are plotted against $\dot{M}$ for various values of the central white dwarf mass. In Fig. 2 the soft X-ray luminosity L (> 0.15 keV) is plotted against $\dot{M}$ for the same values of white dwarf mass. It is apparent that a sizeable fraction of the accretion

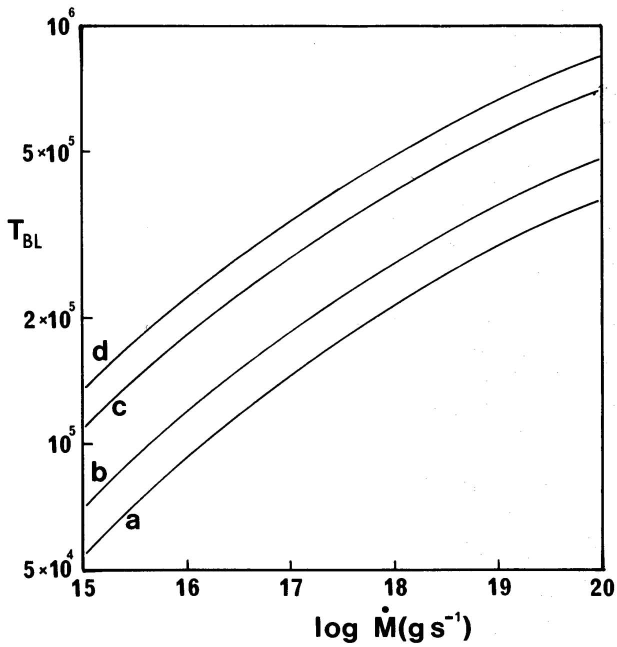

Figure 1. The effective temperature of the boundary layer as a function of accretion rate for various values of the mass of the central white dwarf: (a) $M = 0.51 M_\odot$, $R = 9.75 \times 10^8$ cm, (b) $0.75 M_\odot$, 8×10^8 cm, (c) $1.1 M_\odot$, 5×10^8 cm, (d) $1.24 M_\odot$, 3.9×10^8 cm.

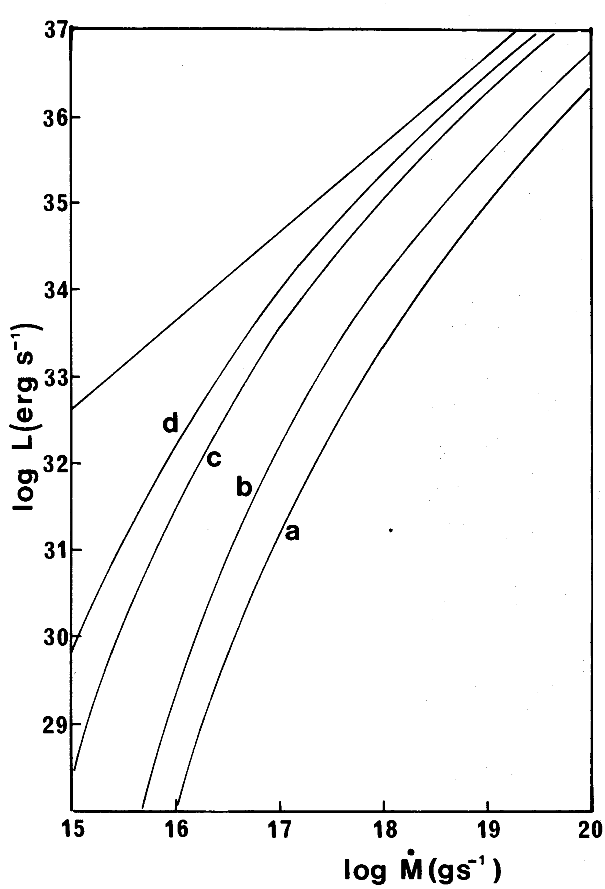

Figure 2. The luminosity of the boundary layer at energies greater than 0.15 keV as a function of the accretion rate for various values of the mass of the central white dwarf: (a) $0.51 M_\odot$, (b) $0.75 M_\odot$, (c) $1.1 M_\odot$, (d) $1.24 M_\odot$. The straight line corresponds to the total boundary layer luminosity from the $1.24 M_\odot$ white dwarf.

luminosity can be emitted as soft X-rays and also that the soft X-ray flux is a sensitive function of the accretion rate. This latter dependence also implies that the actual values shown in Fig. 2 should be treated with caution since they probably depend sensitively on our assumptions as well. We re-examine these below.

3.2 DISCUSSION

The general structure we have sketched out for the boundary layer is valid even when $R\Omega \sim V_{\rm k}$, provided that $V_{\rm k} - R\Omega \gg C_{\rm s}$. The formula $B \sim H^2/R$ also holds when the effective viscosity is due to supersonic turbulence and H is determined primarily by turbulent pressure. Magnetic viscosity can be taken into account in a similar fashion. The analysis can be readily applied to other astrophysical situations as long as calculated disc thickness is much larger than the scale-height in the atmosphere of the accreting star.

At the temperatures (Fig. 1) and probable densities (Shakura & Sunyaev 1973) we are considering, electron scattering opacity dominates over free–free and bound–free. While this means that we were correct in taking the Eddington luminosity $L_{\rm E}$ in (3.6) it also implies that the emergent spectrum is not blackbody. Using the value for the surface emissivity of $1.3 \times 10^4 H^{-1/3} T^{17/6} \,\mathrm{erg\,cm^{-2}\,s^{-1}}$ given by Shakura & Sunyaev (1973; see also Zel'dovich & Shakura 1969), ignoring radiation pressure and making the same other assumptions as above we find the boundary layer temperature to be

$$T_{\rm ES} = 8.4 \times 10^5 \dot{M}_{18}^{6/19} \left(\frac{M}{M_\odot}\right)^{8/19} R_{8.7}^{-18/19} \,\mathrm{K}. \tag{3.7}$$

This may be compared with the blackbody temperature given by (3.3). We may therefore expect the temperature to be slightly higher than the calculated blackbody value. The net effect on the soft X-ray flux is not clear, however, since the spectrum from an electron-scattering dominated atmosphere peaks at $1.7\,kT$ rather than at the blackbody value of $2.7\,kT$. A larger error is probably introduced by our assumption that the region emitting the boundary layer luminosity radiates at a single temperature. Before realistic comparison can be made with observations a more detailed model of the radiative transfer in the boundary layer region is probably required. In addition, although for the parameters we consider we expect the boundary layer region to be optically thick, further complications would be introduced in this and other applications were this not the case. We would expect the radiation to be less thermalized in these circumstances and the temperature to be above the blackbody estimates.

We must also consider how much of the emitted soft X-ray radiation is likely to be observable. Quite apart from absorption by interstellar material, the mass transfer process itself is likely to give rise to the presence of considerable absorbing material in and around the binary system. For dwarf novae, the mass transfer process is by Roche lobe overflow and the circumstellar gas is likely to be reasonably confined to the orbital plane. Thus soft X-ray emission should be more readily observable from systems with smaller inclination angles i. This conclusion is enhanced by consideration of the geometry of the emitting region. When $i = 0$, the whole boundary layer can be seen, whereas for $i \gg H/R$ only half of it can be seen directly, the rest being obscured by the white dwarf. This also implies that re-radiation of soft X-rays absorbed by the white dwarf should also be taken into account. The shape of the emitting region also produces a dependence of observed flux on i, which requires a better model for the emitting region than we have given to evaluate realistically.

One feature of the soft X-ray flux from dwarf novae that should be readily observable is its variability. If dwarf nova outbursts are indeed accretion events (Bath *et al.* 1974), and provided that the quantity of ambient gas in the system is not too great during outburst, the soft X-ray flux should vary dramatically (Fig. 2). Moreover a number of dwarf novae display low-level oscillatory phenomena during outburst which are thought to be possibly associated with non-radial pulsations on the white dwarf surface (see review by Warner 1976). If so, the soft X-ray flux may be expected to show similar, but more highly modulated behaviour (E. L. Robinson, private communication). It is even possible that such pulsations could be driven by processes occurring in the boundary layer.

The soft X-ray luminosities calculated here for disc accretion on to a white dwarf contrast with the relatively hard emission to be expected when the accretion is radial (Hoshi 1973; Fabian, Pringle & Rees 1976; Katz, in preparation). We note in particular that, if a white dwarf in a binary system accretes primarily from the stellar wind of its companion in such a manner that the accretion can switch from radial to non-radial without a substantial change in accretion rate (see discussion in Fabian *et al.* 1976), then the resultant apparent variability in a given wave band would be disproportionately large. It is possible that some of the transient (hard) X-ray sources may be of this nature. A search for soft X-ray emission after the hard X-rays have declined could provide verification of this.

4 Conclusion

We have shown that a considerable fraction of the accretion energy liberated by matter accreting via a disc on to a white dwarf can be emitted as soft X-rays. If there is sufficiently small circumstellar and interstellar absorption along the line of sight, they should be detectable from some of the brighter dwarf novae, especially during outburst. The oscillatory behaviour seen in the optical flux from a number of dwarf novae during outburst may be much more evident in soft X-rays. Observation of this phenomenon in the X-ray band should shed light on the nature of the oscillations. The estimates of soft X-ray flux presented here are relevant to any systems in which a white dwarf accretes material via an accretion disc. The calculations can be extended in a straightforward manner to other systems containing circumstellar accretion discs.

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References

Bath, G. T., Evans, W. D., Papaloizou, J. & Pringle, J. E., 1974. *Mon. Not. R. astr. Soc.*, **169**, 447.
Fabian, A. C., Pringle, J. E. & Rees, M. J., 1976. *Mon. Not. R. astr. Soc.*, **175**, 43.
Flannery, B. P., 1974. *Mon. Not. R. astr. Soc.*, **170**, 325.
Heise, J., Brinkman, A. C., Schrijver, J., Mewe, R., Groneschild, E. & den Boggende, A., 1976. *Astrophys. Space Sci.*, in press.
Henry, P., Cruddace, R., Lampton, M., Paresce, F. & Bowyer, S., 1975. *Astrophys. J. Lett.*, **197**, L117.
Hoshi, R., 1973. *Prog. theor. Phys.*, **49**, 776.
Kato, T., 1976. *Astrophys. J. Suppl.*, **30**, 397.
Lin, D. N. C. & Pringle, J. E., 1976. *Proc. IAU Symp. 73.* eds P. P. Eggleton *et al.*, Reidel, Dordrecht, in press.
Lubow, S. H. & Shu, F. H., 1975. *Astrophys. J.*, **198**, 383.
Lynden-Bell, D. & Pringle, J. E., 1974. *Mon. Not. R. astr. Soc.*, **168**, 603.

Rappaport, S., Cash, W., Doxley, R., McClintock, J. & Moore, J., 1974. *Astrophys. J. Lett.*, **187**, L5.
Robinson, E. L., 1973. *Astrophys. J.*, **180**, 121.
Robinson, E. L., 1976. *A. Rev. Astr. Astrophys.*, 119.
Shakura, N. I. & Sunyaev, R. A., 1973. *Astr. Astrophys.*, **24**, 337.
Tucker, W. H. & Koren, M., 1971. *Astrophys. J.*, **168**, 283 (erratum, **170**, 621).
Warner, B., 1974. *Mon. Not. R. astr. Soc.*, **167**, 47P.
Warner, B., 1976. *Proc. IAU Symp. 73*, eds P. P. Eggleton *et al.*, Reidel, Dordrecht, 119.
Zel'dovich, Y. B. & Shakura, R. A., 1969. *Sov. Astr. A.J.*, **13**, 175.