THE ORIGIN AND EVOLUTION OF CATACLYSMIC BINARIES*

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ABSTRACT

Some cataclysmic binaries may be products of Case C evolution of low mass stars (orbital period $\sim$ 1 yr; masses $\sim$ 1 - 4 $M_{\odot}$), involving a common envelope phase. Other mechanisms, probably involving late Case B and even early Case B, but with significant loss of angular momentum, may be necessary to account for some evolved binaries such as AA Dor or V Sge. Further angular momentum loss, probably by magnetic braking coupled with tidal friction, causes secular evolution in cataclysmic binaries. It is suggested that tidal friction may account for the shortage of cataclysmics with periods $\lesssim$ 1.3 hr; but this cutoff, as well as the gap in the period distribution between 2 and 3 hrs, is hard to explain and imposes more severe constraints on possible theories than is commonly acknowledged.

1. INTRODUCTION

Cataclysmic binaries were presumably young binaries once, but it has long been difficult to see clearly what kind of young system evolves into the typical close white dwarf/red dwarf configuration of a cataclysmic binary. Kraft (1963) suggested W UMa systems, whose angular momenta and galactic distribution are similar; but it seems more likely (Webbink 1976, Robertson and Eggleton 1977, Bopp and Rucinski 1981) that W UMa binaries evolve into single rapidly-rotating red subgiants. Current thinking, stimulated largely by Paczyński (1976), is that the binary was once wide enough to have contained a red supergiant, with the present white dwarf as its core. The main sequence secondary, after causing Case C (or very late Case B) mass transfer, became rapidly embroiled in the distended convective supergiant envelope, and spiralled inwards within a differentially rotating "common envelope". It is necessary to suppose that this spiralling-in

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process removed just enough angular momentum from the orbital motion (depositing it in the common envelope) to reduce the orbital period from $\sim$ 100 days to $\sim \frac{1}{2}$ day, and that the gravitational energy released in this process was efficiently directed into blowing off the common envelope before the period could become so short that the two cores might coalesce.

It seems likely, but perhaps not inevitable, that some kind of common envelope phase occurs if a binary starts with such a period that Case C mass transfer is to be expected. It is less clear, however, that what will emerge from the common envelope will be a cataclysmic binary, or something closely related. But the idea received strong support from the discovery of a short-period eclipsing binary (UU Sge, Miller *et al.* 1976) at the centre of a planetary nebula (Abell 63) shortly after Paczyński (1976) suggested this kind of evolution. UU Sge, however, is sufficiently wide that it will have to lose a significant further amount of angular momentum before it can become cataclysmic; this might be by a combination of magnetic braking (by stellar wind) and of tidal friction (Huang 1966, Eggleton 1976, Verbunt and Zwaan 1981).

In Section 2, possible evolutionary paths are discussed for systems of fairly low mass and long period. In Section 3, various systems are described which might be thought of as post-common-envelope, pre-cataclysmic binaries. In Section 4 I discuss the period gap in the distribution of cataclysmic binaries. This gap has very important implications for the evolutionary precursors of cataclysmics. Section 5 summarises the main conclusions.

2. EVOLUTIONARY PATHS FOR LONG-PERIOD LOW-MASS BINARIES

Figure 1 shows, very schematically, three evolutionary paths which might start from systems with initial periods $\gtrsim$ 100 days, and with component masses sufficiently low that either star on its own would evolve to a white dwarf rather than a supernova, neutron star or black hole. An obvious fourth path, where the separation is too great for any significant interaction to happen, is omitted. It will, in the long run, save space if I use a shorthand to describe various types of system, thus:-

MM; D - Main sequence star + Main sequence star; Detached
MS; S - Main sequence star + Supergiant; Semidetached
SW; C - Supergiant + White dwarf; Common envelope.

The other acronyms can be inferred from these. The paths in Figure 1 are based on the assumption that any Roche lobe overflow from a red supergiant (i.e. Case C or possibly late Case B) will be followed by formation of a common envelope, with spiralling-in. If this assumption is not correct other possible paths would have to be considered, but they would also have to involve substantial angular momentum loss (hereinafter "AML") if they are to lead to cataclysmic binaries.

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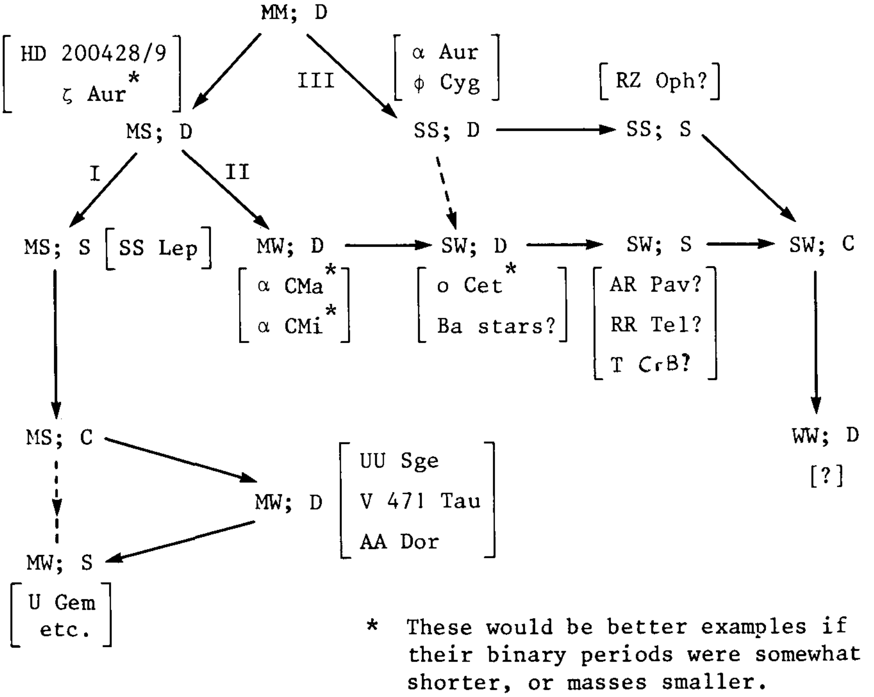

Figure 1. Schematic paths of binary evolution, for systems of low mass and fairly long period (P ∿ 100 – 1000d). Path I may apply to shorter periods within this range and Path II to longer periods. Path III may apply to systems of closely equal initial mass. Acronyms such as "MM;D" are explained in the text (beginning of Section 2). Possibly typical systems at various stages are indicated in brackets.

Path I refers to systems with periods of perhaps 100-300 days, systems which interact strongly when the initial primary becomes a supergiant. Shortly before this interaction we might have an MS;D system like ζ Aur, although this well-known binary is perhaps more massive, and has a longer period, than we would like. A better example would be HD200428/9 (KO III + A5 V, P = 113d, Griffin *et al.* 1976). Once the system becomes semidetached (MS;S) the convective character of the loser's envelope may ensure a rather drastic phase of Roche-lobe overflow followed by a common envelope phase (MS;C). What emerges will hopefully be something of the character of UU Sge (MW;D), which may after further AML become a cataclysmic binary (MW;S).

Path II starts with somewhat longer periods (maybe 300-1000d), so that the initial primary becomes a supergiant (MS;D) and then a white dwarf (MW;D) before significant interaction takes place. Then the companion evolves to a supergiant (SW;D), and some interaction begins to take place, initially between the white dwarf and a wind from the supergiant but later from Roche lobe overflow (SW;S). There are several types of observed system which are thought (Starrfield *et al.* 1976, Tutukov and Yungelson 1976, Paczyński and Rudak 1980) to consist of interacting white dwarf/red supergiant pairs,, i.e. symbiotics (like Z And), slow novae (like RR Tel) and recurrent novae (like T CrB). Some of these systems are possibly semidetached, but others are almost certainly detached, with wind rather than overflow providing the observed line-emitting gas. But once overflow begins it may become drastic, as on Path I, and be followed by a common envelope phase (SW;C). Presumably, by analogy with Path I, this leads to the blowing off of the envelope, leaving a close detached pair of fairly massive white dwarfs (WW;D). However, Sparks and Stecher (1972) suggested that the outcome of a rather similar scenario would be the coalescence of the two white dwarf cores, which could lead to a single core exceeding the Chandrasekhar limit and hence to a supernova. This seems at least as plausible an outcome. If it were correct, it rather suggests that at the analogous stage in Path I the main sequence companion would simply be disintegrated as it spiralled in very close to the white dwarf core. It is a major problem with the common envelope model to see why the envelope should dissipate at the convenient separation rather than too early or too late.

Path III refers to systems with nearly equal initial masses, so that both stars evolve into giants and supergiants at about the same time (SS;D). This might seem to require improbably nearly equal masses, but some systems (α Aur, ϕ Cyg) achieve this all the same. Even so, when the components begin to interact one will probably be appreciably larger than the other and become the loser in a Roche lobe overflow (SS;S), as appears to be the case for RZ Oph (Hiltner 1946). This could lead to a common envelope (SS;C), which would probably not be different in principle from the SW;C step in Path II, and so might also lead to a close pair of white dwarfs (WW;D). Alternatively, particularly if the period were a little greater, the more advanced supergiant may blow off its envelope as if it were single, to leave a white dwarf (SW;D), which also links up with Path II.

Figure 1 was drawn up partly on the basis of what might be expected theoretically, assuming the common envelope mechanism, and partly on the basis of what kinds of systems are observed. There seem to me to be at least three discrepancies between these two approaches, which may have to be resolved. On Path I, there are several known systems in the last two states (MW;D and MW;S) and yet a shortage, as far as I can tell, in the preliminary stage MS;S. This might only mean that the MS;S stage is very short-lived, whereas the two later stages can apparently be quite long-lived. However, on Path II one sees several types of system which have been attributed to the analogous SW;S phase (or perhaps to a slightly earlier phase when the supergiant is close to filling its lobe), and one would expect this phase to be about equally short-lived. On the other hand there are no known WW;D systems to belong to the end of Path II. Such systems would be hard to recognise, of course, but not necessarily harder than some of the close MW;D systems like UU Sge (see Section 3). This point makes me wonder if several symbiotic and related systems contain accreting main sequence stars rather than white dwarfs, the accretion process heating them up so that they somehow resemble hot blue subdwarfs.

A second point, reinforcing the first though independent of it, is that one might not expect Path II to be followed at all. For if the binary was close enough to interact during the SW;D stage, it was presumably already close enough to interact at the earlier MS;D stage, and so to follow Path I. This might be another reason for supposing that symbiotics etc. contain main sequence stars rather than white dwarfs; but it may also be that there is some AML when a supergiant in an MS;D binary blows off its envelope on the way to becoming a white dwarf (the main sequence component giving some of its orbital angular momentum to the proto-planetary nebula), so that the remaining system is somewhat closer in the SW;D stage than in the earlier MS;D stage. Since the separation is proportional to the square of the angular momentum, a modest amount of AML goes a fairly long way.

A third point derives from the binary RZ Oph (no. 700 in the catalogue of Batten *et al.* 1978), which appears to be a semidetached pair of supergiants (F3 Ib + K5 Ib, P = 262d). The system is surprisingly like a normal Algol (Hiltner 1946), despite considerably greater radii, and so seems to imply that Case C mass transfer need not always be drastic. However, the system presumably started with nearly equal masses; and since the more evolved star may have lost some mass by stellar wind before filling its Roche lobe, the primary may have already been the less massive component before it began to overflow. Hence its convective envelope may not have been faced with the usual difficulty of trying to fill a contracting Roche lobe while wanting to expand in response to mass loss.

An alternative picture of RZ Oph is that the hotter supergiant is actually a bloated accretion disc or ring around, say, a main sequence star. If so, the initial masses were presumably less closely equal, so it is the more surprising that the onset of mass transfer did not, apparently drive the system into a common envelope. The same conclusion appears to follow if the gainer is a bloated white dwarf rather than main sequence star. Generally, it seems possible that systems starting with equal or moderately unequal masses may avoid the common envelope phase if the primary suffers substantial single-star mass loss as a red supergiant before filling its lobe.

I shall argue in the next two sections that many of the low-mass main sequence components of cataclysmic binaries and UU-Sge-like systems must have been low-mass M dwarfs (or even black dwarfs) all along, and not just because they lost mass during and after the common envelope phase. This leads me to suppose that there should be a class of MS;D and MS;S binaries in which the main sequence component is an M dwarf.

Table 1

Name (Name 2)	Period (days)	Spectra	Binarity indicator*	Mass Function	Notes	Ref
NGC 2346	16.0	AV† + SDOB?	SB1	.007	a,b	1
BD $-3^{\circ}5357$ (FF Aqr)	9.2	G8III† + SDOB	ecl,SB1	.019		2
NGC 1630 (CPD $-26^{\circ}389$	8.21	? + SDO†	SB1	.19	a	3
Feige 24	4.23	MVe† + WDOBe	SB1	.13		4,5
PG 1155+492 (BE UMa)	2.29	? + SDOBe†	ell,SB1	.20		6,7
Case 1	0.67	M2Ve† + WDA	SB1	.11		8
HZ 22 (UX CVn)	0.57	? + SDB†	ell,SB1	.13		9,10
HZ 9	0.56	M4.5Ve† + WDA	SB1	.12	c	11
BD $16^{\circ}516$ (V471 Tau)	0.52	K2V† + WD	ecl,SB1	.18	c	12,13
V Sge	0.51	AVe? + SDOBe	ecl,SB2	2.8+0.75	b,d	14
Abell 46 (V477 Lyr)	0.47		ecl		a	15
Abell 63 (UU Sge)	0.47	KV + SDO	ecl		a	16,17
PG 1413+01 (GK Vir)	0.34	M2V + WDOB	ecl			18
LB 3459 (AA Dor)	0.26	WDe? + SDO†	ecl,SB1	.001	b	19,20,21
NGC 6826	0.24	? + SDOBe†	SB1		a	22
Abell 41	0.11		ell		a	23

* SB1, SB2 = single-lined, double-lined spectroscopic binary; ecl = eclipsing; ell = "ellipsoidal" light variations.

† the component with measured radial velocity amplitude (if SB1).

Notes
a. Nucleus of planetary nebula
b. Spectral type of one component conjectural (see text)
c. A member of the Hyades
d. Possible contact binary; m $\sin^3 i$, not mass function, in previous column.

References on next page.

Clearly such a companion would he hard to recognise next to an M supergiant; but if heated by accretion could it nevertheless resemble the kind of hot blue object seen in symbiotics, as much as would a more massive main sequence star or a white dwarf?

3. DETACHED BUT CLOSE BINARIES WITH A WHITE DWARF OR SUBDWARF COMPONENT

In Table 1 some information is listed for a collection of sixteen somewhat heterogeneous objects, whose only common factors are that (a) one component appears to be the highly evolved remnant of something which was presumably once a red giant or supergiant (b) they are detached (c) the period is sufficiently short (except perhaps for the first three objects) that it is hard to see how a giant, let alone supergiant, could have been contained in the system unless there has been considerable AML. Six of these objects are in planetary nebulae. These six might be thought to have just emerged from a common envelope, while the other ten may be somewhat older so that the nebula has dissipated. Do they all look like the expected products of common envelope evolution? My own view is that some do (e.g. V471 Tau) and some do not (e.g. AA Dor).

In NGC 2346, it is not clear (Mendez and Niemela 1981) that the second component of the 16d spectroscopic binary is the subdwarf OB star which excites the nebula: the system might conceivably be triple, with the hot subdwarf some substantial way away from the single-lined spectroscopic binary. Triple systems are not at all rare, of course, but Mendez and Niemela opt for the less complicated possibility. In AA Dor, the secondary is thought (Conti *et al.* 1981, Kudritzki *et al.* 1982) to be essentially a black dwarf of very low mass (perhaps $\sim 0.05\ M_{\odot}$, given the low mass function despite an inclination high enough to give eclipses). The black dwarf shines mainly by reflected light, to give the spurious appearance of a second hot subdwarf; it should be thought of as a failed main sequence star rather than as the white dwarf remnant of an evolved star. In V Sge, Herbig *et al.* (1965) suggested both components were hot stars below the main sequence. However, a re-analysis of their light-curve (Wilson and Eggleton, to be published)

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1. Mendez & Niemela (1981)
2. Etzel *et al.* (1977)
3. Mendez & Niemela (1977)
4. Margon *et al.* (1976)
5. Thorstensen *et al.* (1978)
6. Margon *et al.* (1981)
7. Ferguson *et al.* (1981)
8. Lanning (1982)
9. Young *et al.* (1972)
10. Greenstein (1973)
11. Lanning & Pesch (1981)
12. Nelson & Young (1970)
13. Nelson & Young (1976)
14. Herbig *et al.* (1965)
15. Grauer & Bond (1981)
16. Miller *et al.* (1976)
17. Bond *et al.* (1978)
18. Green *et al.* (1978)
19. Kilkenny *et al.* (1978)
20. Conti *et al.* (1981)
21. Kudritzki *et al.* (1982)
22. Noskova (1980)
23. Grauer & Bond (1982)

suggests the possibility that (a) the system is in contact, rather than semi-detached, and (b) the secondary also shines mainly by reflected light, so that its true nature may be a fairly normal star of spectral type ∿ A V, roughly in accordance with the mass estimate of Herbig *et al.* (1965), and with the radius implied by Roche geometry. The primary has to be considerably more luminous than most of the other hot objects in Table 1, in order to be as hot as observed and yet to fill its Roche lobe, so it is probably a helium burning core with a hydrogen burning shell; it may resemble the expected remnant of a star of ∿ 5 $M_\odot$ which has lost its envelope during core helium burning. Note, however, that the minimum masses in Table 1 should be taken with some reserve, as explained by Herbig *et al.* (1965).

Possibly the hardest object to explain in terms of common envelope evolution is AA Dor, although a lot hinges on the mass estimates (Kudritzki *et al.* 1982) of ∿ 0.25 $M_\odot$ for the SDO component and ∿ 0.05 $M_\odot$ for the putative black dwarf. These estimates were based on eclipse geometry, as well as the mass function, and give fairly consistent radii if the SDO component still has a hydrogen burning shell. Such an object would be the remnant of a subgiant, rather than a giant or supergiant. Presumably the subgiant lost an envelope of ∿ 0.75 $M_\odot$. Could such a massive envelope have been ejected by the spiralling-in of such a small companion? There does not appear to be enough orbital energy available, even if this was directed with 100% efficiency into mass loss. It seems more likely, in this case, that the inherent tendency of a giant or subgiant to lose mass slowly, by stellar wind, was somehow enhanced by the presence of a small (but possibly close) companion, much as subgiant companions in RS CVn binaries show unusually strong chromospheric activity (Walter and Bowyer 1981). Indeed, some RS CVn's show evidence for the loss of ∿ 0.1 - 0.2 $M_\odot$ (Popper and Ulrich 1977) from the more evolved subgiant component. Perhaps in AA Dor the black dwarf spiralled in within the comparatively rarefied "envelope" of the wind emanating from the subgiant, rather than within the relatively dense "envelope" of the subgiant's outer regions. Note that it is only necessary for a subgiant at the base of the giant branch to have a wind of ∿ 10^{-9} $M_\odot$/yr, in order to end up as a low-mass white dwarf.

FF Aqr (Table 1) may have also been something like an RS CVn binary in the past. In fact, since the two components must have started with nearly equal masses (so that both could have been subgiants simultaneously before one lost its envelope to become a hot subdwarf), the resemblance to an RS CVn system may have been quite close. I find it almost impossible to believe that a system like FF Aqr containing a giant can have emerged from a common envelope phase. It seems much more probable to me that this system has simply suffered extensive mass loss from at least one component. Observations establishing the velocity curve of the subdwarf as well as the giant (and hence giving both masses) would be of enormous value in understanding not just this system but the overall problem of forming objects like those in Table 1. Given the small mass-function (Etzel *et al.* 1977) and the eclipses, it is hard to believe the subdwarf is more than $\sim 0.5\ M_{\odot}$, and it could be less if the G8III companion has also lost mass, as seems likely.

Four of the systems in Table 1 have recognisably M-dwarf components. Given that it is difficult, though not impossible, to see how an M dwarf will eject a supergiant envelope in the "common envelope" scenario, is it possible that all these M dwarfs are actually remains of originally more massive companions, the companion having also lost some of its envelope during the spiralling-in phase? There are two arguments against this. Firstly, it takes even more work to strip the outer layers off a main sequence star than to do the same service for a sub-giant or giant (per unit mass lost). Secondly, if a G dwarf, say, has perhaps half its mass stripped away in the $10^3 - 10^4$ years of a common envelope phase, it will emerge as a very hot subdwarf, and should take about as long to cool down as its white dwarf companion once the envelope has been ejected. In GK Vir and Feige 24 the companion is a very hot white dwarf, presumably not very old, and yet the companion is already a fairly normal M dwarf. In GK Vir, especially, the M dwarf is 7 magnitudes fainter than the hot white dwarf (Green *et al.* 1978) which does not suggest to me that they both emerged from the fiery furnace at the same time; not, at least, if the M dwarf lost half its mass in the furnace, although even if it conserved its mass I would find this extreme case rather hard to accept. The other two systems (Case 1, HZ 9) are less worrying in this respect, although Lanning and Pesch (1981) remark of HZ 9 "It is curious that after such an evolution [i.e. common envelope] the component stars should appear so ordinary".

V Sge (Table 1) is also awkward. Although its structure, let alone its evolutionary status, is not clear, it is not unlike the product expected from early Case B evolution, except that its period is much too short. Whereas early Case B should lead in many circumstances to a compact helium-burning star and a main sequence companion, the final period should be $\sim$ 100d, not $\sim$ 0.5d. This suggests to me simply that in some, though not all, Case B systems angular momentum and mass are not conserved. V Sge may be a system which has lost $\sim$ 50% of its mass and $\sim$ 80% of its angular momentum. It is interesting that the helium-burning component may, after helium exhaustion, become a C/O white dwarf without going through a further red giant phase (since helium stars with $\lesssim 0.9\ M_{\odot}$ do not expand much in the shell-burning phase, Paczyński 1971), and so the system may reasonably become cataclysmic without going through a further detached phase, and without having been through a common envelope phase.

A final comment about the systems of Table 1 is that, even though several are nuclei of planetary nebulae, it is not clear that the planetary nebula was produced by the same mechanism as the one which is thought to operate for single red giants (Abell and Goldreich 1966, Wood and Cahn 1977). For instance, the hydrodynamic mass transfer (Whyte and Eggleton 1980) that can be expected in close white dwarf/red dwarf systems, if the red dwarf is more massive than the white dwarf when mass transfer begins, might easily lead to substantial mass loss from the binary, and so to the formation of something not unlike a planetary nebula. The expected binary remnant would be a detached system of somewhat longer period than before, with the red dwarf substantially reduced in mass and the white dwarf not much altered. This might be rather like UU Sge; however, I would expect the "red" dwarf to be a very hot object for some considerable time, as it may not cool off much faster than a white dwarf.

4. THE PERIOD GAP AND PERIOD CUTOFF IN CATACLYSMIC BINARIES

It now seems clear that there is a real shortage of cataclysmic binaries in the period range 2 - 3 hrs (Warner 1976, Whyte and Eggleton 1980). I will assume this gap to be real without further qualification. There is also, though not quite so clearly, a cutoff at $\sim$ 1.3 hrs. There are $\sim$ 20 binaries known in each of the period ranges 1.3 - 2 and 3 - 4.5 hrs, and no more than 2 in the ranges 0.9 - 1.3 and 2 - 3 hrs together. It also seems clear that AML (whether by gravitational radiation or by magnetic braking) is the main cause of the long-term evolution of cataclysmics, although nuclear evolution may be a significant driving mechanism in a few systems like GK Per. AML can be expected to operate as well on MW;D systems (Table 1) as on MW;S systems of comparable period, and so MW;D systems must not be omitted in a discussion of the period distribution of cataclysmics. Figure 2, a plot of orbital period against secondary mass, shows in a highly schematic form some of the factors that must influence the period distribution. No less than 5 constraints seem to be imposed by the existence of the gap and cutoff:-

(i) MW;S systems with P > 3 hr cannot evolve steadily to periods < 3 hr; either they turn round at $\sim$ 3 hr, or they accelerate or decelerate their evolution strongly, or they cease to be cataclysmic

(ii) the same applies, *mutatis mutandis*, to MW;S systems with P < 2 hr

(iii) MW;D systems with periods short enough to be affected by AML must avoid secondary masses in the range $\sim$ 0.2 - 0.3 $M_{\odot}$

(iv) similarly they must avoid masses in the range $\sim$ 0.01 - 0.02 $M_{\odot}$

(v) secondaries in the mass range 0.02 - 0.15 $M_{\odot}$ cannot be in thermal equilibrium, even if detached, at periods less than $\sim$ 1.3 hrs.

These constraints are not always independent. If the answer to (i), (ii) is that systems speed up their evolution considerably on reaching the gap, then (iii), (iv) may not be necessary. But if on the contrary systems slow down, or cease to be cataclysmic (by becoming detached, Robinson *et al.* 1981), then (iii), (iv) are necessary.

Figure 2 shows lines corresponding to semidetached black dwarfs (BD) and main sequence (MS) stars in thermal equilibrium. For secondary masses $\lesssim$ 0.5 $M_{\odot}$ a departure from thermal equilibrium usually means

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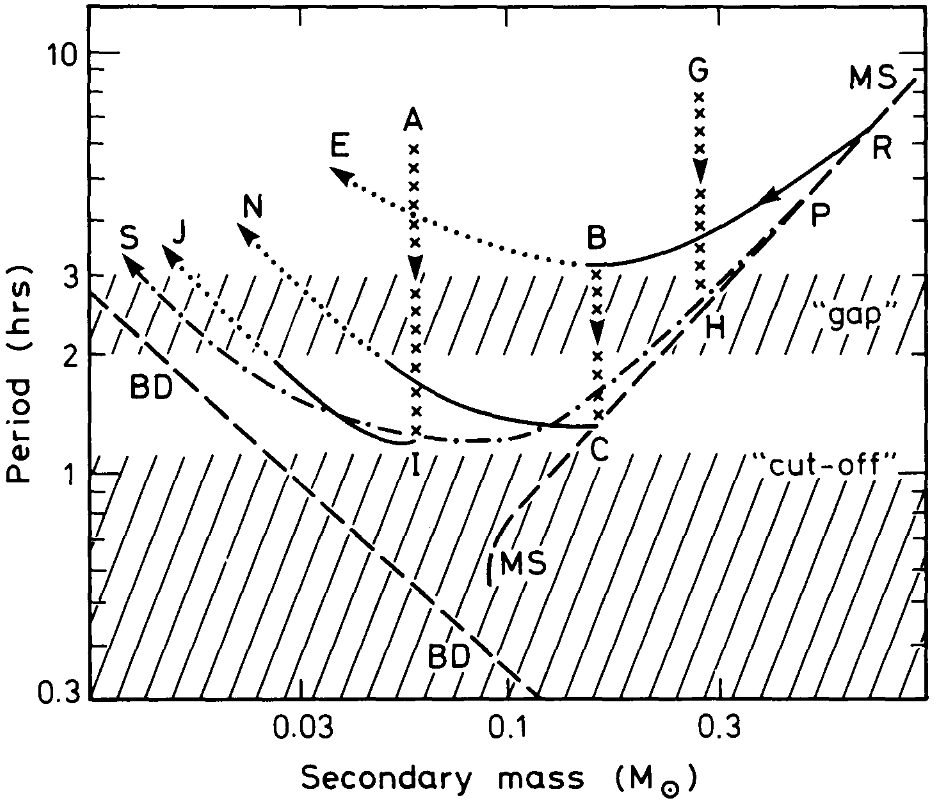

Figure 2. Schematic picture of the secular evolution of cataclysmic binaries. Period is plotted against mass of secondary. Systems containing semidetached "black" dwarfs or low-mass main sequence stars, in thermal equilibrium, would lie on the dashed lines BD and MS. The dash-dot line PS is the model of Paczyński and Sienkiewicz (1981), involving angular momentum loss by gravitational radiation only. The line RBCN is an interpretation of the suggestion of Robinson *et al.* (1981) that cataclysmic binaries become detached (crosses, BC) at periods of ∿ 3 hr. G and A are possible locations of the detached systems GK Vir and AA Dor (Table 1). The paths GH, AIJ, BE are speculative possibilities discussed in the text. Dotted lines represent faster semidetached evolution than solid lines.

lower densities, hence longer periods. Thus the BD and MS lines should be a lower envelope. Evolution by AML can lead to considerable departures from thermal equilibrium for low-mass secondaries, if the AML timescale is comparable to or shorter than the thermal timescale, which can be $\sim 10^{10}$ yrs in the region where the BD and MS lines approach each other. The path PS on Figure 2 is the path that would be followed if the secondary starts somewhere on the MS and evolves by gravitational radiation only (Faulkner *et al.* 1972, Paczyński and Sienkiewicz 1981). This might explain the cutoff, provided all systems started with $m_2 \gtrsim 0.15\ M_\odot$, but fails to explain the gap, although a second passage through the gap might be avoidable simply because evolution is so slow that no system may have got there yet. The path RBC corresponds roughly to the suggestion of Robinson *et al.* (1981), who noted that a small number of systems just above and just below the gap appear to switch off mass transfer, at least temporarily. It would appear to be necessary that the secondary be far from thermal equilibrium at B: otherwise a small amount of AML would make it semidetached again, at a period within the gap. Fairly rapid AML (perhaps by magnetic braking) might lead to a path like RB. Presumably when the system becomes semidetached again, at C, it will again depart from thermal equilibrium, and follow a path like CN. So another mechanism is needed to prevent it reappearing in the gap.

A detached system like AA Dor, indicated (very tentatively) as A on Figure 2, poses a further problem. If AML reduces its period on a reasonable timescale, it should become cataclysmic at a period of ~ 0.5 hr, well below the cutoff; any secondary mass in the range $\sim 0.03 - 0.15\ M_\odot$ could do this. I speculate that tidal friction, which is inevitably involved in AML by magnetic braking, may heat such a secondary sufficiently, once $P \lesssim 2$ hr, that it is out of thermal equilibrium and so fills its Roche lobe sooner than otherwise. It might then follow a path like AIJ in Figure 2. If there is an MW;D system at a point like G (and GK Vir may be near there, although the spectral type quoted in Table 1 suggests a slightly greater mass) it might be expected to become cataclysmic at H. Hence either there is a shortage of systems near G, or MW;S systems near H evolve much more rapidly than at either longer or shorter periods.

The following set of assumptions, while not put forward as a "theory", is intended to illustrate the complexity forced on any model which attempts to explain both the gap and the cutoff in terms of secular evolution of cataclysmics. The assumptions are

(a) two different mechanisms lead to the formation of MW;S (and also MW;D) systems; one mechanism produces secondaries in the mass range $m_2 \gtrsim 0.4\ M_\odot$, the other in the range $0.02 - 0.2\ M_\odot$.

(b) AML by magnetic braking and tidal friction operates on timescales $\sim 10^9$ yr, decreasing to $\sim 10^8$ yr for secondaries with $m_2 \lesssim 0.03\ M_\odot$. Tidal friction causes heating in the secondary, which may be its main source of luminous energy at low mass and/or short period.

These assumptions may ensure that

(i) systems starting from the main sequence above the gap follow a path in Figure 2 like RBE, but evolve rather rapidly on the section BE. If by some accident they become detached at a point like B, they might follow the sort of path RBCN implied by Robinson *et al.* (1981), but evolving progressively more rapidly on the section CN so that they spend most of their life below the gap;

(ii) Systems never start from either the MS or the BD curve near where they nearly join, because such a secondary will always be heated by tidal friction and so be out of thermal equilibrium. Such systems will therefore start cataclysmic life at points like C or I, perhaps having already had detached evolution from a point like A. The MW;S systems will follow paths like CN, IJ, but spend most time near points C, I respectively.

It is not difficult to fault such an elaborate scheme both for the implausibility of its assumptions and for the optimistic interpretation of their consequences. But can one do better? It is not going to be easy to explain both the gap and the cutoff; and there are many other observed features with which the explanation must also be compatible.

5. CONCLUSIONS

There are several difficulties in accounting for both the origin and the subsequent evolution of cataclysmic variables. These are interdependent: for if a theory of their origin predicts a smooth distribution of secondary masses from say 0.1 or 0.5 $M_{\odot}$ upwards, then evolution has a harder (but maybe not impossible) job of explaining the observed period distribution.

I feel that possibly three different mechanisms may lead to the formation of cataclysmics:-

1. a common envelope mechanism (Paczyński 1976), which might produce detached systems like V471 Tau, and semidetached systems like EM Cyg.

2. a mechanism where the outer layers of a *subgiant* can be stripped off, and by a companion of low mass; this might lead to detached systems like AA Dor, and semidetached systems like VW Hyi

3. non-conservative early Case B, in fairly massive binaries; this might lead to a system like V Sge, and then perhaps to a system like Sco X-1, supposing that the compact companion in Sco X-1 is a white dwarf rather than a neutron star.

Once an MW;D or MW;S system has been formed by whatever route, I believe that angular momentum loss by magnetic braking and tidal friction cannot be ignored, even though this may not make the overall picture any easier to understand. The tidal friction may be an important cause of thermal disequilibrium in short-period systems. Magnetic braking may introduce randomness into binary evolution, as it appears to do for single main-sequence B stars. Magnetic B stars often have low, or very low, angular momentum, but this is probably not going to affect their interior evolution very much. In contrast, the evolution of a *binary* depends enormously on the angular momentum, so the spread of possible evolutionary paths should be much greater.

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DISCUSSION FOLLOWING P. EGGLETON'S TALK

BATH: The evidence that you have got white dwarfs in these SWS systems does not exist, it is purely a myth. There has been a lot of discussion of symbiotic star models, containing white dwarfs, with no observational evidence that these systems exist at all, and yet they have become accepted. I would argue that in fact the symbiotic stars where the blue component gets brighter in the optical than the giant, must contain main sequence stars, unless they are losing considerable amounts of mass and have a pseudo photosphere around the white dwarf. This is because the white dwarf is just too small ever to be hot enough (below the Eddington limit) to be bright enough in the optical, to compete with the giant.

EGGLETON: In the case of Z And at least, the ourbursts have been thought to have something to do with whether you have steady nuclear burning or unsteady nuclear burning. That is not something I personally believe.

BATH: Yes, but the point is that now we know that you can produce eruptions by accretion events. It is much easier to explain symbiotic star eruptions in many cases, by accretion events than by nuclear burning, that is particularly the case with Z And CI Cyg which is even a better example.

EGGLETON: I agree with you.

SHAVIV: The spiralling-in sotry, which was the basis of a large part of this kind of overall picture does not necessarily end at a close binary, they might really amalgamate into a single star so you have the problem how to stop such a successful process.

EGGLETON: Well, I wonder whether in fact that might not be the most common outcome of a common envelope situation and I only put it forward in the most tentative way, but it might be a reason for a shortage of moderate mass secondaries, around 0.25 $M_\odot$, maybe you need a more massive secondary than that to survive the common envelope process. I don't think that anybody has really claimed that the common envelope situation would inevitably end with a binary of the sort of period that we would like to see, which would be something of the order of half a day to a day. It might be ten days, or it might be one hundredth of a day, which effectively means that one has amalgamated in the other. Some of the systems that I have shown, do have periods of several days but it is not clear to me that they actually are products of common envelope evolution. Another thing one must bear in mind about the common envelope, is that we shouldn't equate all red super-giant envelopes with each other. There are red super-giants and there are orange super-giants which are very different from red super-giants in the fact that their envelopes are largely radiative, whereas the red super-giants would have envelopes which are largely convective and this can make an enormous difference to the way things happen. Also, if you have a red giant, the envelope is very much less favourable for being blown off in the process of the common envelope scenario. I don't find it difficult to imagine that you would blow off the envelope of an extreme red super-giant fairly easily, by some kind of common envelope mechanism, but I do find it difficult to imagine you can blow off the envelope of an ordinary red giant, because it is much more tightly bound. Yet, at least one of these objects on the list seems to be a rather low mass white dwarf.

SHAVIV: Bob Williams has introduced the idea that it might very well be that the secondaries are highly evolved, with a composition which is different from solar. What if in at least part of the binaries the companion is highly evolved?

EGGLETON: I certainly wouldn't be surprised if it weren't solar. However, very tentative as the data is, the secondaries do seem to fit in with being fairly normal main sequence stars. I can well believe they are enriched in He^3, for instance.

SHAVIV: So it does pose a serious problem.

EGGLETON: It does, indeed.

SUGIMOTO: I did not understand what is the essential physical difference between the common envelope evolution and the two other mechanisms you are proposing. What is the contents of the new mechanism?

EGGLETON: What I would like in the kind of mechanism which I refer to as being more or less a planetary nebular thing, is that the spiralling-in of the secondary would take place within the more dilute envelope that you might get if the envlope from the primary is already expanding on its way to becoming a planetary nebula envelope, rather than being in the comparatively high density environment of a red giant or even a red super-giant envelope. So I wouldlike the star to loose its envelope first and then the spiralling-in take place within that, rather than to have the spiralling-in take place and lead as a consequence, at a mugh later stage, when the binary has become much closer, to the blowing-off of the envelope.

SUGIMOTO: Is this a theory of speculation ?

EGGLETON: My feeling is that, based on the observations, particularly those observations of this set of systems, you would have a hard job explaining most of these by what I understand to be the common envelope scenario as put forward I think basically by Paczynski and as elaborated by several other people subsequently.

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