THE EVOLUTION OF MODERATELY CLOSE AND MODERATELY WIDE BINARIES

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ABSTRACT. We discuss evolutionary processes in binaries where the primary becomes a red giant with a deep convective envelope before it fills its Roche lobe. Such binaries (late Case B or late Case C, if they evolve conservatively) ought to suffer drastic mass transfer, on a hydrodynamic timescale. In some circumstances this may lead to a common envelope, spiral-in, and finally either a very short-period binary or coalescence. But there appear to be other circumstances in which the outcome is an ordinary Algol, or a wide binary with a white dwarf companion as in Barium stars and some symbiotics. We try to demonstrate that stellar-wind mass loss, enhanced one or two orders of magnitude by tidal interaction with a companion, can vitally affect the approach to RLOF, and indeed may prevent RLOF in binaries with periods over 1000 d. Such mass loss is probably accompanied by angular momentum loss, by magnetic braking combined with tidal friction. The result is that it will not be easy to predict definitively the outcome of evolution in a given zero-age binary.

1. INTRODUCTION

The descriptions 'moderately close' and 'moderately wide' for binary systems appear vague, but for present purposes we adopt the following four definitions, based on Cases A, B, C of Kippenhahn & Weigert (1967):

'close': Case A, early Case B or early Case C; the primary (by which we shall always mean the *initially* more massive component) has a predominantly radiative atmosphere at the onset of RLOF (*i.e.* Roche Lobe Overflow).

'moderately close': late Case B; the primary has a deep convective envelope, and has not yet ignited helium, at the onset of RLOF.

'moderately wide': late Case C; the primary has a deep convective envelope, and a helium-burning core or shell, at the onset of RLOF.

'wide': the two components are too far apart to have RLOF.

In the above definitions, we refer to the behaviour expected in *conservative* evolution (Kippenhahn & Weigert 1967). Since we intend to discuss mainly the effect of non-conservative processes, *ie* mass loss by stellar wind, and consequential angular momentum loss, the actual evolution may be quite different.

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Moderately close binaries, as defined above, will mostly have periods in the range

$$0.8\ m_1^2 \lesssim P \lesssim 400\ m_1^{-2} \tag{1}$$

where m_1 is the primary mass in solar units and P the period in days. Formally, condition (1) requires $m_1 \lesssim 5\,M_\odot$, but in practice systems with $m_1 \gtrsim 4\,M_\odot$ have only a rather narrow range of periods in which they can undergo late Case B evolution. This is because helium ignition occurs quite soon after the star has reached the base of the giant branch. Moderately wide binaries, on the other hand, require periods in the range

$$\max\left(1.2m_1^{2.5}, 400m_1^{-2}\right) \lesssim P \lesssim 10^{3.7} m_1^{0.1} \tag{2}$$

The upper limit in (2) represents the lower limit for periods of 'wide' binaries as defined above.

Most computations of RLOF in binaries that have been undertaken so far refer to 'close' binaries in our sense, because they are binaries in which the loser, having a radiative envelope, shrinks in response to mass transfer, and so is able to stay at (or rather fractionally above) its Roche radius throughout the mass-transfer phase. However, there are several classical Algols whose orbital periods are sufficiently long, in relation to their primary masses, that they were probably only 'moderately close' to start with. It has been known for at least 20 years that these present a substantial problem, which might even be dignified with the term 'second Algol paradox'. For the primary would have had a deep convective envelope at the onset of RLOF, its radius would therefore have *increased* when subjected to mass loss, and mass transfer should have become extremely rapid, approaching perhaps $10^{-2}\,M_\odot$/yr. Paczyński (1976) suggested that this would lead to 'common envelope' evolution, in which the two components would find themselves immersed in an envelope of material released so rapidly by the primary that the secondary would probably be unable to accept it. Paczyński anticipated that this envelope would be non-corotating, and that dynamical friction between it and the two stellar cores would cause 'spiralling in', with the final product being a very short-period binary (say $P \sim 0.5$ d) consisting of the secondary and the white-dwarf core of the primary.

Some such drastic mass transfer appears almost unavoidable (Paczyński & Sienkiewicz 1972) if (a) the primary has a deep convective atmosphere, and (b) the mass ratio at the onset of RLOF satisfies

$$m_1/m_2 \gtrsim 0.7. \tag{3}$$

Condition (a) would ensure that the primary expands as it loses mass, and condition (b) that its lobe will contract, or expand less than the star, as it loses mass. The ultimate outcome is perhaps less certain. We believe (following Livio & Soker 1988) that if the primary is only a red *sub*-giant, then a more likely outcome is coalescence: the product would be a single sub-giant in rapid rotation, with the core of the primary embedded in an envelope containing some of the material of both stars. Our reason for believing this is that even the considerable gravitational energy available from the shrinking of the orbit may not be sufficient to blow to infinity all the envelope of a sub-giant, especially since it is not likely that 100% of this energy will go into mass outflow: Livio & Soker (1988) suggest $\sim 30\%$. There is, of course, a third possibility - that, notwithstanding the drastic character of the mass transfer, the system may somehow manage to settle down into much the same configuration as it would have had if the mass transfer were slow and reasonably conservative. This might apply if (3) were satisfied by only a fairly narrow margin.

Superficially, of course, one would expect that (3) would always be satisfied, since $m_1 > m_2$ by definition at zero age. However, stellar-wind mass loss by the primary, after it becomes a red sub-giant but before RLOF, might alter this, at least if the wind is enhanced by (say) dynamo activity due to tidal friction (Tout & Eggleton 1988a, b). Even without the assumption of tidal enhancement, stellar wind mass loss is clearly important in some 'wide' binaries. Both Procyon and Sirius seem to have suffered such mass loss; although in the latter case the separation of the stars, at least at periastron, is arguably small enough that some mass transfer might also have occurred. But there are some binaries with shorter, or even much shorter, periods which *may* be showing evidence of substantial mass loss prior to RLOF, and it is mainly these which we wish to discuss in the remainder of this article.

2. DISCUSSION

Aspects of the evolution of moderately close and moderately wide binaries are hinted at by several types of star, among which are the following:

(i) RS CVn binaries: with red giant or sub-giant primaries, and periods in the range $\sim 2 - 100$ d, most of these are 'moderately close'.

(ii) Red giant binaries: many red giants are SB1s with $P \gtrsim 100$ d, and so are 'moderately wide'. They represent a relatively large data base (Griffin 1983, 1985) from which some statistical inferences regarding the distribution of mass-ratios and periods may be drawn.

(iii) Algol-like symbiotics: some symbiotics appear to have main sequence companions to the statutory M-giant component. Orbital periods are often not known, but have to be at least 'moderately wide'.

(iv) Algols: many, though not all, of the Algols with red giant or sub-giant losers must be descendants of moderately close binaries, *e.g.* RS CVn's with periods in the range $\sim 2 - 10$ d; several, however, could be descended from 'close' binaries, and so would not have had to run the risk of drastic RLOF.

(v) 'post-Algols': a small and heterogeneous collection of binaries containing a white dwarf or hot sub-dwarf in an orbit ($P \sim 1 - 10^4$ d) with a fairly normal star.

(vi) Pre-cataclysmic and cataclysmic binaries: these are usually taken to be the outcome of common envelope evolution in 'moderately wide' systems, although the star-planet scenario (Livio & Soker 1984a) represents an important alternative.

(vii) Barium stars: these may, according to McClure *et al.* (1980) and Böhm-Vitense (1980), be descendants of moderately wide binaries that have been through a mass-transfer phase, and contain a white dwarf remnant of the star which s-processed the material that is now visible in the red-giant companion. If this hypothesis is correct, then Ba stars, which are quite common ($\sim$ 54 brighter than $V \sim 6.5$) are probably the most important tracers of the evolution of moderately wide binaries.

(viii) Nova-like symbiotics: some symbiotics appear to have a white dwarf or hot sub-dwarf companion, and so presumably are at a later stage of evolution than the Algol-like symbiotics, and the Ba stars. As with (iii), orbital periods are usually not known, and may well in some cases be $\gtrsim$ 50 yrs, so that wind-interaction rather than RLOF is substantially more likely.

(ix) Double-white-dwarf binaries: although there are over a dozen common-proper-motion pairs of white dwarfs, descendants of 'wide' binaries, only one (EG52: Harrington *et al.* 1981) seems plausibly to belong with 'moderately wide' systems. Three ultra-short-period binaries (Nather 1985) may also be double-white-dwarf descendants of moderately wide systems, by way of common-envelope evolution. The 'Period Gap' which in ordinary CVs extends from $\sim$ 2 hr to $\sim$ 3 hr extends, for double-white-dwarf systems, from $\sim$ 1 hr to $\sim$ 20 yr!

A major evolutionary process hinted at by (i) is tidally-enhanced stellar wind in detached binaries where (a) the primary is close to its Roche lobe and (b) it has a deep convective envelope (Popper & Ulrich 1977, Tout & Eggleton 1988a). Not only are the red sub-giant components of RS CVn's known to be unusually active compared with the majority of red sub-giants (Hall 1976), but there are also a few (*i.e.* Z Her, VV Mon and RW UMa; Popper 1980, 1988) in which the primary has slightly less mass than the secondary, presumably as a result of stellar wind mass loss. This wind must be substantially greater than in single stars; otherwise there would not be many single red giants, since any reasonable extrapolation would suggest that the entire stellar envelope would be lost well before such a star could climb from sub-giant to giant luminosities. So we infer that tidal friction, presumably, via hydromagnetic dynamo action, enhances stellar wind by up to something like two orders of magnitude. The effect of such mass loss, prior to RLOF, could well be to violate condition (3), and hence to ensure that RLOF is not the drastic hydrodynamic process discussed by Paczyński & Sienkiewicz (1972), but is instead a relatively leisurely process, taking place on a nuclear timescale (Tout & Eggleton 1988b).

In Fig. 1 we show how RLOF may be affected, over a wide range of initial mass ratios (q) and orbital periods (P) by a tidally enhanced stellar wind comparable to what can be inferred from RS CVn's with inverted mass ratios, viz a mass-loss rate as determined empirically by Reimers (1975), multiplied by a factor that increases rapidly from $\sim$ 1 to $\sim$ 150 as r_1 (the primary's radius) increases from $\sim 0.2\, r_{L_1}$ to $\sim 0.5\, r_{L_1}$. We see that there is a substantial area in the (q, P) plane where RLOF is a non-drastic process. This region is sandwiched between a region of longer P where RLOF is prevented altogether, because the entire envelope is lost by wind before its radius reaches the lobe radius, and a region of shorter P where RLOF is drastic because the mass loss was not sustained long enough to

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violate condition (3). Fig. 1 also illustrates the possible importance of magnetic braking, since the difference between parts (a) and (b) of the Figure is whether the Alfvén radius of the flow from the primary is one or two times the primary's radius.

Examples of possible 'undersize giants' have been in (and out of) the literature for a number of years. Undoubtedly it can be difficult to tell from a light curve whether the cool component fills its Roche lobe or is, say, 10 - 20% smaller. Nowadays, if spectroscopic evidence suggests the cooler star is much less massive than the hotter, the reasonable presumption tends to be made that it fills its Roche lobe. We would not quarrel with this, but feel it is quite possible that there may be slightly detached systems with mass ratios already reduced from $q_0 > 1$ to $q \sim 0.5$ or even less. The systems SX Cas, RX Cas and UX Mon all seem like possible cases. Two somewhat wider binaries, V643 Ori (K7III + K2III; 1.9 + 3.3 $M_\odot$; 52.4 d; eclipsing; Imbert 1988) and RZ Oph (MIII + F5Ib; 0.7 +5.7 $M_\odot$; 41 + 5$R_\odot$; 262 d; Knee *et al.* 1986) seem like further possible examples. Both of these *may* have had an episode of RLOF, followed by shrinkage of the primary after helium ignition, but equally, they *may* have reached their present mass ratios by means of tidally-enhanced wind.

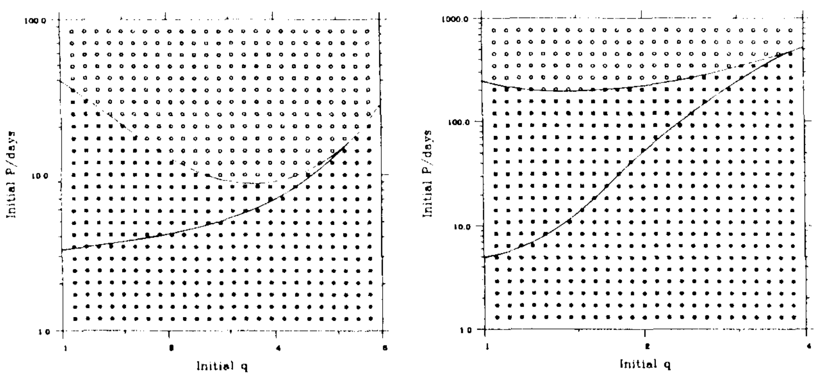

Fig 1: How RLOF may commence in pre-Algols subject to binary-enhanced stellar wind and magnetic braking, for a grid of initial mass-ratios and periods. The initial primary mass was 2 $M_\odot$ in all cases. Open circles: primary reduced to white dwarf without RLOF. Squares: mild RLOF, because q is reduced below 0.7 before RLOF. Filled circles: drastic RLOF. The primary's Alfvén radius is (a) equal to, (b) twice, the stellar radius.

Under heading (ii), the statistics of well-detached red giant binaries have been commented on by Griffin (1985), who concluded that the frequency of spectroscopic binaries per unit interval of log P *increases* with P, at least between $10^{1.5}$ and 10^4 days, contrary to what has often been claimed earlier. He also concluded that $\sim$ 25% of a reasonably unbiased (as to binarity) sample of K giants are spectroscopic binaries with $P \lesssim 10^4$ d. Most of these will have periods $\gtrsim 10^2$ d and so will be 'moderately wide'. We believe it is important to note from this that arguably 20% of *all* G, K giants, and not just giants known to be binary, are 'moderately wide' binaries.

We collected data from the literature for 169 spectroscopic binaries where one component has spectral type G4 - K9 II - IV, and where $P > 10^{1.5}$ d. We excluded known

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interactive systems (Algols, symbiotics), and we also excluded Ba stars, and a handful of binaries with an observed white dwarf or hot sub-dwarf component. The set includes 11 double-giant binaries (Griffin 1986), but each has been counted only once, under its more evolved component; and it excludes a handful of known triples, where the companion of the giant is a known short-period binary. The 169 entries are shown in Table 1. They show clearly a trend to lower mass-functions at longer periods up to $10^{3.5}$ d; beyond that, not many orbits are published, and the observational cut off (which we take somewhat arbitrarily at $K \sim 2$ km/sec) would remove the bulk of the orbits if the trend at shorter periods continued. Table 1 includes a comparison with continuous theoretical distributions of mass and mass-ratio that have (a) 45%, (b) 80% and (c) 97.5% of mass ratios in the range 1 to 2. It can be seen that the distributions at $\log P \sim 3.25$, 2.75 and 1.75 roughly resemble (a), (b) and (c) respectively, except that all the observed columns show more objects in the bin for $\log f = -0.25$ than any of the theoretical distributions. Possibly this is still part

Table 1. Distribution of periods and mass-function in red-giant binaries

			log P					model	
log f	1.75	2.25	2.75	3.25	3.75	> 4	(a)	(b)	(c)
0.25	1	-	1	-	-	-	-	-	-
-0.25	5	2	8	5(1)	1	2	5	19	43
-0.75	11	13	12(1)	5	4	-	125	274	480
-1.25	6	9	13(1)	12(3)	2	1	261	368	280
-1.75	3	4	7(3)	12(2)	1	-	250	181	119
-2.25	2(1)	1	2(1)	9(2)	-	X	186	88	44
-2.75	1(1)	2	7	2	X	X	83	38	18
<-3	-	1	2	X	X	X	90	32	16
Total	29(2)	32	51(6)	46(8)	8	3	1000	1000	1000

Entries are binned in half-decades of period and mass function
X - not observable with $K \lesssim 2$ km/sec
() - systems with a Ba star and/or WD (or hot SD) component.

of the obvious selection effect of large velocity variations, though it may also reflect the inadequacy of the theoretical distribution. It could also mean that either (a) some red giants have already lost significant amounts of mass (as we argue for V643 Ori above), or (b) some may have companions which are themselves binary, as in β Cap (K0II-III + (B8V + ?; 8.7d); 1373d, f = 1.1 $M_\odot$, Sanford 1939).

Under (iii), we put objects, of which T CrB, V748 Cen and CI Cyg are examples, where an M giant either fills its Roche lobe or is very close to it, and the companion is at least arguably a main sequence star. Unfortunately, it is very hard to distinguish observationally the situations where (a) a main sequence star is accreting at (say) $10^{-6}\,M_\odot$/yr, and (b) a white dwarf is accreting at $10^{-8}\,M_\odot$/yr (Kenyon & Webbink 1984). In both cases the main luminosity from the gainer is liable to be from an accretion disc. T CrB in particular (M3III + Be:; 2 + 1.6 $M_\odot$; 228d; Kraft 1958, Kenyon & Garcia 1986) has reasonably well-

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determined minimum masses, and since there is a fairly pronounced ellipsoidal variation (though no eclipse) it is likely that the giant is close to, or at, its Roche lobe. Since the mass ratio satisfies (3) we should expect drastic RLOF. But what is seen, of course, is recurrent nova outbursts, apparently due to intermittent mass transfer (Webbink 1976). On the one hand, this could be telling us that drastic RLOF does not lead to common envelope evolution, but instead to a pulsed mass transfer which may in the long term average to something like nuclear or thermal timescale RLOF. On the other hand it could be that the system is slightly detached, and that the recurrent nova outbursts reflect enhanced activity in the giant, caused by tidal interaction, or else reflect pulsational instability. Lines *et al.* (1987) have found a semi-regular pulsation in T CrB of about 55d, superimposed on the ellipticity effect with orbital period. It seems reasonable to suppose that occasionallly, *i.e.* about every 30 yrs, a pulsation is large enough to trigger a pulse of mass transfer. Alternatively, or in addition, the instability mechanism of Bath (1975) may be relevant. Presumably the primary has already lost some mass by stellar wind (and the secondary gained a proportion of it). Further mass loss of 0.5 to 0.8 $M_\odot$ could lead to fairly quiet RLOF; a smaller amount might lead to drastic RLOF.

Under heading (iv) there are Algols, of which AR Mon (K3 + K0; 0.8 + 2.7 $M_\odot$; 14 + 11 $R_\odot$; 21.2 d; Popper 1980) is a clear example, that must have started mass transfer in late Case B, and thus should under conservative assumptions have suffered drastic RLOF. Since both components of AR Mon are giants, it is almost certain that the initial mass ratio was within 5% of unity. Thus if its evolution had been conservative its initial parameters would have been roughly (1.8 + 1.7 $M_\odot$; 7.5d), and the primary would have been well advanced on the giant branch before RLOF began. We suggest however that at least the detached portion of the evolution involved enhanced stellar wind from the primary (and also, in this case, from the secondary, although less since the secondary is always further within its Roche lobe). Thus the initial configuration may have been more like (2.3 + 2.2 $M_\odot$; 5.1d), evolving towards (1.4 + 2.1 $M_\odot$; 8.4d) at the onset of RLOF. With this estimate q is reduced from 1.05 to 0.67 before RLOF, condition (3) is violated, and so RLOF is a mild process, taking place on a nuclear timescale. In practice, we think that magnetic braking as well as enhanced stellar wind will influence the detached phase, so that the initial orbital period might well have been 10d rather than 5d. It is also rather likely that both the enhanced wind and the magnetic braking continue *during* RLOF. One consequence of this could be that the rate of evolution during the semidetached phase would be speeded up, to the shortest of the nuclear, mass loss, and magnetic braking timescales. That some Algols lose significant angular momentum during RLOF is illustrated by AS Eri (K0 + A3; 0.2 + 1.9 $M_\odot$; 2.2 + 1.8 $R_\odot$; 2.7d; Popper 1980, Refsdal *et al.* 1974), which has too little angular momentum at present to have ever been two detached main sequence stars.

Under (v), the possible post-Algols that we would draw attention to are systems such as FF Aqr (SDOB + G8III; 9.2d; Dworetsky *et al.* 1977), V651 Mon (SDOB + A5V; 16.0d; Méndez and Niemela 1971), HD185510 (SDB + K2III; 20.7d; Balona 1987) and AY Cet (WD + G5IIIe; 56.8d; Simon *et al.* 1985). These systems are not unlike what we would expect as the aftermath of Algol evolution, when the loser has lost all of its envelope and the hot core is exposed. But the periods are all rather shorter than we would anticipate if RLOF were conservative. We suggest that modest angular momentum loss by magnetic braking is responsible for this. Some of the above four systems, and especially V651 Mon, which is the central star of the planetary nebula NGC 2346, might be supposed to be remnants of 'common envelope' evolution, *ie* of an initially much wider system. We wish to emphasise that the same kind of remnant can be achieved by the milder process of binary-enhanced stellar wind with magnetic braking. That the mass lost in the wind should form a planetary nebula once the hot core is exposed is not surprising in either case.

We are not arguing, however, that common envelope evolution, under heading (vi), never takes place – only that it may not be easy to distinguish its products from the products of Algol-like evolution with magnetic braking. In fact, the mass of the WD, or hot SD, is probably the critical determinant. Common envelope evolution almost certainly requires a highly evolved red giant and hence a fairly massive WD ($\gtrsim 0.6\,M_\odot$, Livio & Soker 1984b), while the remnant of a magnetically-braked Algol will be little more than $0.3\,M_\odot$, and perhaps $< 0.2\,M_\odot$, as must be the case for AS Eri. All of the four 'post-Algols' of the previous paragraph have small mass-functions (0.002 to $0.02\,M_\odot$), roughly consistent with the low masses we suggest for the WD/SD. On the other hand, V471 Tau (WDA + K2V; $f_K = .178\,M_\odot$; 0.52d; Young 1976, Bois *et al.* 1988) has a relatively high mass-function, and is a prime candidate for the outcome of common envelope evolution. Other likely examples are UU Sge and V477 Lyr, the eclipsing SDO cores of the planetary nebulae Abell 46 and Abell 63 (Bond *et al.* 1978, Grauer & Bond 1981). But there are some pre-cataclysmics, such as AA Dor (SDO + ?; 0.25: + 0.05:$M_\odot$; 0.26d; Kudritzki *et al.* 1982) and V Sge (WN5 + A5?; 0.8 + $2.8\,M_\odot$; 0.51d; Herbig *et al.* 1965), which do not fit well (Eggleton 1983) into either the common-envelope (Paczyński 1976) or the star-planet (Livio & Soker 1984b) scenarios.

An especially interesting recent observation relating to the possible formation of CVs by common-envelope evolution is of the triple system 4 Dra (Reimers *et al.* 1988), containing an M giant in orbit with a CV: ((WDe + ?; 0.166d) + M3III; 1703d). A quick reaction is that the sub-binary precursor of the CV will not have been anything like as wide as one would have liked to suppose. For in most triples the period ratio is $\gtrsim 100$ (Fekel 1981; eg β Cap referred to earlier), and so the ancestor of the CV might be expected to have had a period of 10 to 30d, say. However, even though no triple is known with a period ratio < 8, an initial period as large as 500d for the subsystem would still have been possible without dynamically disrupting the larger orbit (Bailyn 1984). We do not therefore have a complete contradiction of the current view that CVs descend from 'moderately wide' binaries via common envelope evolution.

Under heading (vii) we have the very interesting hypothesis, first suggested by McClure *et al.* (1980), that all Ba stars are binaries with white dwarf companions, and that the Ba comes from nucleosynthesis in the companion before it became a white dwarf. The direct evidence of binarity (viz. spectroscopic orbits, for about a dozen Ba stars by now) is quite compelling, as is the fact that WD companions have been recognised directly in the UV in two cases, ζ Cap and ζ Cyg (Böhm-Vitense 1980, Dominy & Lambert 1983). However WD companions are also known for non-Ba red giants, including some which have occasionally and apparently mistakenly been labelled Ba stars, for example 56 Peg, ξ^1 Cet, a Pup. The last two have orbital periods (1642d, Griffin & Herbig 1981; 2660d, Christie 1936) which lie in much the same range as Ba stars (458 to 2300d, with one at 81d). Significant difficulties with McClure's hypothesis have been noted by Luck & Bond (1982), and Dominy & Lambert (1983). Recently the hypothesis has been somewhat reinforced by the discovery of similar binarity among S stars: BD Cam (WD + S3.5; 596d; Griffin 1984, Peery 1986), and o^1 Ori (DA3 + S3.5; Ake & Johnson 1988). However Ake and Johnson (1988) note that one WD found in 5 S stars that they looked at is no different from normal field giants. A recent study of S and MS stars (Smith & Lambert, 1988 preprint) appears rather favourable to McClure's hypothesis: some S giants show Tc, and so are presumably *currently* s-processing, while others do not show Tc, and are presumably descendants of Ba stars, not quite evolved enough yet to do their own further s-processing. Stars of the latter category would have to have WD companions, but stars in the former category need not be binary at all.

Table 1 includes in brackets 12 Ba binaries with known orbits, and 5 binaries with known WD companions (ζ Cap being both). Their distribution of f in the bins at P = $10^{3.25}$d is not very different from the other systems, but there is more difference (saving small numbers!) at shorter periods, in the direction expected. The rough agreement at P = $10^{3.25}$d might be interpreted *against* McClure's hypothesis, as showing that the two populations are basically the same, *ie* that Ba stars and ordinary G/K giants have main sequence and WD companions in much the same ratio. However, it would not be especially surprising if the average mass of WD companion left behind by an s-processing red giant, say $0.75\,M_\odot$, was much the same as the average mass of main-sequence companion for G/K giants, given the trend towards less equal masses at longer periods that we have already seen. Note that if for the sake of argument there were no RLOF at all, so that binary components evolved independently, then the ratio of WD companions to main sequence companions for red giants would depend just on the distribution of initial mass-ratios: it would be about 0.4 for the distribution of mass-ratios giving column (a) of Table 1, and close to unity for column (c).

Independently of whether Ba stars *all* have WD companions, the fact that any red giant or indeed main sequence star has a WD companion with P $\sim 10^3$d is important in telling us that spiral-in of some sort is not the inevitable outcome of late Case C evolution. In fact spiral-in can quite easily be avoided through the agency of companion-enhanced wind, at least for systems with $1 \lesssim q_0 \lesssim 2$ (Fig. 1). It may also be avoidable if the mass transfer is pulsed, as may be suggested by T CrB (above). A particularly interesting binary in this context is a Pup (SDB6 + K1-2II+a; f_K = 0.35 $M_\odot$; 2660d; Christie 1936, Parsons *et al.* 1976, Hoffleit 1982). Because both a hot SD and a K supergiant are short-lived states, it is likely that this system started with quite closely equal masses. The large mass-function (which however may be very uncertain; see Batten *et al.* 1976) suggests that if the SD has less mass than the Chandrasekhar limit then the giant is less massive still, presumably because of wind. Following this line, the system seems destined to produce a second WD less massive than the first, and this suggests the system is closer now than it was originally, *ie* that some angular momentum as well as mass has been lost. We believe that this interesting binary would repay further observational as well as theoretical work.

Binaries like a Pup and ζ Cap must be heading for a second symbiotic stage, under heading (viii), having presumably had a first symbiotic stage, under heading (iii). Plavec (1982) has distinguished these two stages as 'Algol-like' (first) and 'nova-like' (second). In a conservative picture the second stage would presumably be even more likely to be drastic than the first, since the mass ratio would be likely to be more extreme. But having inferred from a Pup that the present giant may already be less massive than its hot SD companion, we can see that a non-conservative picture might allow both stages to be mild episodes of RLOF, or might even prevent RLOF in one or both stages. Unfortunately for no symbiotic that can be put (at least arguably) in the 'nova-like' category can one check condition (3), for instance, or determine whether the giant completely fills or only half fills its Roche lobe.

The outcome of this second interactive stage has been variously suggested as a supernova (Sparks & Stecher 1974), an R CrB (Webbink 1984), or a close pair of white dwarfs

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like GP Com (Nather 1985). These all assume a drastic kind of interaction, however, followed by spiral in (and complete coalescence in the first two cases). But given that drastic RLOF is apparently quite often avoided first time round, a more likely outcome from the second time round would be a moderately wide white dwarf binary. Greenstein (1986) discussed cpm pairs of WDs at some length. But only one system that we are aware of has an orbital period in the 'moderately wide' range: EG52 (DC9 + DC9; 20.5yr; Harrington *et al.* 1981). Many selection effects must militate against discovering such systems if they have shorter periods, until one gets to periods in the CV range of a few hours, or minutes; although Thackeray (1970) found an SDO binary in which he speculated that the companion is unseen because it is a WD: HD 49798 (SDO6 + ?; 1.55d; $f_O = 0.27\,M_\odot$). We suspect that WD + WD binaries with periods intermediate between 1d and 20yr may be the most common final outcome of moderately wide binaries.

3. CONCLUSION

What can we say of the nature, and outcome, of interaction in binaries where the primary becomes a red giant, with deep convective envelope, substantially before interaction takes place? Under conservative assumptions, at least prior to RLOF, we expect something rather drastic, with perhaps three main possibilities: (a) common envelope, then spiral-in, then a pre-cataclysmic or cataclysmic binary; (b) common envelope, then spiral-in, then coalescence; or (c) pulsed mass transfer, *averaging* as fairly slow RLOF, and perhaps restablishing an eccentricity which had previously been diminished by tidal dissipation. The last of these might be reasonably conservative, in the sense that the fractional systemic mass loss and angular momentum loss might be modest. There is some evidence that each of these possibilities may apply in different systems, perhaps with initial mass ratio being the main discriminant. However, two further possibilities seem open if in fact the evolution prior to RLOF is non-conservative: (d) mild mass transfer, on a nuclear timescale (or on a magnetic braking timescale, which might be substantially shorter) leading to an ordinary Algol; or (e) no RLOF at all though perhaps some mass transfer), because all of the primary's envelope is lost by wind while the system is still detached. In cases (c) to (e) the product can be a fairly wide binary containing a white dwarf, and in this case the evolution of the *secondary* may lead to a similar series of options. At least one of these, analogous to (c) - (e), must allow the system to end as a wide pair of WDs; while some other, presumably analogous to (a), may be responsible for interactive ultra-short-period pairs of WDs. The ramifications, however, are clearly capable of great complexity. We believe that in the present state of knowledge it would be a rash person who claimed to see how a particular specimen of moderately close or moderately wide binary would complete its evolution.

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DISCUSSION

Livio and Plavec, while conceding the attractions of a model for T CrB involving pulsed mass-transfer onto a main-sequence star, sounded some notes of caution. Livio cited work by Selvelli, Casattella and Gilmozzi, presented in Torun in 1987, who had examined the C IV emission line in the spectrum of T CrB and found that it was quite invisible at high dispersion. They interpreted this as meaning that line was so broadened as to be indistinguishable from the continuum. This in turn implies material moving with velocities of some thousands of km s^{-1}, which could be an indication that the accreting star is a white dwarf. Plavec said that scans in the optical region made by himself and C.D. Keyes did not show the flux to be expected from a main-sequence star. He felt that the case is still wide open. Eggleton agreed but pointed out that S.J. Kenyon and M.R. Garcia (Astr. J. **91**, 125, 1986) had found rather strong evidence for a massive hot star, and it seemed to him that the masses of this system were somewhat better determined than those of many symbiotics - although he personally would prefer T CrB to be a "nova-like" symbiotic rather than an "Algol-like" one! Hall remarked that a recent paper by H.C. Lines, R.D. Lines and T.G. McFaul (Astr.J. **95**, 1505, 1988) gave evidence of photometric variations that suggested the late-type star was a semi-regular pulsating variable. This supported the idea of pulsed-transfer since the variable might only occasionally overflow its Roche lobe, thus producing dramatic but brief episodes of mass-transfer and the recurrent nova outbursts. Hall also commented that in chromospherically active stars it is rapid rotation, rather than tidal interaction itself, that enhances the stellar wind. Eggleton accepted the point but stipulated that tidal interaction in RS CVn stars appeared to be the cause of the rapid rotation.

Tomkin referred to Webbink's statistical comparisons of eccentricities and mass-functions of barium-star binaries with those of otherwise similar systems containing red giants that are not barium stars (this work was reported at the 1985 Beijing conference). Webbink found that the barium-star binaries have smaller orbital eccentricities and mass-functions - both of which favour the conclusion that all barium stars have white-dwarf companions. Eaton referred to McClure's thorough discussion of this matter, just presented at I.A.U. Colloquium 106 in Bloomington, Indiana. McClure has found it very likely that all barium stars, CH stars and CH subgiants are binaries. His statistical results are similar to Webbink's but based on a much larger sample. In Eaton's opinion, however, the relation between the binary parameters and the spectroscopic peculiarities is not clear. Eggleton replied that he had not yet seen either of the papers just referred to. His own result, based on a comparison of barium stars with normal giants only in the approximate period-range 300^d to $3{,}000^d$ suggested that there is not a clear difference in the distributions of the mass-functions. He thought it very probable that barium-star companions were indeed always white dwarfs, and would be happy to be completely persuaded. If, however, even one barium star turns out to have a main-sequence companion, it becomes difficult to explain the connection between their duplicity and their unusual spectra.

Plavec remarked that strong support for the general idea presented by Eggleton and Tout is provided by the work of Friend and Castor, who developed a theory of a strongly enhanced stellar wind which is also strongly anisotropic (focussed toward the companion star and imitating Roche-lobe overflow, even when the "windy" star is large but not filling its Roche lobe).