The stream-disk interaction

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Abstract. I review theoretical aspects of the interaction between the accretion stream and the disk in interacting binary systems, concentrating on recent hydrodynamic calculations. At low accretion rates, cooling is expected to be efficient, and the interaction leads to a nearly ballistic stream overflowing the disk rim towards smaller radii. If cooling is ineffective, the shocked gas produces a bulge on the disk rim, and there is no coherent stream inward of the disk edge. Results are presented for the mass fraction and velocity structure of the overflowing component, and the implications for X-ray observations of ‘dips’, and doppler tomography of cataclysmic variables are briefly discussed.

1. Introduction

Mass transfer via Roche lobe overflow onto an accretion disk occurs in a diverse range of non-magnetic and weakly magnetic cataclysmic variables, low-mass X-ray binaries, and supersoft X-ray sources. In all of these systems an accretion stream from the inner Lagrange point strikes the outer regions of the disk in a highly supersonic impact, producing most obviously a hot spot at the disk edge. However it has long been realised that the impact can also have interesting secondary consequences (for a review, see e.g. Livio 1993). For example the stream material may be able to overflow the disk rim (Lubow & Shu 1976; Frank, King & Lasota 1987) or the interaction might throw stream gas high above the disk plane. Either possibility could well lead to marked departures from axisymmetry in both the absorption towards the central object (producing ‘dips’ in the X-ray and UV light curves; Mason, 1989; Hellier, Garlick & Mason 1993), and in the structure of a disk wind.

In this contribution I discuss first the dynamics of the stream flow up to the point of impact with the disk, following the approach of Lubow & Shu (1975, 1976), and Lubow (1989). This analysis demonstrates that the stream is potentially more extended vertically than the disk at the point of impact and can thus overflow the disk rim – and additionally serves as initial conditions for three-dimensional hydrodynamical calculations, using the ZEUS code, that are presented later. The use of such simulations is necessary to explore fully the complex structure of the impact region, and the subsequent interaction of stream and disk material. Here I analyze the simulation results with a view towards the observable quantities – the mass fraction of stream gas that overflows, and the velocities attained by the overflowing component.
2. Stream flow dynamics

A detailed analysis of the formation and dynamics of an accretion stream arising from Roche lobe overflow is given by Lubow & Shu (1975, 1976). The stream scale height, $H_s$, on leaving the vicinity of the inner Lagrange point is given by,

$$H_s = \frac{c_s}{\omega_z}, \quad \omega_z^2 = -\frac{\partial^2 \phi}{\partial z^2}|_{x_{L1},y_{L1}}$$

(1)

where $c_s$ is the sound speed at the surface of the mass losing star and $\phi$ the gravitational plus binary centrifugal potential. To order of magnitude the stream thickness is $\sim c_s/\Omega_B$, where $\Omega_B$ is the binary angular velocity (Livio 1994). Note that this is much larger than the pressure scale height at the surface of the secondary. Once the stream has left the vicinity of $L_1$, it flows inward on an essentially ballistic trajectory until it meets either the disk edge or the magnetosphere of the accreting star. However, because the flow inward occurs on a dynamic timescale, the stream is unable to adjust its vertical structure fast enough to maintain hydrostatic equilibrium. This inertia effect, which is analyzed in Lubow & Shu (1976) and applied to the dwarf nova Z Cha by Lubow (1989), makes the stream thicker than it would otherwise be.

Figure 1 shows the results of applying this analysis to a system like Z Cha (mass ratio 1/7). The stream when it reaches the edge of the disk is much thicker than it would be if it were in local hydrostatic equilibrium, and thus although the central density of the stream is much less than that of the disk (as for the disk $v_R \ll v_\phi$), at a few scale heights above the plane the stream density may exceed that of the disk. The upper part of the stream may thus be able to overflow the rim of the disk, before collapsing onto the disk surface, at a phase of $\sim 0.5 - 0.6$ – almost independent of mass ratio.

This analysis clearly establishes the potential for stream overflow to occur, but cannot address either the interaction of the stream as it flows over the disk surface, or the possible hydrodynamic effects at the impact point that might disrupt the stream.

Even within the context of this simplified picture, stream overflow is not expected for all systems, at all times. Since the relevant comparison is the scale height of the stream as compared to the disk at the disk edge, overflow will be favored if the disk is thin – i.e. if the temperature at the edge is low compared to that of the secondary. This will favor large disks, with low accretion rates. Conversely, shorter period systems, with small disks, or systems in outburst where $\dot{M}$ is large, are unlikely to allow simple ballistic stream overflow.

3. Hydrodynamics of the stream-disk interaction

Simulations of the stream impact with a disk in a binary potential were presented by Armitage & Livio (1996). In those calculations, which employed smooth particle hydrodynamics with an isothermal equation of state, the dominant cause of non-axisymmetric structure at high elevation was found to be stream overflow. Additional non-axisymmetric structure arose from the eccentricity of the disk, though this would only be visible in absorption for viewing angles rather close to the disk plane (for a discussion of the emission from such distorted disks,
Figure 1. Results of a vertical integration of the stream dynamics, following Lubow (1989), showing (top) the path taken by the gas stream in the Roche potential. The upper panel shows the scale height of the stream (solid line) as a function of the fractional radius $R/a$, where $a$ is the binary separation. The thickness expected if the stream were in local hydrostatic equilibrium is shown as the dashed line. The lower panel depicts the vertical velocity of the stream at one stream scale height, in units of the stream sound speed. The dashed circle and vertical lines denote the observed disk radius in Z Cha. At the disk edge, the stream is (i) thicker than its hydrostatic value, and (ii) converging on the disk at moderately supersonic velocities at a few scale heights above the midplane.
see e.g. Murray, this volume). However, the resolution of the impact region in the SPH calculations was rather poor, and insufficient for a detailed comparison with either observations or the Lubow (1989) analysis.

To investigate the impact region and subsequent stream-disk interaction in more detail, we have used the ZEUS-3D hydrodynamics code developed at the Laboratory for Computational Astrophysics. ZEUS-3D is a finite difference code that uses an artificial viscosity to capture shocks, for details see the papers by Stone & Norman (1992a,b) that describe the earlier, two-dimensional, version of the code.

3.1. Initial conditions

The simulations cover a computational box surrounding the impact point, with the disk and stream inflow prescribed as boundary conditions. For the disk, we assume a hydrostatic vertical structure with a Mach number at the disk edge of 30. The disk is isothermal both vertically and radially, though relaxing the latter requirement does not greatly alter the results. Beyond the disk 'edge' the density is assumed to fall off as a gaussian, with radial scale length equal to the vertical scale height.

For the stream, we use initial conditions akin to those obtained from the vertical integration presented in the preceding Section. The stream density is assumed to fall off as a gaussian, with a vertical velocity $v_z \propto -z$. The Mach number of the stream at the disk edge is 30, and the stream makes an angle of 15° with the radial direction. The ratio of disk to stream central density is 100. We vary the assumed ratio of stream to disk scale heights, $H_s/H_d$, and the equation of state, here either isothermal or adiabatic. Simulations including optically thin radiative cooling are generally similar to the isothermal runs for all reasonable accretion rates. Further details of the calculations are discussed elsewhere (Armitage & Livio 1997). Note that we do not include any of the effects (such as irradiation of the disk by a central X-ray source) that distinguish CVs from X-ray binaries or supersoft sources, see Blondin (1997) for a description of simulations specifically modelling X-ray binaries.

3.2. Cooling and the effective equation of state

For accretion rates normally encountered in cataclysmic variables, the density of stream and disk gas is sufficiently high that optically thin cooling is rapid (i.e. fast compared to the dynamical time) in the disk midplane. In this regime of rapid optically thin cooling, the general hydrodynamics is similar to an isothermal equation of state (see Blondin, Richards, & Malinowski, 1995, for a discussion of this applied to simulations of accretion in Algol). At higher accretion rates, however, the emission from the shocked gas will cease to be optically thin, and we expect that the hydrodynamics will be 'more like' that seen in an adiabatic simulation, though there are many complexities that such an assumption ignores.

To estimate the critical accretion rate where the hot spot emission first becomes optically thick, we consider the opacity both of the cold inflowing stream gas, probably arising from H$^{-}$, and the hot shocked layer where the opacity is assumed to be from electron scattering. With large uncertainties, either opacity suggests that $M_{\text{crit}} \sim 10^{-9} \, M_\odot\text{yr}^{-1}$ (Armitage & Livio 1997). Although very
crude, this suggests that the hotspot region in low accretion rate CVs may well be able to cool efficiently, whereas nova-like and super-soft X-ray sources with much higher accretion rates are almost certainly unable to do so. The former are possibly better described by the isothermal calculations, the latter by adiabatic simulations.

3.3. Results

Figure 2 shows results from an isothermal calculation with $H_s/H_d = 2$, and an adiabatic run with $H_s/H_d = 2.5$. For the isothermal run, the stream is stopped rapidly in the disk midplane by the denser disk gas. Moving above the midplane, at around 2 disk scale heights the stream and disk densities become comparable, and we resolve the twin shocks in the disk and stream gas seen in earlier two dimensional calculations (Rozcyczka & Schwarzenberg-Czerny 1987). However the 3D calculations do not reproduce a hot spot region highly extended along the disk rim, as was seen in 2D. Moving further upwards, the stream rapidly dominates. At 3 $H_d$ the stream overflows almost freely, with some modest deflection at the edge facing the incoming disk material.

The corresponding slices from the adiabatic run are very different. In the midplane, there is pronounced ‘splashing’ of hot material downstream of the impact point, while at 3 $H_d$ there is no coherent stream overflowing the disk, only a broad fan of material moving across the disk surface.

A slice along the stream flow direction shows a prominent bow shock in the adiabatic simulation, in this case material is expanding in a wide fan downstream and above the impact point. Viewed as isodensity surfaces, the effect is to produce a bulge in the disk rim downstream of the impact, though the material in the bulge is definitely not close to hydrostatic equilibrium – it is expanding and cooling rapidly. Conversely the isothermal simulation looks very similar to the stream overflow proposed by Lubow & Shu (1976) or Frank, King & Lasota (1987), though even in this case there is much more swept up disk gas or entrained stream material than freely overflowing material, with this additional gas showing intermediate inflow velocities.

3.4. Overflowing mass fraction

For the simulations with efficient radiative cooling, Figure 3 shows the fraction of stream gas that is overflowing with $|v_R| > v_{cut}$ as a function of $H_s/H_d$. Results from the simulations have been fit with curves representing the most naive assumption – that all of the stream with $z$ greater than some $z_{crit}$ overflows, while everything below $z_{crit}$ is stopped on impact. For $z_{crit}$ we take,

$$z_{crit} = \frac{\beta H_d H_s}{(H_s^2 - H_d^2)^{1/2}} \left(\ln \frac{\rho_d}{\rho_s}\right)^{1/2},$$

where $\rho_d$, $\rho_s$ are the midplane disk and stream densities. $z_{crit}$ is the height where the stream and disk densities are equal, multiplied by a factor $\beta$ included as a free parameter.

From the Figure, it is evident that this fitting formula, with $\beta$ close to unity, provides a fair estimate of the amount of highly supersonic stream overflow i.e. roughly as much material overflows the rim as one would naively expect. This
Figure 2. Flow in a hydrodynamic calculation of the stream-disk interaction (Armitage & Livio 1997). The upper panel is a slice along the initial stream flow direction for an adiabatic equation of state, the lower panels are slices parallel to the disk midplane at $z = 0, 2, 3$ disk scale heights $H$, for both isothermal and adiabatic calculations. The stream enters from the bottom left, the disk is flowing left to right across the frame which covers $\sim 50\%$ of the disk radius. Density contours are plotted at $\Delta \log \rho = 0.2$. 
Figure 3. Left panel – the overflowing mass fraction as a function of the ratio of stream to disk scale height, for efficient radiative cooling. The symbols show the fraction overflowing with radial velocity greater than $5c_s$ (crosses), $10c_s$ (squares) and $20c_s$ (triangles). The curves are a fit described in the text. Right panel – the velocity of material along a line of sight to the primary $32^\circ$ downstream of the impact point, and $12^\circ$ above the disk midplane. The solid line is the result for the efficient cooling simulation – almost identical to the free-stream model shown as the dashed line. The long dashed line is the adiabatic result, more mass overflows in this case and it has a much broader range of velocities.

implies that $H_s/H_d$ must be around 2 or greater for the overflowing fraction to be reasonably large. Note also that there is much more material overflowing at lesser, but still highly supersonic, velocities than there is ballistic stream gas.

Despite the striking qualitative distinction, a similar (or rather larger) mass fraction overflows the disk in the adiabatic simulation. In this case though the material extends to much higher above the disk midplane, and of course has a much broader range of velocities.

3.5. Velocity profiles – a first look

The velocity structure of the stream gas after reaching the disk edge is potentially observable via doppler mapping techniques. For example the structure of the disk rim near the hot spot has been considered in OY Car by Billington et al. (1996), and for SW Sex by Dhillon, Marsh & Jones (1997). We have not, yet, attempted to generate synthetic doppler maps from the simulations, but Figure 3 provides some idea of the velocity profile of gas along a line of sight to the primary. Plotted are the results for isothermal and adiabatic simulations, and a comparison ‘free-stream’ run which included the internal stream pressure effects but omitted entirely the disk.
At high angles above the disk midplane, the velocity profiles for the isothermal and free-stream calculations are essentially identical, implying that for studies of absorption at high angles a ballistic stream approximation is probably adequate (if the cooling is indeed efficient). However closer to the disk plane there is a large contribution from entrained material with a lesser radial velocity – this might well appear in emission as the stream reaches the point where it reimpacts the disk (see, e.g. Hellier 1996). As expected from the appearance of the flow, inefficient cooling leads to a much broader range of line-of-sight radial velocities, which are generally of smaller magnitude than for the isothermal simulation. Of course the observed profile will strongly depend on the degree of cooling that does take place as the shocked gas expands – we have here considered only the limit of no radiative cooling at all. Nonetheless the prediction is that inefficient cooling is likely to lead to absorption with a broad range of radial velocity, and be more significant at larger angles from the disk plane.

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