ALGOLS: WHEREFROM, WHERETO, AND WHAT IN BETWEEN ?

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Abstract. Four different aspects related to the evolution of Algols are discussed: the occurrence of a contact phase during the mass transfer, the evolution of short period systems evolving through case A mass transfer, the influence of the mass transfer on the surface abundances of both components, and the problem of the initial parameters of Algol systems. For the latter, a search is made for conservative case B systems. UZ Cyg seems to be a good candidate for such evolution. Finally, some remarks are given on the initial values of the low mass Algol S Cancri.

1. Introduction

Although the general picture of the formation and evolution of Algols is well established since long, it becomes more and more clear that modeling individual systems is absolutely necessary to explore remaining problems. It is also clear that this will lead to a modified and, above all, diversified picture of the formation of Algol systems.

The first real attempt was undertaken by Plavec (1973), who confronted the assumption of conservative mass transfer with the characteristics of U Sge. Since then, only a few attempts were published. However, both the efforts in analysing observations of individual systems, taking into account information from different methods and wavelengths, and the progress in computing the evolution of the two components simultaneously, allow for new hope for the near future. Only from studies, such as performed on the 'near-Algol' SV Cen (Nakamura and Nakamura, 1982) and on TV Cas (De Greve et al., 1984), we can deduce constraints on the generic relations between detached, semidetached and more advanced systems, and get a more precise idea on mass and angular momentum loss.

In the following the initially more massive star is indicated as primary (star 1), the companion as secondary (star 2).

2. Contact, so what ?

2.1. OBSERVING CONTACT

The observational evidence that a contact configuration forms a common evolutionary episode in the life of a Algol or would-be Algol, is found in the existence of early-type contact binaries.

Webbink (1976) gathered 27 early-type EW systems of type A and B, with an average period of 0.64 d. Most of them were not very well studied, exception made for the systems S Ant, V535 Ara, V1073 Cyg and TY Men (Rucinski, 1974, 1976). He also predicts the existence of socalled latent contact systems.

Packet (1988) compiled a catalogue of 21 systems with a suspected or proven contact nature, of spectral type O and B. From their characteristics he concludes that they form

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an inhomogeneous group. Their mass ratio distribution and the distribution of the effective temperature distinguish them from the W UMa binaries. In some of them energy transfer seems to work efficient, in others inefficient (see also Lucy and Wilson, 1979).

2.2. THEORETICAL CONSIDERATIONS

Benson (1970) first investigated the evolution of a binary system during mass transfer, following the two components. Since then several studies showed that large accretion rates lead to a rapid expansion of the mass gaining star, soon resulting in a contact configuration. Hence, the formation of contact systems is often inevitable for systems evolving through case A or early case B. But recent investigations show that such configuration does not affect the further evolution in a severe way. Packet (1988) summarizes the scene:

- Binaries with mass ratios near one will hardly encounter a contact phase during mass transfer.
- Binaries with extreme mass ratios will overflow their outer critical surface and evolve through a common envelope phase (Paczynski, 1976).
- In between there must exist a group of systems that come into contact and, afterwards, return to a semidetached state.

2.3. CONTACT NOT RELEVANT FOR ALGOLS ?

From an investigation of the effect of a contact phase on the characteristics of the exponents, Packet concludes that, at least for the two systems studied (with mass M_1=9 M_o), the contact phase has no influence on the mass transfer phase as a whole. The resulting semidetached systems show no trace whatsoever of a preceding contact phase. This is reflected in the comparison of two models given in Table 2.1. It shows the results of a calculation taking the contact condition into account (C) and of one without (SD), starting from the same initial model just before contact. Both models are nearly identical.

Packet also explored the influence of energy transfer. Energy transfer causes a luminosity redistribution in the common envelope. This process is at the basis of the W UMa lightcurves. In stars more massive than 1 - 2 M_o, the structure of the radiative envelope depends on the run of the luminosity. Hence, the spatial distribution of the energy source or sink is important for the structure of the envelope. Packet (1988) studied the influence of an additional energy loss or input in an early case B contact

Table 2.1. Comparison of models of losers for the system 9 M_o + 5.4 M_o, P_i=2.27 d, shortly after the end of contact. The model marked 'C' is calculated with a contact condition taken into account, the model marked 'SD' is calculated as semidetached throughout. It is taken at the same mass as the C-model. The symbol t' denotes the time elapsed since the beginning of the mass transfer (Packet, 1988).

	C	SD
$t'/10^4$ yr	22.900	22.865
M/M_o	6.30	6.30
dM/dt ($10^{-4} M_o$/yr)	-1.64	-1.61
log L/L_o	1.699	1.707
R/R_o	5.78	5.78
log T_c	7.51	7.51
log rhoc	1.17	1.17
M_{cc}/M_o	0.62	0.61

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model and followed its evolution (original system: 9 M_O + 5.4 M_O, P=2.98 d; model used: 7.98 M_O + 6.42 M_O, P=2.55 d). The energy flow is from the gainer (hotter) to the loser (cooler), opposite to the situation in thermal relaxation oscillation. Contrary to what Webbink (1980) thought, this can happen before mass ratio reversal and with a mass ratio clearly distinct from one.

The most important result is that the overall evolution of the binaries is but little altered if the direction of the energy flow is opposite to the direction of the net mass flow between the components. This may not be the case in contact systems resulting from early case A evolution. Of course, the observed surface parameters do depend on the energy transfer!

Finally, with van 't Veer (1979) we stress the importance of 'moderate' angular momentum loss to prolong the contact phase and to reach more extreme mass ratios than in the actual theoretical models. The nature of the necessary feedback for such regulated angular momentum loss is still unknown (Smith, 1984).

2.4. THE DURATION OF THE CONTACT PHASE

For the systems with M_1=3 and 5 M_O, calculated by us, those calculated by Packet (1988) with M_1=9 M_O, and those of Nakamura and Nakamura (1984, 1987a,b) with M_1=10.4 to 13.4 M_O, we gathered the total time of contact per sequence and compared this with the main sequence lifetime of the primary stars and with the timescale of the semidetached phases. They are evaluated as a function of the initial period (figures 2.2 and 2.3). Apart from the obvious relation with the mass of theprimary for the absolute values , we clearly remark a general decrease of the time of the contact phase with P_i. The following conclusions can be drawn:

1. The duration of the contact phase decreases with increasing initial period.
2. The timescale of the contact phase amounts to a few percent of the main sequence lifetime, only for periods less than 1.2 days. For larger periods the phase passes almost unnoticed.
3. Even compared to the semidetached timescale, the contact phase amounts to less than 3 percent in most cases, though with a less pronounced relation with P_i.

3. What is going on in SPSDS ?

3.1. A DEFINITION

Short period semidetached systems (SPSDS) are very likely systems undergoing a case A of mass transfer. In addition to the contact phases discussed in section 2, the evolution of initially detached systems with short periods is rather peculiar. Their evolution in the low mass region was explored by Webbink (1976), while the evolution at higher masses was calculated by Nakamura and Nakamura (1984, 1987a,b). The poster papers'Who is who in Algol land, I and II' by Packet and myself, explore the medium mass range. The calculations point out that, at least in the mass range 3 to 12 M_O, successive phases of semidetached mass transfer occur of comparable duration, with reversed direction of the mass stream.

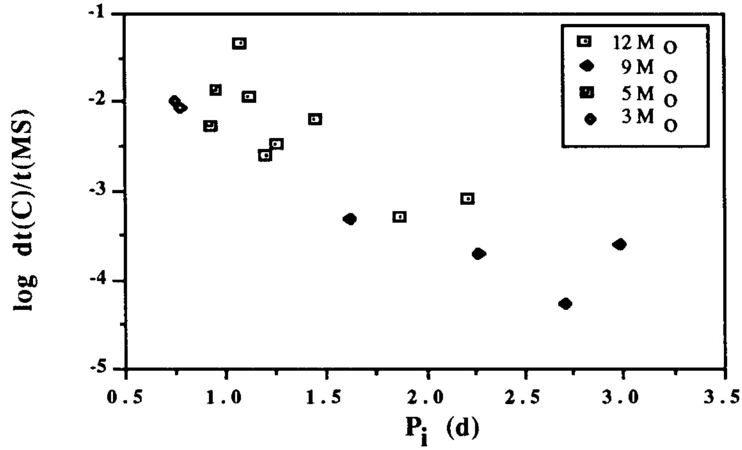

Figure 2.1. Timescales of contact phases, normalized to the main sequence timescale of the primary star, as a function of the initial period P_i. For references of the computations, see text.

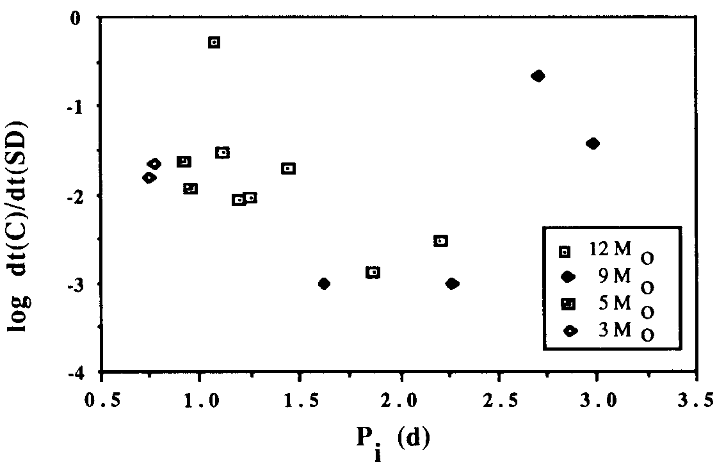

Figure 2.2. The same as in figure 2.1, but now normalized to the total timescale of the semidetached phase.

3.2. THE EFFECT OF GROWING FAT.

The results of mass loss and accretion on the evolution of a system are illustrated in figure 3.1 representing the evolution of the central hydrogen content with time for 3 M_O + 2.7 M_O. After a fast phase of mass transfer, during which the mass ratio is reversed, hydrogen is consumed

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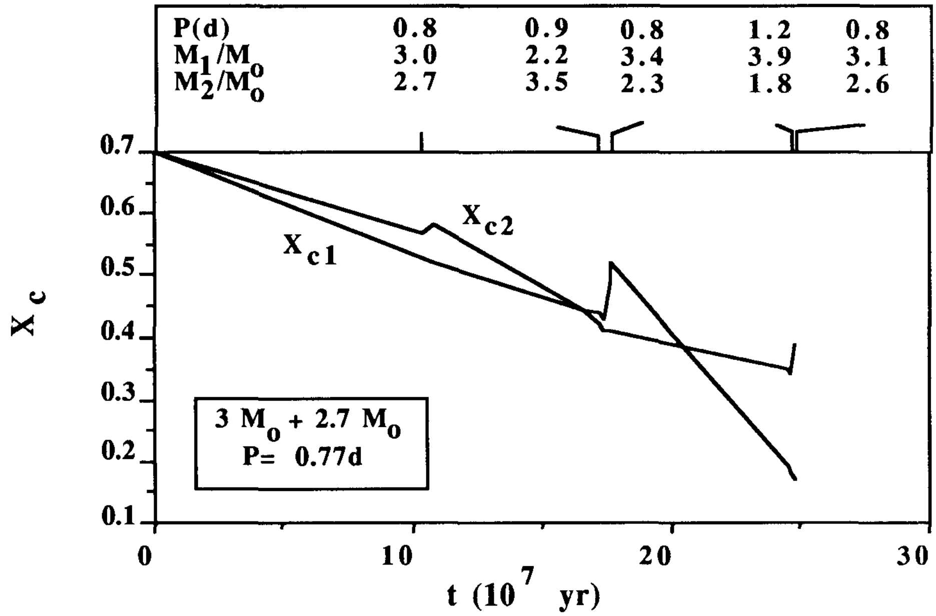

Figure 3.1. Evolution of the central hydrogen content in a binary system, before and during a case A of mass transfer. The initial parameters are indicated at the bottom left. System parameters at important points are given at the top.

much faster in the core of the secondary, and consequently X_{c2} decreases faster. At approximately X_{c2}=0.4 , the evolutionary expansion of the secondary results in reversed mass transfer. The mass ratio is reversed once again, and fresh hydrogen is mixed in the core of the original primary, increasing X_{c1}. During the following slow (semidetached) phase, the now more massive primary evolves faster and finally refills its critical Roche lobe. This occurs while both components are still burning hydrogen in the core (for another system, with M_1=5 M_o and a slightly larger period, this happens during hydrogen shell burning of the primary). The outer critical surface through L_2 is then reached rapidly, resulting in large scale mass and angular momentum loss from the system.

What are the important differences with our previous knowledge ?

The alternating phases of mass transfer, due to the overtake in evolution by the mass gaining star, has a profound influence on the mass ratio. Figure 3.2 shows the evolution of this parameter with time for 2 different masses of the primary. The mass ratio is confined to the range 0.35 to 2.5, larger values being attained in each successive phase (see also Packet and De Greve, this volume).Figure 3.3 summarizes the actual

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state of affairs for different types of mass transfer and

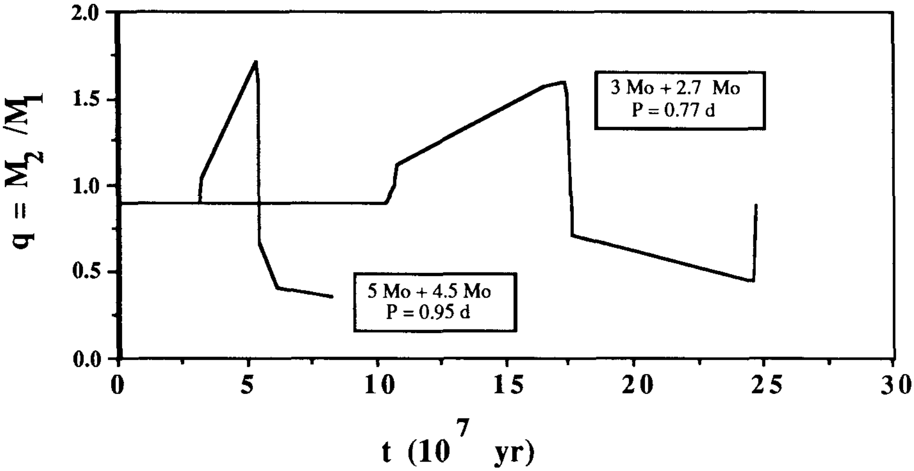

Figure 3.2. Evolution of the mass ratio with time, for two different systems, during case A of mass transfer, including reversed phases of mass transfer.

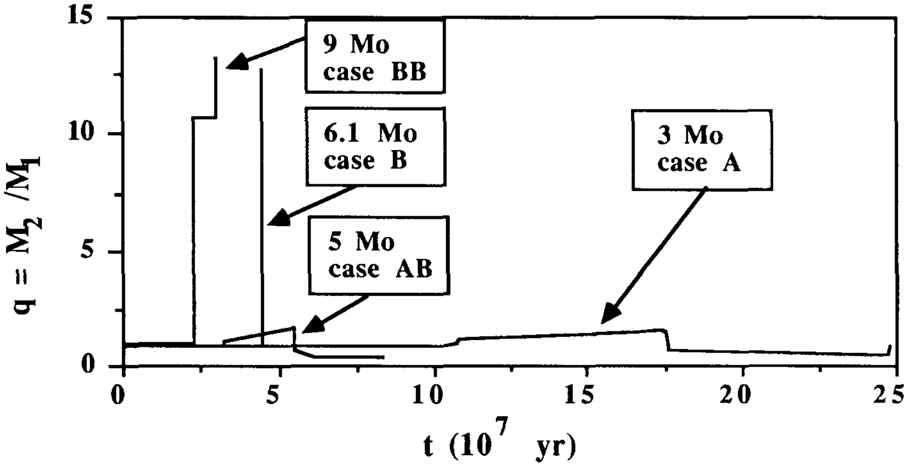

Figure 3.3. Evolution of the mass ratio with time, for four different masses of the primary, and four different types of mass transfer.

different masses. From this it seems obvious that large mass ratios are correlated with post main sequence mass transfer. But then, what to think of systems like SU Boo, AB Cas, Z Dra, AL Gem and V338 Her, all with periods in the range 1.3 to 1.6 days and mass ratios from 4 to 10?

These systems are very likely examples of nonconservative mass transfer like TV Cas (De Greve et al., 1984). Their present, apparently long enduring semidetached phase shows that mass and angular momentum must have been removed without a catastrophic common envelope evolution. This points towards case AB or early case B of mass transfer or to a feedback mechanism regulating the angular momentum loss (Smith, 1984).

Although small observable differences are found between the two successive phases, the actual situation is such that SPSDS with mass ratios around 1 - 2 cannot be traced back to their real origin. Further analysis of the results, over a larger mass range, may possibly result in restrictive conditions on the initial parameters of such systems. On the other hand, such systems may be quite rare. Their progenitors, the detached systems with small periods are hardly found in the litterature. Candidate Algol systems that may be in one of the two phases, are systems such as X Tri, AI Dra, V505 Sgr, SX Aur, ZZ Cyg and MR Cyg (taken from the list of Giuricin et al. (1983)).

After consideration of the positions of the components in the HRD, SX Aur (7.9 $M_\odot$+ 4.7 $M_\odot$, P=1.21 d) seems to be the only real candidate. However, for a further comparison much better absolute dimensions are required.

4. Surface abundances in interacting binaries.

Studying the chemical composition of the components of semidetached binaries provides evidence for the hypothesis of mass transfer. Indeed, spectrum analyses such as undertaken by Parthasarathy et al. (1983), Dobias (1985) and Cugier and Hardorp (1988), reveal serious carbon underabundances in systems like Algol, U Cep, U CrB and others. This is in agreement with the large-scale mass transfer theory, as illustrated in figure 4.1 (taken from De Greve and Cugier, 1988). It gives the carbon profile with mass (expressed as a proportion of the initial surface value) for two components of a close binary with the following initial characteristics: M_1=9 $M_\odot$, M_2=8.1 $M_\odot$, P_i=3.13 d. The profiles are shown with the centers at opposite ends. Also indicated are the moment that the hydrogen abundance at the surface decreases and the end of the Roche Lobe Overflow (RLOF).

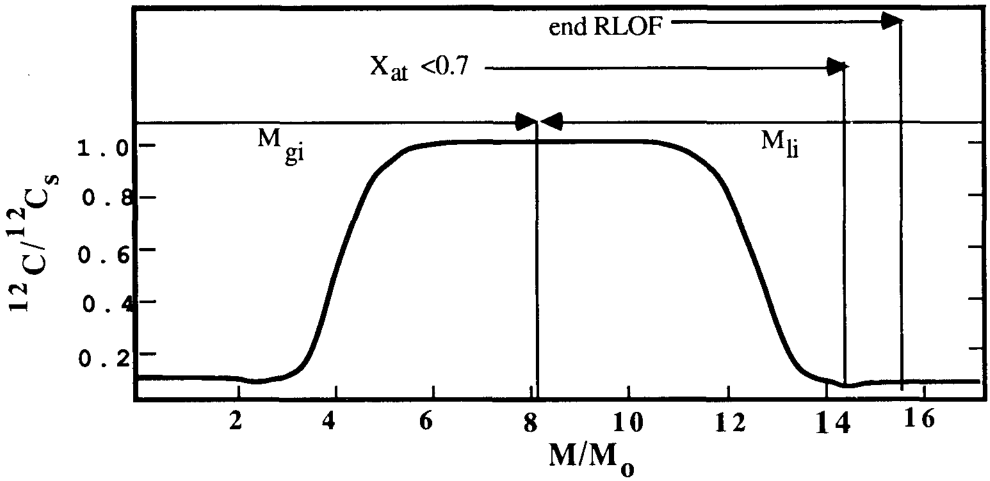

Figure 4.1. Carbon profile (normalized to the initial surface value) for the components of the binary system 9 $M_\odot$ + 8.1 $M_\odot$, P_i=3.13 d, at the onset of case B of mass transfer. The profiles are shown with the centers at opposite ends.

During the slow semidetached phase the carbon abundance at the surface of the loser decreases to some 5% of the original value, and reaches 8% at the end of the RLOF. If the transferred matter is simply deposited on top of the secondary component, its surface will reflect the same chemical composition as the loser. However, simple deposition of matter would result in gainers with strong helium enriched envelopes, located to the left of the ZAMS in the HR diagram (Packet, 1988), contrary to the observations.

Moreover, recently measured carbon abundances at the surfaces of mass gaining stars in semidetached systems do not reach the very low values predicted by the simple accretion process of figure 4.1 (De Greve and Cugier, 1988). De Greve and Cugier investigated the apparent anomaly between the observed values and the theoretical expectations. They adopted thermohaline mixing in the envelope of the gainer, when hydrogen depleted layers are deposited on top of this star. As a result, hydrogen rich (but also carbon rich) layers are mixed with accreted matter, increasing the abundances of these elements. Figure 4.2, taken from their paper, shows the evolution in time of ^{12}C at the surface of the gainer of the same system as shown in figure 4.1. Corresponding masses of the loser are also given. Remark that the minimum luminosity of the loser is reached at t=2.739 10^7 yr (M_1=4.1 M_O). Thermohaline mixing sets in soon after. This means that the evolution of ^{12}C during the slow semidetached case B phase is given by the right, slowly decreasing part of the curve, showing 80 to 60% of the original 12C abundance. For a case A of mass transfer the picture changes essentially with respect to the timescales involved . Here very small and large fractions are seen at the surface of the gainer for about equal amounts of time. The present findings, obervational as well as theoretical, though still primitive and too inaccurate for a detailed comparison, are encouraging enough to ask for enhanced further efforts in this domain.

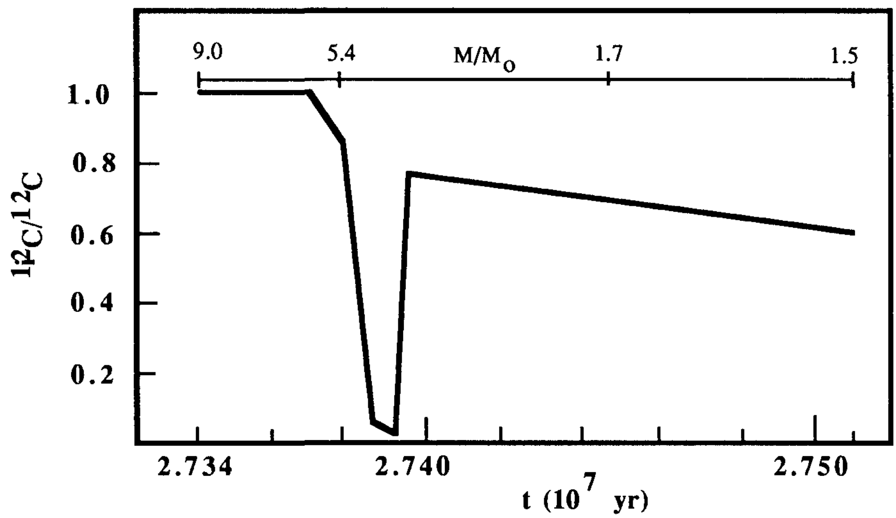

Figure 4.2. Evolution of carbon abundance at the surface of the gainer (normalized to the initial value) of the system of Figure 4.1, during a case B of mass transfer (De Greve and Cugier, 1988).

5. The initial value problem.

5.1. A METHOD

Although the first attempts to match theoretical models with individual Algols (Plavec, 1973; Refsdal et al., 1974) resulted in more questions than satisfying answers, the theoretical study of well observed systems is still the most promising approach to deduce a possible dependence of mass and angular momentum loss on the system parameters. From a sufficient number of such studies, some trends may emerge.
The scheme for tackling an individual system was forwarded on one hand by Andersen et al. (1988) with the study of the detached system AI Phoenicis, on the other hand by De Greve et al. (1984) with the study of TV Cas. In the latter paper, the following steps were taken to derive a possible model:

1. Limits and contradictions are explored, assuming conservative mass transfer.
2. The possibility of a case B is investigated by two means:
   a) The lower limiting period PI for the occurrence of a case B (Plavec, 1968).

b) The resulting age of the system (approximately equal to the main sequence lifetime of the mass losing star). This determines the onset of accretion for the gainer. Combined with quasi thermodynamic equilibrium this also determines the present radius (and thus HRD position), as this radius reflects X_c. The quantity X_c is a function of ΔM and X_{ca}, the value of X_c at the onset of accretion. Both values are determined by the mass of the primary (De Greve, 1986).

3. Nonconservative mass transfer considerations, to derive constraints on the fraction of mass loss (1-ß) and angular momentum loss.

For TV Cas (2.8 M_o + 1.3 M_o, P=1.8 d) this resulted in a mass loss of 75 % (ß=0.24) of the transferred mass, which represents only 25 % of the total initial mass. About 40 % of the initial angular momentum was removed from the system. Systems that are possible candidates for a similar evolutionary scenario are BF Cen (8.7 M_o + 3.8 M_o, P=3.69 d) and U CrB (4.9 M_o + 1.45 M_o, P=2.49 d).

5.2. IN SEARCH FOR CONSERVATIVE CASE B REMNANTS.

After the description in section 3 of the rather destructive case A interaction, we can ask ourselves: 'What about case B ? Are there binary systems that survive the rapid mass transfer phase and 'quietly' proceed towards the end of the semidetached state ?'

We can easily find out how systems will look after evolving through a conservative case B. To fix the ideas we restrict ourselves to very specific theoretical cases and then try to find out if the obtained results can also be found in the observed world. We therefore calculate the mass of the primary, the mass ratio and the period after the primary has lost 70% and 90% of its mass. These fractions correspond respectively to a point somewhere in the slow semidetached phase and to the end of the mass transfer (even somewhat beyond for more massive stars). The masses of the primary stars are 3 M_o and 9 M_o, the initial mass ratios 0.9 and 0.5. In all the cases the initial period is taken equal to P^I (minimum period for case B, Plavec, 1968). We then looked in the list of Giuricin et al. (1983) for systems that were as close as possible to the resulting border points. Figure 5.1 gives the variation of q and P as a function of mass M_i=3 and 9 M_o. Left endpoints correspond to Δ =0.90, right endpoints to Δ=0.70. Selected systems are indicated.

From the figure it seems that TU Mon is a massive sd system at the beginning of the slow phase. The most interesting system is KU Cyg, which looks like a system at the end of the mass transfer, originating from a 3 M_o star with a 2.7 M_o companion.

As a next step, we check whether or not these findings agree with corresponding positions in the mass luminosity diagram. From earlier work (De Greve, 1986) we derived the positions of theoretical models of the losers at the end of an early case B mass transfer and at minimum luminosity. Except for RY Per and UZ Cyg the positions agree well with the results of figure 5.1. Especially UZ Cyg remains interesting because it coincides with the end relation. In spite of the badly known dimensions (a spectroscopic study of this system is desirable!), we explore its origin in somewhat more detail in the next subsection.

To conclude this small, restricted investigation, the position of the mass gaining stars is evaluated in the mass-radius diagram . Assuming that they are in thermal equilibrium during the slow semidetached phase, we derive from it information on their evolutionary state. We find that the massive companion of UZ Cyg is at the end of core hydrogen burning, implying that it will fill its own critical volume soon. Let us look at the possible origin of this system a little closer.

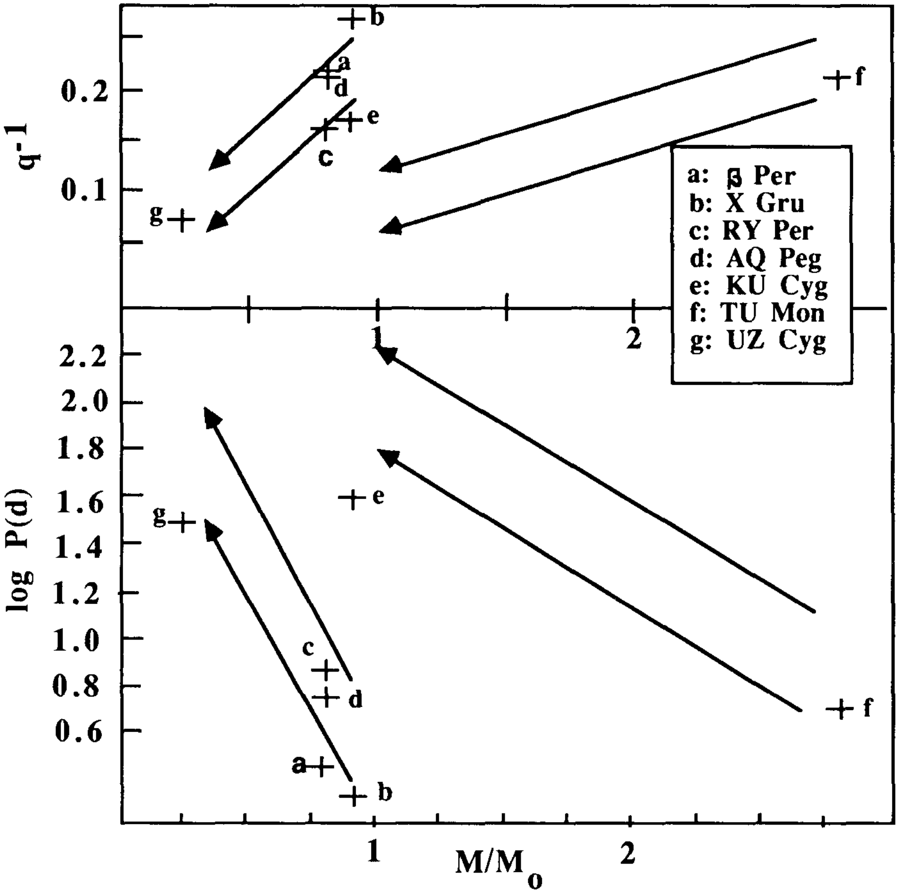

Figure 5.1. Mid and endpoints of slow semidetached mass transfer (conservative case B), in the mass-mass ratio and the mass-period plane, for specific initial conditions (see text). Selected systems, taken from Giuricin et al. (1983) are also indicated.

5.3. UZ CYG, A CLASSICAL, CONSERVATIVE CASE B ?

Assuming that 90% og the mass of the primary is transferred (roughly corresponding to the end of case B), we found that the system UZ Cyg coincides with specific theoretical mass ratio and period boundaries, computed according to a conservative mass transfer scenario. The position in the mass-luminosity diagram also points to a case B remnant. The initial conditions can then readily be calculated. The initial mass follows from the relation given by De Greve (1980), while mass ratio and period follow from the conservative assumptions on mass and angular momentum. This leads to the values

$$M_1=2.2\ M_o\ (\pm 0.7\ M_o) \qquad M_2=1.65\ M_o \qquad P_i=0.48\ d.$$

If we calculate the minimum value of P for the occurrence of case B, for q=0.7 (Plavec, 1968, De Greve, 1986), we find $P^I=0.8$ d! However, the actual uncertainties in the determination of the absolute dimensions can easily account for the discrepancy. Changing the observed masses by only 0.05 M_o already leads to $P_i=0.8$ d. Hence, UZ Cyg may be considered as one of the rare systems observed at the real end of case B mass transfer. As such it deserves a more detailed study of its characteristics and evolution.

5.4. S CANCRI, A TANTALIZING PUZZLE.

S Cancri (HD 74307, P=9.48 d, B9.5V + G8-K0III) is at present the binary system with the smallest measured mass of a star. Awadalla and Budding (1982) made a detailed analysis of the photometric behaviour of this system. Popper and Tomkin (1984) reconsidered photometric and spectroscopic evidence and attributed it the values shown in table 5.1.

Table 5.1. Absolute dimensions of S Cancri, from Popper and Tomkin (1984)

	star 1	star 2
$M/M_\odot$	2.3 $\pm$0.07	0.18 $\pm$0.04
$R/R_\odot$	2.18 $\pm$0.04	4.83 $\pm$0.09
log T_{eff}	3.997$\pm$0.01	3.690$\pm$0.02
log $L/L_\odot$	1.62 $\pm$0.04	1.08 $\pm$0.09
log g	4.13 $\pm$0.02	2.32 $\pm$0.10
M_V	0.8 $\pm$0.1	2.2 $\pm$0.2

Is the system at the end of a conservative case B of mass transfer ?

The total mass of 2.48 $M_\odot$ requires a minimum mass of 1.24 $M_\odot$ for the loser. In that case the ratio M_l/M_{min}=0.145, and the loser has still to transfer one third of its present mass. If the system is at the end of case B then, according to theoretical computations, the initial mass is M_{li}=1.65 $M_\odot$, resulting in a companion of 0.83 $M_\odot$. The mass ratio is 1.0 for the minimum condition, 0.50 for the end condition. However, the respective initial periods are 0.19 and 0.26 d, far too small for a case B (for which the limiting periods P^I are 0.59 and 0.64 d resp.). In fact, they are even too small for a case AB.The initial mass ratio cannot be too small, because in that case the 2.3 $M_\odot$ star should still be unevolved, whereas it is observed at 1/3 main sequence.

And what about a nonconservative picture ?
For the sake of simplicity, let us adopt the model that we derived for TV Cas (de Greve et al., 1984), still assuming that the present state is the end of the mass transfer. In that case we run into a new problem! Adopting $\beta=\Delta M_g/\Delta M_l$=0.24 as in TV Cas and combining this with M_{li}=1.65 $M_\odot$, we find M_{gi}=1.95 $M_\odot$. In fact, the condition $M_{gi} \leq M_{li}$ leads to $M_{li} \geq 1.9$ $M_\odot$. However, we can easily escape from this contradiction, if we look somewhat closer to the system TV Cas. Its present state is still far from the end of the mass transfer (M_l/M_{li}=0.43, whereas the final value is 0.20). If the major mass loss from the system has occurred in the past (and simplifying to a conservative continuation from the present state on), the average value of ß for the whole interactive phase is $\langle\beta\rangle$=0.46. With this value M_{gi}=1.62 $M_\odot$ (q_i=0.98). This solution can account for the evolved state of the secondary, the nonconservative picture of TV Cas and the end-of-the-mass-transfer idea! But we emphasize that a detailed evolutionary model should start from a careful evaluation of the present state and structure of the mass gaining star. Furthermore, evolutionary models of close binaries (case B), involving the two components, are required for the mass range 1.5 to 2.0 $M_\odot$.

6. The end.

I would like to end this talk citing the idea of my colleague and friend Wim Packet, expressed in its Ph. D. thesis, because it corresponds so well to the message that I advocate since a number of years:

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Despite the difficulties (related to the combined approach and analysis of one individual system), this approach is probably the most promising way to learn more about the history of Algols. As several disciplines are involved (spectroscopy, photometry, evolutionary calculations,...), this type of research should be an eminent domain for collaboration between different research groups.

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DISCUSSION

Leung commented that he had also found the concept of reverse mass-transfer useful in explaining systems near the borderline between detached and contact configurations. Plavec remarked that he and Jan Dobias had become sceptical of many of the parameters quoted for binary systems in the literature; in particular he wondered how reliable the values quoted for UZ Cyg might be. Hall replied that he had confidence in the light-curve and its solution, but since no spectroscopic study was available to him, he had estimated absolute dimensions by assuming that the secondary fills its Roche lobe and the primary obeys the mass-luminosity relation. He felt that the resulting values were probably fairly reliable. De Greve agreed with Plavec's caution but said that UZ Cyg interested him because it appeared to be at the end of the mass-transfer. It is crucial to the derivation of good initial parameters for a system, to know at what stage of mass-transfer it is now. The only way to be sure of this is to find a system at the end of the process. For this reason he felt UZ Cyg deserved further attention. Polidan commented that he had observed Hα emission during an eclipse of UZ Cyg and that there is, therefore, some circumstellar matter in the system.

Polidan also asked a question about the expected surface carbon abundances. As he had remarked in his own paper, he could observe no carbon at all in the spectrum of the mass-losing star of V356 Sgr. De Greve said the answer depended on how far mass-transfer had progressed. If the loser had passed through its minimum of luminosity, the surface carbon abundance could be almost two orders of magnitude lower than normal; i.e. lines of carbon would probably be undetectable in its spectrum.

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