The Emission from Post-Shock Flows in mCVs

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Abstract

We re-examine the vertical structure of the post-shock flow in the accretion region of mCVs, and the X-ray emission as a function of height. We then predict X-ray light curves and phase-resolved spectra, taking into account the vertical structure, examine the implications and check whether the predicted heights are compatible with observation.

1. Introduction

The accretion processes in magnetic CVs are considered to be important astrophysically because they are one-dimensional and quasi-collimated. This advantage is accompanied by relatively tractable physical conditions in the accretion region coupled with a wide range of diagnostic observations over a large range in wavelength, including polarised optical emission.

Whether directly in a stream or from the inner edge of the accretion disk, the accretion flow is constrained to follow the magnetic field lines to the surface of the white dwarf primary. There material in supersonic free-fall is brought to rest, forming a stand-off shock, with the temperature of order the randomised free-fall velocity $\sim 10-50$ keV. Behind this shock is a column of hot plasma, which can settle onto the white dwarf only by cooling. In mCVs this occurs by emitting bremsstrahlung radiation and, if the magnetic field is sufficiently strong, by cyclotron radiation.

The characteristics of the accretion column depend principally on the mass of the white dwarf (which, via the free-fall velocity, sets the post-shock temperature), on the local accretion rate (which affects the density, and therefore the rate at which the region can radiate) and on the magnetic field (which determines how much additional cooling will be produced due to cyclotron radiation). With appropriate boundary conditions, the equations of conservation of mass, momentum and energy can be used to calculate the temperature, density and other hydrodynamic variables as a function of height within the column. How easy it is to do this depends on the assumptions of the model. An analytic solution (Aizu 1973) can be found in the case of bremsstrahlung radiation as the only heating/cooling mechanism, with no gravity. Otherwise, at present the equations have to be computed numerically (eg. Imamura & Durisen 1983 and many others), but for some cases the situation is better, with the existence of closed integral forms (eg. Wu, Chanmugam & Shaviv 1994). Models now include the cooling by cyclotron emission, the effect of the variation of gravity within the flow, the formulation of 2-fluid descriptions for ions and electrons, and time dependent forms also exist.

With a prescription of temperature and density as a function of height within the flow, the X-ray emission spectrum from this flow can be calculated. This is typically done by the summation of optically

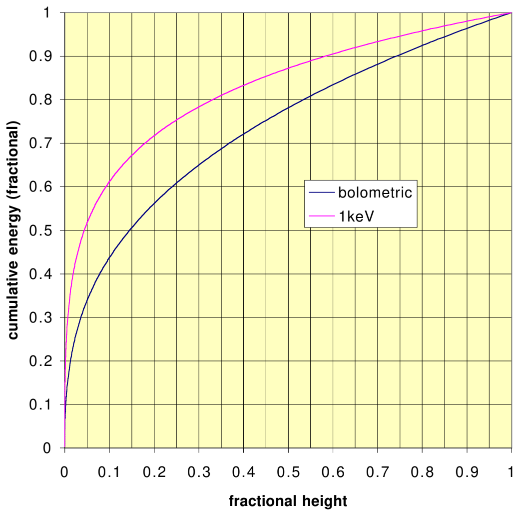
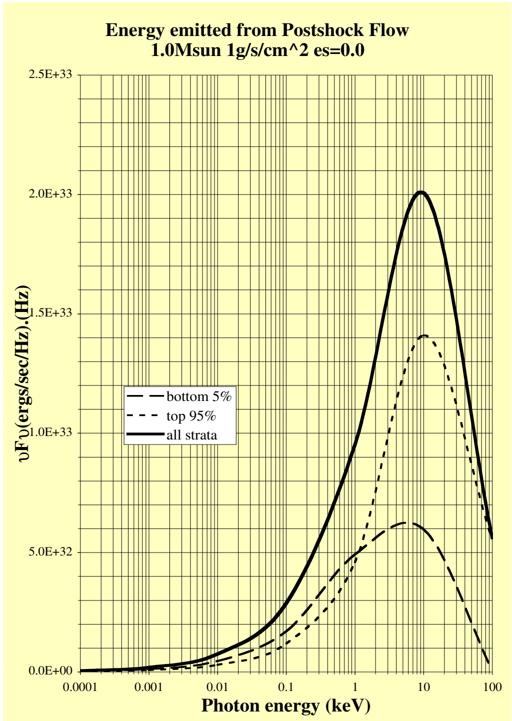


Figure 1 (above) The cumulative energy fraction as a function of height in the accretion column at 1 keV and in total bolometric luminosity, for a 1.0 $M_\odot$ white dwarf with no cyclotron cooling accreting at 1 g/s/cm^2.
Figure 2 (right) The energy spectrum in νF_ν emitted from the bottom 5% of the column in Fig. 1, the top 95% and in total.



thin emission spectra calculated using standard optically thin models (eg. Cropper, Ramsay & Wu 1998). By comparing these multi-temperature model spectra to X-ray data, the basic parameters of the model such as the white dwarf mass and the mass transfer rate can be determined. Generally good fits are obtained, and a number of cross-checks have been made with other methods of white dwarf mass determination (Ramsay et al. 1998): these suggest that the method may yield mass determinations which are higher than generally expected. Some difficulties are clearly caused by inappropriate absorption models used in the fits to the X-ray data, even at high energies (Done & Magdziarz 1998). Other difficulties may be caused by inappropriate assumptions within the modelling, which we now explore.

2. Emission at the Base of the Accretion Region

One of the assumed boundary conditions in all the above work is a cold, hard white dwarf surface. Because bremsstrahlung emission is proportional to the square of the density, and towards the base of the region the density is rising rapidly (to infinity at zero temperature) *most* of the emission from the column is from its base (Fig. 1). For a 1.0$M_\odot$ white dwarf accreting at 1 g/s/cm^2, $>$ 50% of the emission is in the lowest 5% of the column at typical *Rosat* energies of 1 keV. In νF_ν terms (where a direct comparison cam be made of the energy output), most of the energy is emitted at $\sim$ 8 keV – see Fig. 2. However, even at 8 keV, or in bolometric terms (Fig. 1), $\sim$ 1/3 of the emission is from the bottom 5%.

It is worth appreciating the degree to which the emission is most intense at the base of the region. This is evident in Fig. 3, which shows the spectrum from 0.1 to 10 keV for the 1 $M_\odot$ case above as a function of height plotted on a linear greyscale. The high intensity of emission near the x-axis (the surface of the white dwarf) is clear. What is even more striking from this figure is that the emission from the lower part of the column exceeds that from higher up even to 20 keV. Only at energies approaching the shock temperature ($\sim$ 50 keV for the 1.0 $M_\odot$ white dwarf) does the emission from the top of the

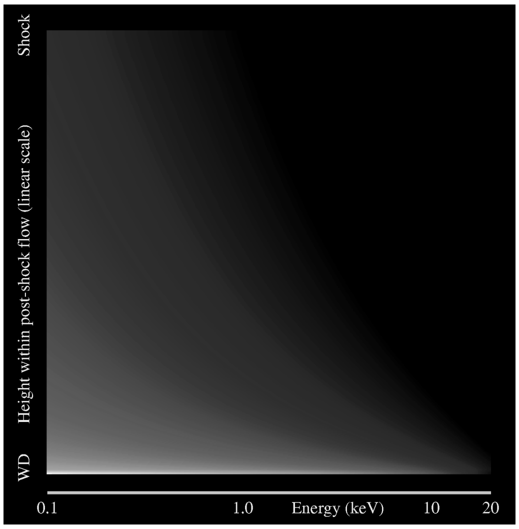


Figure 3 The spectrum from 0.1 to 20 keV plotted as a linear greyscale in intensity as a function of height within the column. System parameters are a 1.0 $M_\odot$ white dwarf accreting at 1 g/s/cm^2.

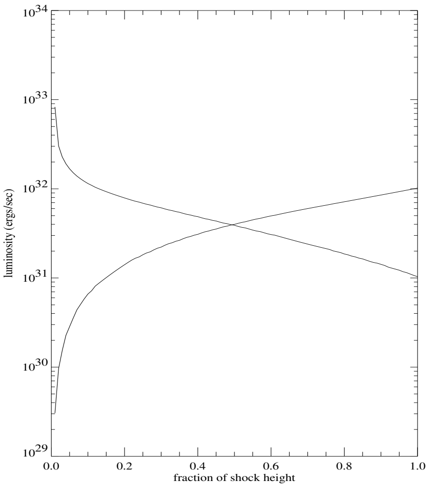


Figure 4 The bremsstrahlung (increasing towards the white dwarf surface) and cyclotron (decreasing) luminosity as a function of height for the system in Fig. 3, but with a 23 MG field and a fractional area over which accretion takes place of $f = 0.008$.

column immediately below the shock approach that from the base near the white dwarf.

The implications of this are twofold. Firstly there is the practical problem of the sampling of the strata at the base of the column in the modelling routines: those routines which sample the base of the column more finely will tend to predict softer spectra, and therefore will predict higher mass white dwarfs in order to match any observed spectrum, than those with coarser sampling. The selection of the centre, top or bottom of any stratum to designate its height will also have an effect, as the lower strata contribute so heavily to the overall spectrum.

Secondly, and of more interest scientifically, the boundary condition used for the base of the column is clearly inappropriate. At this point the hydrodynamic flow ought to be matched to the hydrostatic atmosphere, and the conduction of heat across this interface included in the calculations for the temperature and density structure of the column (see Wu 1999). Inappropriate modelling of the base of the column will lead to larger corrections to the emitted spectrum than formerly appreciated, even in the 1 – 10 keV range, in the direction of making the spectrum harder and leading to lower mass white dwarfs from fits to data.

3. Soft emission

Towards the base of the column opacity effects will become important. Observing from infinity into the column, and ignoring the effects of any pre-shock flow, it can be shown that for a 1.0 $M_\odot$ white dwarf accreting at 1 g/s/cm^2 over a fraction $f = 0.008$ of its surface, the free-free optical depth within the flow is negligible down to 10^{-4} of the fractional height in both transverse and parallel directions. However, electron scattering can be important (Rosen 1992). For the column above, electron scattering optical depths of unity in the transverse direction are reached at a fractional height of 0.02. This is significant when taking into consideration that the bulk of the emission occurs from these heights. Although wavelength independent, the effect of the electron scattering is to scatter photons from the lower strata out of the lateral line of sight into other lines of sight, making the spectrum from the column as a whole harder and fainter when seen side on and softer and brighter when seen at other angles.

In addition to the continuum opacity effects, line and edge opacities will become increasingly important in the base. Even without a detailed calculation, it is possible to predict that from a side on view, for a cylindrical column there will be a domed surface at the base where the optical depth is unity. The spectrum of the photons from within this surface will be degraded to a black body. Again the implications of this are twofold: firstly, these photons are from the accretion flow, and in terms of the modelling of this region belong to the soft end of the spectrum from this flow. Observers on the other hand will assign these photons to the "black body" component reprocessed from the heated photosphere. The effect of this is for the observer to measure an excess of soft X-rays over what is expected from the standard column (Lamb & Masters 1979). At some level this effect must contribute to the "soft X-ray problem". The extent to which this is the case will depend on the details of the calculations for the opacities, but again, the effect will be more important than formerly appreciated because most of the emission in the range of imaging X-ray instruments is from the base of the column.

The second implication is that at soft energies, such as those seen by *ROSAT* or *EUVE*, the accretion column will appear dome-shaped when seen side on. Such an appearance has been suggested many times from *EUVE* observations eg. Sirk & Howell (1998).

Finally, although limited work has been carried out in this area, the accretion flow will produce a heated photosphere in the region of the base of the accretion column (Litchfield & King 1990) which will also modify the soft X-ray emission from that region by absorption and scattering to a greater degree than previously appreciated.

4. Blobs

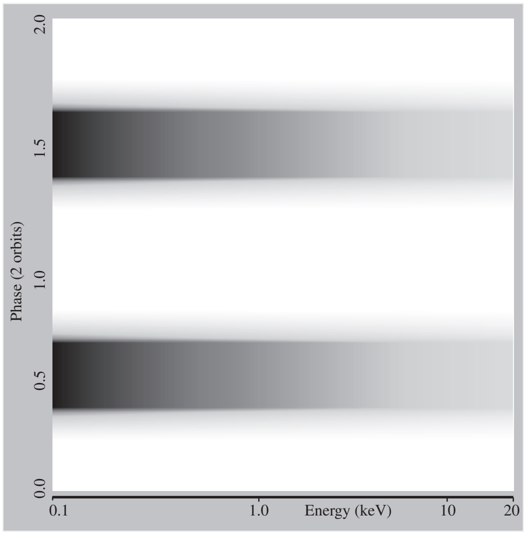
Flares in X-ray and optical light curves are generally considered to be the result of "blobs" or density enhancements in the flow. The standard explanation for the soft X-ray problem is that it results from energy deposited by blobs buried in the photosphere (Kuijpers & Pringle 1982, Frank, King & Lasota, 1988). It is clear that such blobs do exist, and the arguments above do not eliminate their role in producing a soft excess. However, they suggest that this excess can be produced without requiring the majority of the blob to be buried – only the base from where most of the emission emanates. This reduces the requirements on the density spectrum of the blobs, and is consistent with the existence of optical flaring from these systems (eg. VV Pup, Cropper & Warner 1986). Because flares can clearly be isolated to the column (from eclipse studies, Harrop-Allin et al. 1999) they are cyclotron radiation, which is emitted preferentially from the hot upper parts of the column (Fig. 4). This region cannot be buried if optical flares are observed.

Ramsay et al. (1994) and Beuermann & Schwope (1994) found a correlation between soft X-ray excess and magnetic field strength. The standard explanation for this is that denser blobs are formed in stronger field systems, but the complexity of the threading region prevents (at present) an analysis to determine why or whether this may be the case. Alternatively we may explain it in the framework of the standard model of the accretion column above: a blob will cause a local density enhancement, which will reduce the column height; the base of the region will then be relatively more buried than a neighbouring region of greater height or the surrounding photosphere, so that more blackbody soft X-rays are emitted. In addition, because of the higher local density, the domed optical depth of unity surface encompasses more of the base of the column than in neighbouring regions, resulting in more blackbody soft X-ray flux.

Extrapolation of the argument to IPs where column height is expected to be tall (because the local accretion rate is probably smaller than polars and there is no cyclotron cooling) would suggest that this is one contributor to the absence of a soft component in these systems, although local and interstellar absorption is likely to play a greater role.

5. Predictions from the height of the accretion column

The next generation of X-ray observatories such as *XMM* and *Chandra* will potentially provide phase resolved spectra of mCVs as the accretion column rotates into view over the limb of the white dwarf. The rise in X-ray flux will depend on both an increasing fraction of the height of the column becoming visible, and on an increasing fraction of the area over which accretion is occuring. We can easily generate the phase resolved spectra of an accretion column accreting over any prescribed area onto the white dwarf by eliminating the spectra from those strata which are out of view at any phase from the spectral summation. Fig. 5 shows the prediction for a small accretion area, using the models of Cropper et al. (1999), which include the modification of the height due to the changing gravitational potential. The phase-resolved spectra during rise to and fall from maximum can be compared to data to extract the emission characteristics, and therefore the temperature and density as a function of height. These fits can serve as a relatively direct check on the validity of the models for the accretion column.



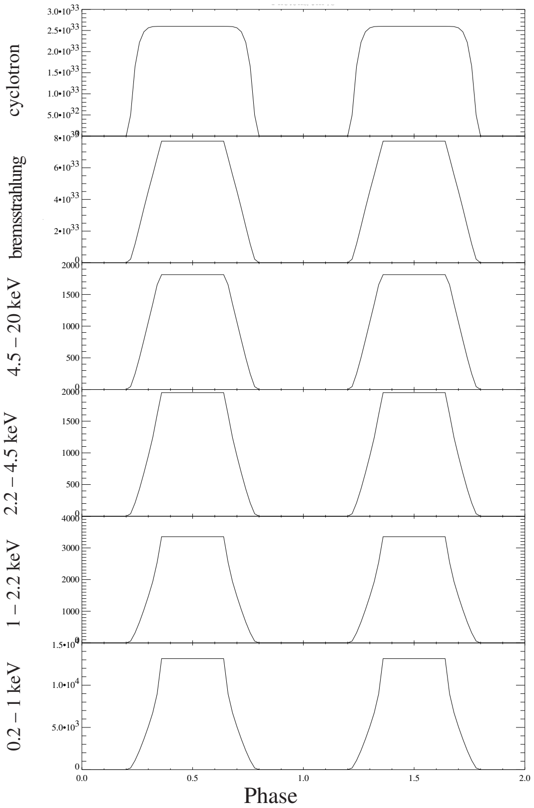


Figure 5 (above) The phase-resolved spectra from 0.1 to 20 keV from the system in Figure 3, with a dipole offset of $\beta = 134°$ viewed at an inclination of $\iota = 56°$. Phases are repeated vertically for clarity.
Figure 6 (right) Cyclotron, bolometric X-ray and X-ray light curves in the 4.5–20 keV, 2.2–4.5 keV, 1–2.2 keV and 0.2–1 keV (bottom) bands for the system in Fig. 5. Phases are repeated for clarity.

X-ray light curves can be generated by summing flux from specified bandpasses from Fig. 5. Because we include the cyclotron cooling in the models, it is also possible to calculate the light curve of the total cyclotron emission. These are shown for the particular inclination and dipole offset ($\iota = 56°$, $\beta = 134°$, Cropper 1986) appropriate to ST LMi, a 2-pole polar (Fig. 6). The duration of the bright phase is shorter for soft X-rays, which are emitted at the base of the column, than that for cyclotron radiation, emitted near the shock (Fig. 4), as this appears from behind the limb at earlier phases.

These light curves can also be compared with X-ray data to extract information on the vertical and spatial structure of the accretion region. Using the models above of the vertical structure and X-ray emission as a function of mass transfer rate per unit area, maps of the accretion rate can be generated using maximum entropy techniques along the lines of those in polarised optical emission (Stokes imaging, Potter et al. 1998), taking into account the 3-dimensional nature of the column. If Stokes imaging maps are available, these can be compared. Moreover, current Stokes imaging maps assume that the cyclotron radiation is emitted on the surface of the white dwarf, whereas Fig. 4 indicates that emission is near the shock. This could lead to inaccurate maps: polarisation reversals such as those at the end of the bright phase in some systems could be the result of viewing a tall column from underneath, rather than or in addition to accretion along non-radial fieldlines.

Finally, we can use the predictions of the accretion column models to investigate whether accretion columns are "tall and thin" or "pillbox-shaped". This issue from the early epochs of mCV research has appeared to be settled by observation in terms of the latter, particularly based on observations of ST LMi, where no polarisation reversals are seen at the beginning and end of the bright phase (eg. Cropper 1986). The predictions for this geometry in Figs. 5 and 6 indicate that the column is sufficienty tall to be seen from "underneath" for a considerable range of phase during the rise to and fall from maximum light. These, however, are for a 1.0 $M_\odot$ white dwarf and no cyclotron cooling. When an appropriate mass (0.45 $M_\odot$, Mukai & Charles 1987) and magnetic field (12 MG, Ferrario, Bailey & Wickramasinghe, 1993) are used, the height of the column drops suffiently that the duration of the rise phase is small enough not to be visible at the phase resolution of the polarisation data. This compatibility indicates that the height of the column in this system is indeed low from both theoretical prediction and observations. However, in those systems with higher mass white dwarfs and/or lower magnetic fields the column will, contrarily, be tall with implications for interpretation of both X-ray and optical data as discussed above.

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