Accretion in “Ordinary” Interacting Binaries

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Abstract. We present preliminary results of our calculations of disk structures and disk spectra in various types of interacting binaries in which the accreting star is non-degenerate. Specifically, we discuss two types of semidetached systems: the Algols and “Algol-type” symbiotics.

1. Introduction

We will discuss accretion phenomena in interacting close binary systems in which both components are “ordinary” (i.e., non-degenerate) stars. These systems do not seem to generate spectacular outbursts or very energetic radiation. Yet they present a wide variety of interesting phenomena. The large variety is due, in the first place, to the many possible combinations of the mass and radius of the accreting star (henceforth the gainer) and the rate of mass transfer. These three quantities, \( m_g \), \( R_g \), and \( \dot{M} \), enter the fundamental formulae in different combinations. Thus the luminosity of one side of the accretion disk can be expressed as

\[
L_d = 7.85 \, m_g \, \dot{M} / R_g
\]  

where the mass, radius, and luminosity are expressed in solar units. We express the mass transfer rate in units of microsunsy, where 1\( \mu sy \) = 10\(^{-6} \) solar masses per year. In this way, for our stars, all the parameters will be expressed in easily comprehensible numbers, since the mass transfer rates range between about 0.1 and 1000 \( \mu sy \).

According to the standard model (Pringle 1981; Frank, King, & Raine 1992), the maximum effective temperature in the disk occurs at a distance of 1.361\( R_g \), and is

\[
T_{\text{max}} = 7375 \, (\dot{M}m_g / R_g^3)^{1/4}
\]

The three parameters, \( m_g \), \( R_g \), and \( \dot{M} \) suffice to define a steady-state accretion disk, and we calculated a series of such disks using program TLUSDISK and the associated spectrum synthesis code (Hubeny 1989, 1990, 1991). This code gives us the detailed disk spectrum as seen under any angle of inclination of the system. Program TLUSDISK also enables us to calculate the vertical dimensions of the disk. The half-thickness of the disk turns out to be considerably larger than in the classical \( \alpha \)-disk formula, as given, for example, by Pringle (1981).
Actually, our numerical calculations of the vertical thickness of the individual rings give values much closer to the formula (5.46) in Frank, King, & Raine (1992), because these authors have correctly considered the disk thickness as determined by the scale height corresponding to the central plane temperature, not the effective temperature for each concentric ring. The vertical extent of the disk plays an important role in systems viewed nearly edge-on, since it can severely affect the range of orbital inclinations available for modeling eclipsing systems.

This brings us closer to realization that additional parameters must also be taken into consideration in modeling, namely the mass $m_l$, radius $R_l$, and spectral type of the loser (and of the gainer, too), as well as the separation between the two stars, $A$. We are not free to choose the radial extent of the disk, since it is limited by the size of the critical Roche lobe of the gainer. We can approximately take $d_{out} = 0.85R^*_g$ for the radial size of the disk. More importantly, we are not free to adopt any value of mass transfer rate, since this is dictated by the parameters of the loser. A very useful formula for the maximum rate of mass outflow was devised by Paczynski (1971):

$$M_{max} = 0.019 \frac{R_l L_l}{m_l}$$

(3)

Here the loser's mass, radius, and luminosity are again expressed in solar units, while the mass loss rate is again expressed in microsunny. It is important to realize that this value of $\dot{M}$ refers to the peak of the mass transfer process from an essentially radiative envelope of the loser, but the star's parameters refer to the onset of the process. If the loser has a deep convective envelope, the mass transfer rate may reach even higher values, and the process may proceed on a dynamical time scale, that is, may become catastrophic.

After these general remarks, let us consider a few selected types of interacting binaries.

2. Algol Symbiotics

In order to construct a symbiotic object, we need i) a source of a late-type optical continuum and absorption lines, ii) a source of circumstellar gas, iii) a source of ionizing photons. The first two requirements may be satisfied simultaneously by a late-type giant with a powerful but slow stellar wind; and indeed, such a star is always observed. We are less sure about the hot source.

Plavec (1982) proposed three possible candidates: a white dwarf (in a nova-like symbiotic), a hot subdwarf similar to the central stars in planetary nebulae (in a PN symbiotic) and a hot accretion disk around an ordinary star (in a Algol symbiotic). It does not happen very often that several diverse models should lead to a remarkably similar phenomenon, but it does happen (remember supernovae). Moreover, diversity is a PC word at California universities! There has been much controversy about which of these types are actually realized in nature. We are reminded of the old Latin proverb: *Mater semper certa, sed pater incertus*.

Here we will concentrate on a narrower problem: Is it possible to construct an Algol symbiotic? And can we find a case in which such a model is realized? We started with a sun-like gainer, $M_g = 1m_\odot$ and $R_g = 1R_\odot$. The potential well
Figure 1. Edge-on view of our model No. 1 of a symbiotic star

is not deep enough, so we must prop up the mass transfer rate in order to get a reasonably hot disk. Here we will consider $M = 8 \times 10^{-5} m_\odot/\text{year} = 80 \mu\text{asy.}$ With these three parameters, we have been able to calculate the structure of the disk rings up to the distance of $d = 20 R_\odot$ where the effective temperature has dropped down to 4487 K. Cooler rings are difficult to calculate and their contribution to the total disk flux at shorter wavelengths (let’s say below 4000 Å) is negligible anyway. However, for good conscience we can assume that we have covered the entire disk, that is that the outer disk edge is about $d_{\text{out}} = 22 R_\odot$, and then the mean critical Roche radius of the gainer is about $R_g^* = 25 R_\odot$.

It is reasonable to assume a mass ratio $q = m_i/m_g = 3$; then the orbital radius is $A = 88 R_\odot$ and the orbital period only 48 days. The loser with mass $m_l = 3 m_\odot$ is supposed to fill its critical Roche lobe whose mean radius is $42 R_\odot$. An edge-on view of the system is shown in Figure 1.

Assume that the loser is an M3 star, then it will pass as an M3 III giant. It can produce the required mass loss rate through Roche lobe overflow. The entire model appears consistent.

The luminosity of one side of the disk is then $628 L_\odot$, higher than that of the red giant; and since the disk peak temperature is 22000 K, the disk radiation comes predominantly at shorter wavelengths, as it should for a symbiotic. Naturally, the flux from the disk will be greatly reduced if we view it at a smaller angle to the orbital plane. The situation is shown in Figure 2. The magnitude scale corresponds to a distance of 500 pc. It is seen that the underlying optical spectrum will resemble a symbiotic object only when viewed nearly edge-on. For smaller inclinations, a composite optical spectrum might be detected.

Now how about the necessary emission lines? The peak temperature of the disk is 22000 K and the inner disk will produce some ionizing photons. Crucial
for the appearance of the emission lines may be the boundary layer. The total energy to be dissipated there is $1240L_\odot$. As everyone knows, probably no one knows how this energy is dissipated. It may be that most of the energy is dissipated non-radiatively.

If we reduce the gas influx from $\dot{M} = 80\mu\text{g}y$ to $\dot{M} = 20\mu\text{g}y$ leaving everything else unchanged, the presence of the red giant in the optical region will be more pronounced, yet still mainly at high orbital inclinations. And the chances of seeing highly ionized emission lines will decrease, since the disk peak temperature is about 15,600 K.

3. Attempt to Emulate Real Symbiotics

Clearly, in order to create a typical symbiotic, we must keep the mass transfer rate high and increase the size of the M giant in order to give it a higher luminosity. The only efficient way of doing this is to increase the overall size of the system. Obviously, here is the explanation why the symbiotics are systems with very long periods.

A case in point is *CI Cygni*, which has been suggested to be an Algol symbiotic by several authors, starting probably with Kenyon and Webbink (1984) and culminating in the recent very comprehensive analysis by Kenyon et al. (1991). They adopt the same mass ratio as we did above, but derive smaller masses: $m_g = 0.5m_\odot$, $m_l = 1.5m_\odot$. Combined with the long orbital period, $P = 855.25$ days, this gives a huge system, with $A = 477 R_\odot$, and with the mean radius of the red star (if it fills its critical Roche lobe) $R_l = 250 R_\odot$. The system is eclipsing, and the orbital inclination is believed to be near 73°. The mass loss rate must be considerably variable, since the system underwent a major erup-
SPECTRUM OF CI CYGNI COMPARED TO MODEL 2

Figure 3. Observed and predicted spectrum of CI Cygni

tion in 1975 and has declined in brightness since then, but in a rather erratic way. Kenyon et al. conclude that the mass transfer rate has generally been in the ballpark of several times $10^{-5} m_\odot$ yr$^{-1}$. Most of the available IUE spectra are good for studying the emission lines, but at the level of the continuum they are terribly noisy. The best low-dispersion spectrum we found is also the latest published, corresponding to phase 5.82 in the Kenyon et al. system, that is, the 5th observed cycle, 0.82 $P$ after the mid-eclipse (when the red M5 III star is in front). Dr. Kenyon kindly provided us with two optical scans.

We find that a fairly high mass transfer rate of 80$\mu$sy leads to a disk spectrum that matches the $\phi = 5.82$ spectrum of CI Cygni quite satisfactorily, as Figure 3 shows. In the combined spectrum, the red giant dominates the visible continuum as observed, and the slope and level of the continuum in the UV is well matched by our disk model. The only large discrepancy, shortward of the Balmer jump, does not speak against our model; it is due to Balmer continuous emission associated with the circumstellar plasma. While the optical spectrum does not seem to fluctuate too much (except in eclipse), this Balmer emission seems to come and go. A detail of the FUV spectrum is shown in Figure 4. Here we calculated a detailed disk spectrum, taking into account also the relative Doppler shifts of the rotating disk rings seen under an angle of 73$^\circ$. One notices that the deep absorption lines whose detailed profiles could be used to identify a disk spectrum are – unfortunately but not surprisingly – mostly obliterated by strong emissions.

The rather high mass influx rate combined with the deeper potential well (the adopted stellar radius is only 0.4 $R_\odot$) guarantees that there will be enough ionizing photons. The peak effective temperature of the disk is almost 37,000 K, the luminosity of one disk side is 785 $L_\odot$, and the energy available in the boundary layer amounts to 1570 $L_\odot$. Everything looks good. Please realize
Figure 4. UV spectrum of CI Cygni compared to our disk model

that we fitted the observed spectrum with our disk located at the distance of 2 kpc as postulated by Kenyon et al. for CI Cygni and that small adjustments of all parameters could probably improve the fit, then we are probably right in concluding that our model is surprisingly good.

There is, unfortunately, one big BUT...

4. The Disk Shape and the Eclipses

We must now examine the role that the disk thickness plays. Figure 1 showed an edge-on view of the system we considered first, with a sun-like star combined with a loser with mass $3 \, m_\odot$ filling its critical Roche lobe of a mean radius of $42 R_\odot$, and $\dot{M} = 80 \mu$asy. We see that the disk is rather thick in its outer parts, reaching a vertical half-thickness of about $6.9 \, R_\odot$ at the edge. From the shape of the disk it follows that for inclinations above $82.6^\circ$, we can see essentially only the outer edge of the disk; certainly the hotter inner parts of the disk (including the boundary layer, whatever shape it has) are permanently occulted by the disk body.

Now the disk whose radiation emulates CI Cygni so surprisingly well! When we first plotted that model, we suspected that we had inadvertently interchanged the radial and vertical dimensions; the “beetle” that represents the disk profile certainly looks turned by $90^\circ$ in Figure 5, compared to Figure 1! Yet there is no mistake here: the disk that should represent CI Cygni is unbelievably thick in the vertical dimension! At a mere distance of 20 stellar radii (that is, 8 solar radii), its vertical half-thickness is already $22.5 R_\odot$! Although unbelievable, this is really not too surprising. The deeper potential well ($R_g = 0.4 \, R_\odot$) makes the disk hotter, i.e. increases the gas pressure in every ring, while the vertical
component of the gravitational attraction of the gainer ($m_g = 0.5 \, m_\odot$) is weaker than in the (1.0,1.0) case, for the same $\dot{M}$. The actual horizontal extent of the disk is probably much larger than we plotted; its outer radius could be as large as $0.85 \, R_g^* = 0.85 \times 136 = 115 R_\odot$. No doubt towards the edge the disk would be even thicker, but we were not able to calculate those low-temperature disk rings.

On the other hand, such calculations would be meaningless anyway. Indeed, this exercise only shows that although it is formally possible to calculate the vertical structure of individual annuli, assuming geometrically thin disk and non-interacting rings, the results do not necessarily represent the reality well. Both the above-mentioned basic assumptions used in modeling break down for the disk with parameters corresponding to our model for CI Cygni. Such disk has to be modeled as a thick disk; and in all probability it would be highly unstable. This behavior can already be expected from the fact that the accretion luminosity is only about 5 times lower than the Eddington luminosity.

The great thickness of the disk in our disk model of a long-period Algol symbiotic has drastic effects on the visibility of the hotter inner parts of the disk (and the boundary layer), and affects the eclipse limits. This must be borne in mind when models of Algol-type symbiotics are considered.

5. **W Serpentis Stars, or Hyperactive Algols**

The enormous thickness of the disk in our model of CI Cygni is exceptional and certainly not realistic. However, a number of our disk models show considerable vertical extent of the disks, whenever the mass transfer rate is high. And it is high for example during the rapid mass transfer phase in the Algols.
Figure 6. Ultraviolet (IUE) spectrum of W Serpentis

Thus we must expect to encounter some eclipsing binaries in which we see primarily the outer edge of the accretion disk, which may permanently occult the gainer and the hot inner parts of the disk. However, the circumstellar material above the disk “sees” them. In such a case we expect to see a cooler optical continuum (due to the disk edge) with superimposed emission lines of fairly high ionization level. Plavec (1980) called these binaries the *W Serpentis stars.* Some of our powerful colleagues hate this name and prefer *active Algols.* This is, after all, a good name, but I must upgrade it to *hyperactive Algols.* U Sagittae is a dormant Algol; U Cephei is no doubt an active Algol, yet you still can distinguish the gainer easily. In the hyperactive Algols, you cannot. Our model of *Beta Lyrae* is an example (Hubeny & Plavec 1991): We suppose that the gainer is an about B0 V star, completely or almost completely hidden inside a thick disk. The toroidal disk edge has an effective temperature approximately corresponding to the disk effective temperature at that distance, thus we see it as an F5 continuum. The anomaly in \( \beta \) Lyrae is that the loser, a B6-8 II star, produces the optically brighter spectrum.

In *W Serpentis,* the optical spectrum again emulates an F5 giant, and we believe this is again the disk edge. Its large variability, reported by many observers, is then easier to understand.

But the ultraviolet spectrum looks mysterious (Figure 6). Some typical emission line stand out, but is there an UV continuum? Probably not. We notice the broad blend of Fe II emissions around 2400 Å. Other Algols show it, too, notably RY Geminorum and UX Monocerotis. Fortunately, in UX Monocerotis the emission lines are narrower, so they are more clearly separated, and we see only a forest of weaker emissions (plus noise), but no genuine continuum. The supergiant system *W Crucis* is a similar case of an hyperactive Algo. From the relative strengths of Fe II / Fe III, Plavec (1989) concluded that the gainer in
Figure 7. Model of an Algol in the rapid mass transfer phase

W Serpentis is about B7, or that it is small cool star surrounded by a hot inner disk. One way to decide between these two alternatives would be to get a good estimate of the mass transfer rate, which should be quite high; the hyperactive Algols are probably observed at or near the rapid mass transfer phase.

6. Rapid Mass Transfer in Algols

We have attempted to model Algol systems undergoing the rapid phase. We adopted a gainer of $m = 2m_\odot$, $R = 2R_\odot$, a mass transfer rate of $50 \mu s y$, and a loser of $4m_\odot$. We were able to calculate disk rings to a distance of $26R_\odot$, where its half-thickness was $3.8R_\odot$, significantly larger than the radius of the gainer. (Figure 7).

Assuming that it is there where the disk ends, we postulate separation between the components $A = 95R_\odot$, and the mean radius of the loser of $42R_\odot$. Now much depends on the nature of the loser – in other words, at which evolutionary stage does the loser fill its critical Roche lobe. If it happens very late, when the loser is an M giant, then the loser will show only in the infrared. The face of the disk dominates both the optical and the ultraviolet continuum – provided you do not observe the system very nearly edge-on! If the inclination is above $80^\circ$, then you see mainly the disk edge, the emission lines, and perhaps, in the infrared, you could detect the loser: this may be the very image of a W Serpentis binary.

If the size of the loser is the same but its effective temperature corresponds to a G8 star, the loser will be much more conspicuous even in the optical (see Fig. 8).
Figure 8. Spectrum of a model Algol in the rapid stage

Figure 9. Spectrum of RY Persei compared to Taygeta (dots)
Figure 10. UV spectrum of RY Persei in total eclipse

7. Moderately Interacting Algols

Although a little early in spectral types than a typical semidetached Algol binary system, RY Persei will serve here as a good example of an Algol observed in the slow mass transfer stage. Parameters of the system are $m_g = 6.6m_\odot$, $m_l = 1.86 m_\odot$, $A = 31 R_\odot$, $i = 81.6^\circ$ (based on Popper 1989, Popper & Dumont 1977, and Van Hamme & Wilson 1986). The spectral type of the gainer is near B6 IV, that of the loser near F9 III. Unfortunately for our disk modeling, the rate of mass transfer is unknown. We can take 1 $\mu$sy as a reasonable upper limit. In that case the accretion disk must be quite cool as well (the effective temperature of the hottest ring is then 4300 K). Its geometrical thickness will also be small compared to the size of the gainer. In spite of that, our calculations show that it will be optically thick, and since we are looking at the system from an angle of $81.6^\circ$, it will permanently obscure nearly one half of the gainer's observable globe.

Yet a more interesting consequence of mass accretion are the emission lines, observed during the total eclipse of the gainer (Plavec 1988; Polidan 1992). They are shown in Figure 10; in contrast to the case of W Serpentis (Figure 6), there are no emission longward of 2000 Å.

These lines must form around the gainer and above and below the disk, since the corresponding sharp absorptions are seen at phases outside eclipse, as Figure 9 shows. These circumstellar absorptions are easily distinguished from the photospheric lines, since the gainer rotates very rapidly (at 330 km s$^{-1}$ in projection), so that the photospheric lines are considerably broadened. A good comparison with a normal star can be obtained by using the spectrum of 19 Tauri (Taygeta), B6 IV.
8. Conclusions

We notice that even a modest mass transfer process generates circumstellar emission lines. The source of material and ionization is most probably in the boundary layer. Unfortunately, its physics is very poorly known, and only very recently – actually at the present meeting – have some promising steps been made towards a better understanding (Narayan & Popham 1993; Popham et al. 1993). We have dealt in this paper mainly with eclipsing binaries, that is, objects observed at such a high inclination that the disk permanently occults the boundary layer. Thus the boundary layer will not show in the spectrum. However, quite obviously many more similar systems exist that are not eclipsing from our point of view; for these our model spectra are incomplete. Observing such systems would provide us with a much better insight into the structure and spectra of disks and boundary layers.

While the boundary layer is not directly visible in the systems that we see as eclipsing, it signals its presence in the emission lines. It is quite possible that an induced stellar wind is generated in the boundary layer, and carries the ionized gas high above the orbital plane. This may explain the presence of the rarefied but ubiquitous circumstellar matter in the Algols (Plavec 1989). Moreover, the circumstellar gas emitting the strong emission lines observed in the symbiotics such as CI Cygni may have (at least partly) the same origin, rather than coming from the red giant. And the question if there exist genuine Algol-type symbiotics (and, specifically, if some of the known symbiotics can be identified with them) also largely depends on good understanding of the boundary layer physics. Thus it seems to us that the problem of the source of circumstellar gas and of its ionization is crucial for further progress in understanding accretion in binary systems; and we conclude with the contemporary (but more politely formulated) slogan: “It’s the emissions, friends!”

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