Some Interesting Hydrodynamical Problems Relating to Binary Stars

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This short review highlights some open questions regarding the dynamics of accretion disks in Algol and related systems. Standard disk theory has been quite successful in cataclysmics, protostellar thick disks, and active galactic nuclei, but our understanding of relatively normal accretion flows remains less satisfactory. Some problems that remain unanswered include the treatment of the Roche surface as a limiting radius, the structure of Algol disks and viscous accretion, and boundary layer.

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1 Introduction

Whatever *Plavec* means in Czech, it has only one translation in astrophysics: "physical processes in binary systems". Mirek has opened most areas of the field and, in quite a few cases, even closed them. He is one of the founders of modern evolutionary computations for close binary evolution. He and his collaborators championed a model involving binary mass transfer to explain Be star phenomenology at a time when such extrinsic explanations were ignored. As a collaborator and student by distance learning, I've watched with awe his Ahab-like quest to bag the Leviathans – extreme mass transfer systems such as β Lyr, W Ser, and UX Mon – through which the details of accretion might be understood. A *festschrift* contribution affords a bully pulpit to exposulate on unresolved issues. It is thus with great pleasure that I offer this review to him, and you the reader, in the hope of raising some interesting questions concerning mass transfer and accretion in close binaries.

2 When Does Mass Transfer Begin?

The Roche surface has acquired enormous significance over since its central role in close binary star was first outlined by Kuiper (1941), who highlighted its role as a limiting surface. With the development of evolutionary models that included mass transfer, in which Mirek played such a pivotal role, it came to underlie all evolutionary scenarios. It does not, however, behave like a cliff in the system. One has the impression that mass is bound up to the point where it contacts the critical radius and then it falls toward the companion. While this is a useful approximation, stars do not have the sharp edges that this picture implies. As the stellar radius comes closer to R_{RL}, its envelope begins to flow. Because of the limited mass zone resolution in stellar interiors codes, a simple approximation, the equivalent volume formalism, is used for the removal of mass but stars may begin mass transfer even when their photospheres are well within the Roche radius provided they have sufficiently distended atmospheres, a point already recognized by Plavec et al. (1973) but little appreciated in subsequent modeling. This transfer can power accretion effects even before the major mass loss occurs and alter the environment encountered in subsequent stages of evolution. If I may be allowed a speculation, magnetic fields may play a role in structuring the loser's atmosphere, as they do for single star winds, and local heating and MHD effects could be important as the photosphere approaches the Roche limit.

The regulation of mass loss and the adjustment of the loser's envelope will be regulated by the requirements of thermal balance. Too high an accretion rate will trigger a thermal instability that changes the inner boundary condition and may eject mass (and angular momentum) from the system. Additionally, a transient common envelope stage can result, as in nova explosions. How this feeds back into the evolution of the system is an important and challenging question. An unsolved problem, comparable in complexity to that of common envelope mass transfer, is what happens to a convective envelope that reaches the Roche surface. Simply stated, thermal convection is driven by buoyancy so its efficiency should drop drastically near L_1. In fact, along an equipotential surface that is really the same as Φ_{RL}, there is a large variation in the surface gravity. While evolutionary calculations treat the stars by finding the equivalent volume and transfer mass with a prescription that has not changed since the earliest treatments, that

$R \geq R_{RL}$, this cannot be correct in detail since the envelope structure is controlled by thermal balance mediated by the convection. One can look at this in terms of the effective Rayleigh number, which is not constant across the layer when g varies. How does the temperature structure adjust to this? More seriously, what happens to the rate of flow through L_1 when during case C the star is on the giant branch?

To see why the Roche surface even matters, we can look at a one dimensional flow problem using a local expansion in the gravitational potential around L_1. Along the line of centers, the gravitational acceleration, $\partial\Phi/\partial x = 0$ at L_1. Expanding the potential around this point for small displacement ξ, we obtain for the equation of motion is an analog to a stellar wind solution with non-constant surface gravity (see, *e.g.* Shore 1992):

$$\frac{1}{v}(v^2 - c_s^2)\frac{dv}{d\xi} = -\Phi''_{L_1}\xi. \tag{1}$$

L_1 is a saddle point so Φ'' vanishes locally. The sound speed, c_s, on the left hand side comes from the pressure gradient and because this is one dimensional and steady state we can write $\rho v =$ constant. Thus, on passing through $\xi = 0$, v must excdeed c_s for a positive velocity gradient. This isn't really surprising, since the flow is infalling once it crosses the point at which gravity vanishes in the binary frame so the pressure-driven acceleration that at the sonic point pushes the mass through the equilibrium point has no way of adjusting to the offloading of mass and the local gravitational acceleration reverses its sign relative to ξ. The result is a highly supersonic flow that launches toward the companion with the sound speed from the L_1 point and is deflected by the Coriolis acceleration. The stream orbits the companion and collides with itself, again supersonically, forming an oblique shock that eventually deflects it into an orbit (*e.g.* Shu and Lubow 1983). The condition for disk formation is that the angular momentum must be sufficient to send material into orbit around the gainer. The equivalent circular orbit is given by equating the angular momentum at the L_1 point with the equivalent Keplerian orbit around the gainer. The specific angular momenta are $j = \omega(m_2 a/M - R_{RL})^2$ at L_1 and $j_K = (Gm_2 r)^{1/2}$ around the gainer, where r is the radius of the circular orbit around m_2.

If the angular momentum is too small, the stream may directly impact the gainer. The result is local shock heating and a deflection of the stream by the gainer's atmosphere. This certainly occurs in some systems but its consequences for observations have not been treated in any detail in the literature. If a disk does form, this interaction point is moved out, but it is still present. The reason is that the supersonic stream can't adjust its structure on the slower sonic timescale. As a result, it slams into the circulating material and forms a standing shock. Since it is an oblique impact, this region refracts the shock and produces a contact, slip, discontinuity at the boundary.

3 Viscous Accretion Disks

Assuming hydrostatic equilibrium, the disk's vertical structure is governed by the tidal component in the acceleration:

$$\frac{1}{\rho}\frac{dP}{dz} = -\frac{GM}{r^2}\frac{z}{r}. \tag{2}$$

The simplest estimate of the disk thickness comes from assuming that it is vertically isothermal, so $P = \rho c_s^2$. Noting that the vertical gravitational acceleration can be written as $g_z = (v_\phi^2 z)/r^2$, the density follows a Gaussian vertical profile with an isothermal scale height:

$$z_0 = \frac{c_s}{v_\phi} r \tag{3}$$

This is a thin disk since generally $c_s/v_\phi << 1$, although because of the radial dependence of the angular velocity, the thickness grows with increasing distance from the central body. A passive disk, one that has no local heating, would then be an absorbing curtain against the stellar photosphere since it is centrifugally supported (you can ignore the hydrostatic adjustment to any external radiative heating). Many physical processes are neglected in this treatment. In particular, thermal balance is not treated. Both are necessary to determine the disk's vertical temperature profile in response to the energy input, since the disk may be heated both by internal turbulent dissipation and radiation from the central star. Much of the work on interpretation of disk spectra comes from addressing this problem.

But the most serious deficiency is that this model can't address how the matter accretes! If the disk material remains dissipationless it will continue to accumulate and circulate, storing angular momentum it gained from infall by the stream. This may actually happen in some binary systems for at least some time. It is evidently important for the stability of the planetary ring systems observed in the solar system. In order to actually transfer mass from one star to another, and complete the picture described earlier for close binary evolution, it is necessary to find some mechanism(s) whereby the angular momentum is reduced and a slow drift can be established that actually places material onto the gainer. Thus the focus of so much of the effort in accretion disk theory: what is the viscous mechanism in accretion flows? Several detailed reviews have recently appeared in the literature, notably Papaloizou and Lin (1995) and Balbus and Hawley (1998). If the binary orbit is eccentric, even by a small amount, the loser in this effectively three body system exerts a torque on the outer parts of the disk that may produce a resonance when the $\omega_K = \omega$ (Lubow et al. 1993). This can drive spiral shocks in the disk that are similar to density waves in a galaxy because of the existence of Lindblad resonances. Such shocks may play a role in angular momentum transfer within the disk, but just how important they are for accretion disks in Algols is currently unknown.

More usually, any change in the angular momentum of the flow is assumed to be due to a viscous torque. Assuming no secular global change in the angular momentum, we can write the angular momentum conservation equation as:

$$\frac{\Sigma v_r}{r}\frac{d}{dr}rv_\phi = \frac{1}{r}\frac{d}{dr}rT_{r\phi} \tag{4}$$

where v_r is the radial velocity, Σ is the surface mass density, v_ϕ is the angular velocity, and $T_{r\phi}$ is the shear stress. The mass flux is provided by the continuity equation:

$$\frac{\partial\Sigma}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}r\Sigma v_r = 0. \tag{5}$$

Notice that this depends explicitly on time for the *radial* mass transport. For a differentially rotating disk, the shear is given by:

$$\sigma_{r\phi} = r\frac{d\omega}{dr}. \tag{6}$$

Following a simple prescription that is well known for laminar and laboratory turbulent shear flows, we adopt the first crucial assumption: the stress tensor is assumed to be directly related to the shear (strain) with the proportionality provided by η, the viscosity:

$$T_{r\phi} = \eta\sigma_{r\phi}. \tag{7}$$

This is not a bad assumption, provided we can assert that the viscous coefficient can be vertically averaged (that it changes slowly with height above the midplane) and that it is independent of the velocity (a linear model). Neither assertion is particularly troubling in the laboratory, but for stellar accretion flows the Reynolds number is enormous and the viscous coupling must be due to turbulence (rather than molecular viscosity) whose source must be the flow itself. But let's defer that problem for a moment and push on with the canonical derivation. A conventional second (global) assumption is that the flow in the disk remains more or less Keplerian *even though viscous*. This requires $v_r \ll c_s$ and $v_r \ll v_K$. Its consequence can be seen by rewriting eq. (4) as:

$$\dot{M} = 2\pi r\Sigma v_r = 2\pi r\frac{d(rT_{r\phi})}{dr}/\frac{d(r^2\omega)}{dr}$$
$$= 2\pi r[\frac{d}{dr}(r^2\eta\frac{d\omega}{dr})]/[\frac{d}{dr}r^2\omega]. \tag{8}$$

This is the radial mass flux which, when substituted into the continuity equation, yields a nonlinear *diffusion* (*i.e.* parabolic) equation for Σ. Nearly all models for cataclysmics and self-luminous disks are based on this *ansatz*. By adopting $\omega = \omega_K \sim r^{-3/2}$, the angular frequency disappears explicitly from the calculation leaving only the need to specify η. If it can be written as $\eta = \Sigma\nu$, where ν is a kinematic viscous coefficient, then the resulting equation for mass conservation is closed and depends only on r.

Unlike the thin isothermal disk, the vertical equilibrium of a viscous disk is governed by its thermal balance under the constraint of hydrostatic support, and if optically thick depends only on κ, the opacity, the surface density, and the temperature gradient through the diffusion equation:

$$F = -\frac{4ac}{3\kappa}T^3\frac{dT}{d\Sigma} \tag{9}$$

But what flux is being transported? In cataclysmics, F comes from the viscous dissipation which produces the self-luminosity of the disk. Around a white dwarf or neutron star, the orbital speeds are so large that any shear generates significant local heating. This can be seen from considering the dissipation rate per unit volume for any viscous fluid:

$$\frac{d\epsilon}{dt} = -T_{r\phi}\sigma_{r\phi} = -\eta\sigma^2_{r\phi} \tag{10}$$

so $\dot\epsilon \sim v_K^2$. Compact gainers thus generate significant energy *locally* in the disk and this must be radiated vertically (the disks are so opaque radially that the radiative transport is all through the disk surface). For Algols and their relatives, however, the heating is *not* local. It comes instead from the central star and the boundary layer even for large accretion rates. The disk behaves more like a very strange atmosphere a passive medium through which the radiation must pass, and the problem actually becomes much harder to determine the vertical structure because of the nonlocality (Hubeny and Plavec 1991; Linnell et al. 1998).

3.1 Whence the Viscosity?

In what has become the standard model, viscosity is due to turbulence. Keplerian disks are normally stable at least in the Rayleigh sense that angular momentum must increase outward and centrifugal force must decrease, so most turbulence models were pretty much *ad hoc* and had to be put in by hand. Although originally developed for black hole disks, the α prescription (Shakura and Sunyaev 1973) has been the most robust in the literature. By dimensional analysis (and through the use of some very insightful arguments about the role of magnetic fields) it requires the velocities to be limited by c_s and takes the pressure scale height, H_P, as a characteristic length:

$$\eta = \alpha c_s H_P \Sigma \tag{11}$$

so this prescription couples the continuity equation to the energy transfer for the standard viscous disk. An alternate argument (Hubeny and Plavec 1991; see also Hubeny et al. (1994) requires the disk to be marginally unstable to turbulence by specifying the Reynolds number, a technique that is justified phenomenologically from laboratory studies. Depending on the vertical temperature profile, gravity wave modes can be excited which turn nonlinear and break in a turbulent cascade. Yet another possibility is nonlinear Rossby waves, which are driven by the differential rotation alone (see *e.g.* Lovelace et al. 1999 who treat the inviscid Eulerian limit of the disk). Any or all of these may come into play in Algol-type disks, but in the portions of the flow that are relatively transparent the radiative cooling may damp the cascade and reduce the viscosity. Taking cues from more energetic accretion flows, I think these processes are worth investigating.

A most promising source for turbulence is the magnetorotational instability (MRI) (see Balbus and Hawley 1998 for a comprehensive introduction) that may be as important for normal systems as it is for compact systems. This MHD instability is *generic* for differentially rotating systems. The MRI requires only a vanishingly small field and is unconditionally unstable when $d\omega/dr$ decreases with distance.[1] Since we know that the losers in Algol systems can display RS CVn style dynamo activity, it is possible that advected magnetic fields could serve as the seeds for the disk dynamo amplification of the instability.

For cataclysmics, eq. (11) provides closure and leads to the time dependent behavior seen in dwarf novae (*e.g.* Frank, King, and Raine 1992; Shore et al. 1994; Cannizzo 2000). The feedback between the temperature and density dependent opacity and the vertical temperature gradient permits domains in which the disk oscillates vertically much like a pulsating variable. For cooler systems convection complicates the picture, and the treatment must be modified to include self-gravity for protostellar disks, but the solutions to eqs. (5) and (9) include thermal limit cycle oscillating disks whose thickness is coupled to the radial flow through the changes in surface density. What might we expect in an Algol system? I don't know the answer, but depending on the mass accretion rate it is possible that the disks alternates between thick and thin states even with external heating by illumination. This, in turn, might account for some of the changes seen in opaque disks (perhaps as noted by Wilson and van Hamme 1999; see also below).

[1] However, it is interesting that a boundary layer (see below) would be stable unless the vertical Brünt-Väisälä is large enough to overcome the positive gradient of the angular frequency (see Balbus and Hawley 1991 for derivation).

4 Boundary Layers

The last problem I'll discuss is no less commonly encountered in the laboratory than the cosmos: what is the proper treatment for the inner boundary region of the accretion disk? Material somehow manages to get onto the gainer's surface regardless of the mechanism that drives the accretion. We have seen that inward drift of gas is produced by the viscous torques, but what happens at the interfacial zone between the disk and the stellar surface remains very poorly understood for *any* disks. This poses a basic problem since somehow the gas, which is moving at the local Keplerian velocity or something like it, succeeds in reducing its angular velocity to that of the underlying star, which for stability must rotate more slowly. This must occur in a very small radial zone and its consequences for the energetics of the inner disk are dramatic. A significant part of the energy of the flow, roughly half, is radiated in this boundary layer. If it is optically thin, the temperature should be independent of the accretion rate and very high, of order GM/kR (k is the Boltzmann constant), and the luminosity depends again on $\dot{M}$.

There are several attempts to treat this region in the literature (*e.g.* Regev 1983; Shore & King 1986; Kley 1991; Paczynski 1991; Popham & Narayan 1991; Regev & Bertout 1995; Hartmann 1998; Collins, Helfer, & van Horn 2000) but none yet captures the complexity of the process. This is not surprising since the effect of a rigid wall in shear flows has been a major laboratory and engineering problem for many decades (see, *e.g.* Schlichting 1960). This layer is turbulent. In fact, it must be by the Rayleigh criterion since gradient of the shear reverses sign. Unlike the rest of the disk, where local dissipation does not lead to significant flux in Algols (Hubeny and Plavec 1991), heating should occur here and the scale height may even exceed the stellar radius. Some evidence was provided for this by Weiland et al. (1995) who modeled the Si IV 1400 doublet emission in W Ser using GHRS medium resolution (R $\approx$ 25000) observations obtained at two opposite conjunctions within a single orbit, the only such UV data I know for this or any other Algol type system with modern photon counting detectors. The profile model requires two spatially separate components: a narrow one arising at the interaction region at the stream-disk shock (this could be seen from the velocity shift between the spectra) and the other coming from a nearly axisymmetric boundary layer (however, because these were obtained with the small aperture before COSTAR the fluxes were too uncertain to be useful). Further evidence supporting the boundary layer interpretation comes from the superimposed absorption spectrum from the cooler parts of the disk. There was no evidence for P Cyg lines akin to those observed in β Lyr.[2] Detailed hydrodynamic 3D modeling is now underway for such systems that along with developments in turbulence theory for sheared systems hold enormous promise but which will not be reviewed here (Bisikalo et al. 2000; see also references therein. I apologize that the limitations of space and time prevent further discussion of this point but thank Petr Harmanec for reminding me of this lovely work!).

To understand what's going on here, picture a simplified accretion flow as a viscous fluid bounded by a spherical wall. The differential motion, if there is a no-slip inner boundary condition, couples the fluid to the wall and communicates a torque throughout the flow. For Keplerian motion, unlike laboratory circulation, the gravitational potential imposes a far field radial dependence $v_K \sim r^{-1/2}$. Assuming there is only weak coupling, the bulk of the fluid moves unhindered by the wall but there is a layer where the radial dependence must change. Specifically, v_ϕ must pass through some maximum value. You know this since we assume the underlying star remains stable, and to corotate with the flow would force the mass to become neutrally bound. Any perturbation would therefore destabilize the star. Yet we observe stars for which the rotational broadening of the photospheric lines is compatible with nearly the Keplerian velocity at the stellar radius. One system that immediately springs to mind is U Cep but others (including Mirek's favorites W Ser and β Lyr may also be like this). How? This is where the concept of a pseudo-photosphere may prove useful. What I'm arguing here is that even in relatively ordinary binary systems, the dissipative region – the boundary layer – may have sufficient density that it appears optically thick and thus looks like a photosphere. Estimates for the thickness of this layer usually employ the argument that the radial gradient of the velocity is small and that either pressure or turbulence supports the gas (assume first that the *rms* turbulent velocity is $< v_t^2 >^{1/2}$):

$$\frac{< v_t^2 >}{\delta_{\rm BL}} = \frac{v_K^2}{R} \tag{12}$$

Then taking $v_t \approx \alpha^{1/2} c_s$ from the α-model, we have:

$$\delta_{\rm BL} \sim \alpha^{1/2} H_P. \tag{13}$$

Alternatively, vorticial flows are described with the Ekman number, $\mathcal{E} \equiv \omega l^2/\nu$, where ν is the kinematic viscosity and l is a characteristic length, in our case $\delta_{\rm BL}$. The epicyclic frequency

$$\kappa = [\frac{1}{r^3}\frac{d(r^2\omega)^2}{dr}]^{1/2} \tag{14}$$

is the inverse of a typical eddy turnover time in the layer and is approximately equal to ω_K. Then the turbulent viscous coefficient becomes $\nu_t \sim \delta_{\rm BL}^2\omega_K$. The Ekman number is of order unity in the boundary layer so we at least gain some idea of its thickness.

If the bulk of the star is unaffected by the accretion, except for readjustments of the structure due to loading with transferred mass, then the equilibrium shape of the boundary layer will depend only on the rotation and the rate of mass transfer. A simple estimate of the effect is as follows. The luminosity of the layer to be due to the accretion shock. In cataclysmics, the disk is self-luminous. That's not surprising when the gainer is degenerate since the orbital velocities and shear are enormous. More normal systems (if indeed we can call Mirek's zoo "normal") release at most 10% of the energy locally compared to cataclysmic systems of the same mass, which is far less than the intrinsic luminosity of the gainer. The disks, in other words, are essentially passive absorbing and scattering environments.

The luminosity of the layer can be estimated without explicit reference to the viscosity (see *e.g.* Kley 1991; Hartmann 1998). For now, call ω the rotational frequency of the star and I is its moment of inertia. The change in angular momentum within the boundary layer is $\dot{J} = \dot{M}R^2\Delta\omega$. The rate of emission of binding energy by the incoming flow is $\frac{1}{2}GM\dot{M}/R$, the rate of change of rotational energy of the gainer is $\frac{1}{2}\dot{M}R^2\omega$, and the dissipation due to the torque in the disk is

$$\dot{E}_d = \frac{J\dot{J}}{I} = \dot{M}R^2\omega\Delta\omega$$

so the total luminosity of the boundary layer is:

$$\begin{aligned} L_{\rm BL} &= \frac{1}{2}\frac{GM}{R}\dot{M} - \frac{1}{2}\dot{M}R^2\omega^2 - \dot{M}R^2\omega\Delta\omega \\ &= \frac{1}{2}\dot{M}R^2(\omega_K-\omega)^2 = \frac{1}{2}\frac{GM}{R}\dot{M}(1-\frac{\omega}{\omega_K})^2. \end{aligned} \tag{15}$$

If the layer is opaque – that is, if it is a pseudophotosphere – its temperature can be obtained from:

$$L_{\rm BL} = 4\pi R\delta_{\rm BL} a T_{\rm BL}^4 \tag{16}$$

so for a main sequence star that is accreting mass at the thermal rate, the effective temperature of this layer should be of order a few times 10^4K for $\alpha \sim 0.1$ in our estimate for $\delta_{\rm BL}$. This is much lower than expected for cataclysmics but can be quite a bit higher than the equivalent radiative estimate for an isolated main sequence star with the gainer's mass. Notice that because of spinup of the gainer, eq. (15) shows

[2] To again speculate, the boundary layer heating could serve as the source for driving a Parker-type thermal wind off the disk.

that as the boundary layer thickens with time its luminosity may decrease.

In a prescient article, Kippenhahn (1974) pointed out that the matter flowing onto the gainer must have a high entropy since it has gone through an accretion shock. Unless it can cool, even with possibly higher mean molecular weight, it acts like salt fingers. Once corotating, centrifugal support plays no role and the material settles onto the surface. There, unless it can cool, it must turbulently mix with the atmosphere since it is double diffusively unstable. The evidence is that the gainer does indeed succeed in absorbing significant amounts of matter from the loser. The observed CNO excesses in many Algols attests to this. In fact, this may be the best tracer we have of the efficiency of the accretion process since the abundance determination for the loser provides the input composition, while any abundance measurement for the gainer gives the mixing fraction for those systems that are still in the process of mass transfer. The abundances of the layer should reflect not those of the gainer but of the incoming stream since this is a mixing layer. A completely optically thick region is thermally stable (King and Shaviv 1984; Shore and King 1986), which makes the structural changes seen in the most extreme disk systems likely driven by either intrinsic dynamical instabilities or tidal driving of density wave-like modes (perhaps the result of small residual orbital eccentricities). If the mass flow is not steady, however, or exceeds a critical value, then as I mentioned earlier disk oscillations in the boundary layer might be possible.[3]

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[3]One more point. Systems with black holes as gainers bypass the boundary layer concept altogether in the sense that the accreting matter never corotates or thermalizes and radiates. This scenario is called an advection dominated accretion flows (ADAF) (see *e.g.* Quataert and Narayan 1999). It is a special plasma-related situation that may explain the absence of observable emission from boundary layers in black hole systems. Such accreters are fundamentally different cases than normal objects because they have no inner stationary surface onto which matter is constrained to settle. Consequently, if it is possible to reduce the efficiency with which the matter radiates energy it will be "darker" than one would expect. Gas at high temperature is not as likely to collisionally cool as at low temperatures because the collision cross section for bremsstrahlung emission falls quickly with increasing energy. Line emission is unimportant compared with free-free emission and all other cooling processes depend on the collision time. If this is short compared to the accretion time, the medium will not radiate. This explanation is not applicable, however for *any* system that has an inner wall, such as we would expect for a main sequence gainer.

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