Triples, Mergers, Pipe-dreams: the Birth, Evolution and Death of Very Close and Contact Binaries

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Very Close Binaries: I define them as having $P \lesssim 3$d, neither component being WD, NS or BH. About 90 (2%) of the naked-eye stellar systems contain VCBs; about 60 of these (70%) are in triples or higher multiples (Eggleton & Tokovinin 2008).

- (A) how are VCBs, and in particular contact binaries, formed?
- (B) what is their structure?
- (C) how do they evolve?
- (D) what is their end-point?

I will start with a series of assertions, and attempt to justify them only after putting them all down.

(A1) Protostars condense within a Star-Forming Region (SFR) by Hierarchical Contraction and Fragmentation (HCF) into binaries and higher multiples. Periods or sub-periods range from $\sim 1\,\mathrm{yr}$ up to $10^4\,\mathrm{yr}$ or more.

(A2) Independent binaries and triples scatter off each other gravitationally, in Gravitational Scattering Events (GSEs) where the shorter periods are shortened further, some to $\sim$ months; longer ones are lengthened. Triples are often formed from two binaries, with the fourth star ejected and the inner pair becoming rather tight. Inner and outer orbit will be typically highly inclined to each other.

(A3) If $P_{\rm in} \sim$ months, and $P_{\rm out} \sim 2 - 1000\,\mathrm{yrs}$, and the relative orbital inclination is between 39° and 141°, then Kozai cycles can cause the inner orbit to make large cycles in eccentricity, while keeping the semimajor axis $a_{\rm in}$(and so $P_{\rm in}$) constant. Thus inner periastron will at intervals be *much* closer than $a_{\rm in}$. Maximal eccentricity depends on inclination only, to lowest order.

(A4) During the close periastra tidal friction takes energy from the inner orbit, thus reducing $a_{\rm in}$ and $P_{\rm in}$. The process (Kozai Cycles with Tidal Friction, or KCTF) only ends when $P_{\rm in} \sim 2-3\,\rm d$, by which point the quadrupolar distortion of the 2 inner components defeats the quadrupolar effect due to the third star.

(A5) F/G/K dwarfs in $2-3\,\rm d$ binaries are rapidly rotating, and so magnetically active. This causes erratic mass loss, which coupled to the magnetic field causes magnetic braking (MB); and this couples with tidal friction (MBTF) to reduce $P_{\rm in}$ further.

(A6) At $P_{\rm in} \sim 0.25-0.4\,\rm d$, $*1$ fills and starts to overflow its Roche lobe (RLOF). It loses mass to $*2$, which expands and usually fills *its* Roche lobe too. Thus the system comes into contact, and acquires a shallow common envelope. Inner pairs with nearly equal masses, however, will evolve into Algols.

(B1) In contact, heat flows in the common envelope from the hotter to the cooler component, until the temperatures are nearly equal. The mechanism of heat transfer is the differential rotation that is observed on the Sun, with equatorial material flowing prograde round *both* components and somewhat faster than the mean due to orbital rotation.

(B2) Heating of the less massive component makes it fill its Roche lobe more than the other, causing a slight flow of mass in the opposite direction. This sets up a cyclic behaviour, which because of (a) continued MBTF, and (b) possible nuclear evolution in $*1$, is superimposed on a slight evolutionary trend towards more unequal masses.

(B3) The light curve cycles between rather equal eclipses during the contact portion of the cycle and less equal eclipses during the (probably rather brief) semi-detached portion ('Near-Contact Binaries', NCBs). But in both cases the light curve is badly perturbed by starspots consequent on the magnetic activity, so that it can be difficult to reach a unique conclusion about the geometry.

(C) On a longish timescale, determined by nuclear evolution or MBTF or both, the system evolves towards very unequal masses (10 to 1, and even 15 to 1, have been observed). At some extreme mass ratio, depending quite a lot on the internal structure of $*1$ – i.e. on whether it is substantially evolved across the main sequence band or not – the system becomes unstable to the Darwin instability, whose timescale may be a few years or even days.

(D1) The Darwin instablity leads rapidly to a merger, as in V1309 Sco in 2008. After the merger the star relaxes to something like a red giant or an evolved MS star, rapidly rotating. But magnetic activity and consequential mass loss brakes the star fairly rapidly.

(D2) The system, formerly a triple, is now a (fairly) wide binary. It may be a rather odd binary, whose two components do not appear coæval, i.e. on the same isochrone. An example may be γ Per, whose A-type subgiant secondary is apparently quite evolved despite the fact that it is only two-thirds the mass of the primary, a G giant. Perhaps the G giant is the merged remnant of a former binary, whose sub-primary was nearer in mass to the A star.

Regarding process (A1), the issue is whether VCBs can condense directly out of an SFR, or whether the SFR produces in the first instance, by fragmentation, only rather wide binaries (the 'Angular Momentum Problem' or AMP). One requires that a subcloud of gas and dust that ends up as a *single* star should have very little angular momentum compared with what is to be reasonably expected in a fairly uniform primordial cloud, but even VCBs have rather little angular momentum compared with expectation, so that they are still subject to the AMP.

Regarding (A2) and (A3), the important point to note is that there are proportionately *far* more triples and higher multiples among VCBs than among binaries in general. Several researchers show that 'triplicity' is found in about 70% or more of various kinds of VCBs, as compared with a normal fraction, for non-VCBs, that is maybe 20%. The numbers are quite consistent with 100%, given that M-dwarf triple companions are rather hard to recognise in many circumstances. But I believe the clinching argument is that (i) not only are triples unusually common among VCBs, but (ii) there exists a clear reason – (A4) above, i.e. KCTF – *why* triples can produce VCBs.

That GSEs (A2) produce remarkable results, unlikely to be produced directly by process HCF (A1), is suggested by:

(i) DI Her, 10 d, B5+B5; *both* components rotate almost *perpendicular* to the orbit.

(ii) η Ori, a quintuple or sextuple system; an 8 d sub-system has one component rotating four times faster, the other two times slower, than the orbit.

(iii) ι Ori, a massive 29 d binary ($e = 0.75$): the secondary is half the mass of the primary, yet more evolved. Far away in opposite directions are two runaway OB stars. There was presumably a collision 2.5 Myr ago between a 10 Myr binary and a 4 Myr binary. One component from each pair ended up together, the other two escaped.

KCTF (A4) need not reduce the period below $\sim 2 - 3$ d, because MBTF (A5) can reduce the period to a value, $0.25 - 0.4$ d, at which RLOF sets in. It is only necessary that *one* of the close components be active. In δ Cap (A9m +G:; 1.023 d), an X-ray source probably on account of activity in the secondary, presumably the *secondary* has already made the period quite small.

For Kozai cycles the *outer* orbit need not be particularly tight: $100 - 1000\,\mathrm{yr}$ will do. It is only necessary that inner and outer orbits be fairly inclined to each other, and this is what we expect if process (A2), GSE, is largely responsible for the triples. Of course (A1), HCF, can also produce triples, though probably these are more nearly coplanar. As an example, suppose inner parameters are $2 + 1\,M_\odot, 50\,\mathrm{d}$, the outer parameters $3 + 0.3\,M_\odot, 100\,\mathrm{yr}$, and the mutual inclination $60°$. Then the Kozai cycle period is $\sim 10^5\,\mathrm{yr}$, and the eccentricity could oscillate between, say, 0.3 and 0.808. This makes the inner pair as close, at periastron, as if P_{in} were $4.5\,\mathrm{d}$, close enough for tidal friction to be significant.

60° is the *median* to be expected, for a distribution generated by random collisions. Note further that the nature of the cycle is not determined by the outer period, but almost entirely by the inclination. It might take 100 or 1000 cycles, but this is still not a long time in the life of an A/F/G star. KCTF stops only when the inner orbit shrinks to $2-3\,\mathrm{d}$, when the quadrupolar distortion of the components, plus general-relativistic apsidal motion, becomes stronger than the third-body effect which drives the Kozai cycles.

A difficult issue is that with late-A/F/G systems having periods of $0.4 - 3\,\mathrm{d}$ it is very likely that nuclear evolution (NCEV) on the one hand and activity-generated MBTF – process (A5) – on the other are competitive in timescale. My results vary alarmingly depending on only modest changes in the formalism for the dynamo-driven MBTF model. Thus in an example like δ Cap it is unclear whether the primary will evolve nuclearly to fill its Roche lobe before the Roche lobe shrinks down on it as a result of the secondary's activity. One way or the other I would expect that the system reaches RLOF, but it could be at a period of say $0.9\,\mathrm{d}$ if NCEV is stronger and $0.4\,\mathrm{d}$ if MBTF is stronger.

The contact systems XY Boo ($0.37\,\mathrm{d}$) at spectral type A9 and V2388 Oph ($0.80\,\mathrm{d}$) at F0 probably reflect this substantial range. Although there is not much doubt about the rate of NCEV, there is much uncertainty about the rate of MBTF, and so it is difficult to model this process convincingly.

Evolution in Contact

There is disagreement about how systems evolve in contact. I think the evolution would have a non-linear, cyclic character, a relaxation cycle or Thermal Relaxation Oscillation (TRO). Transfer of heat from the hotter to the cooler slightly contracts the hotter, and slightly expands the cooler, causing the cooler to overfill its Roche lobe *more* than the hotter, which tends to reverse the flow of mass – which must of course to start with have been from the more massive and hotter to the less massive and cooler component. This reversal of mass flow will then lead to a breaking of contact; but once contact is broken the primary will swell up again, re-establishing RLOF and ultimately contact.

My modeling of heat transport in contact is somewhat ad hoc, but reasonably robust and reproducible. Here is an example, oscillating between a contact binary and an NCB).

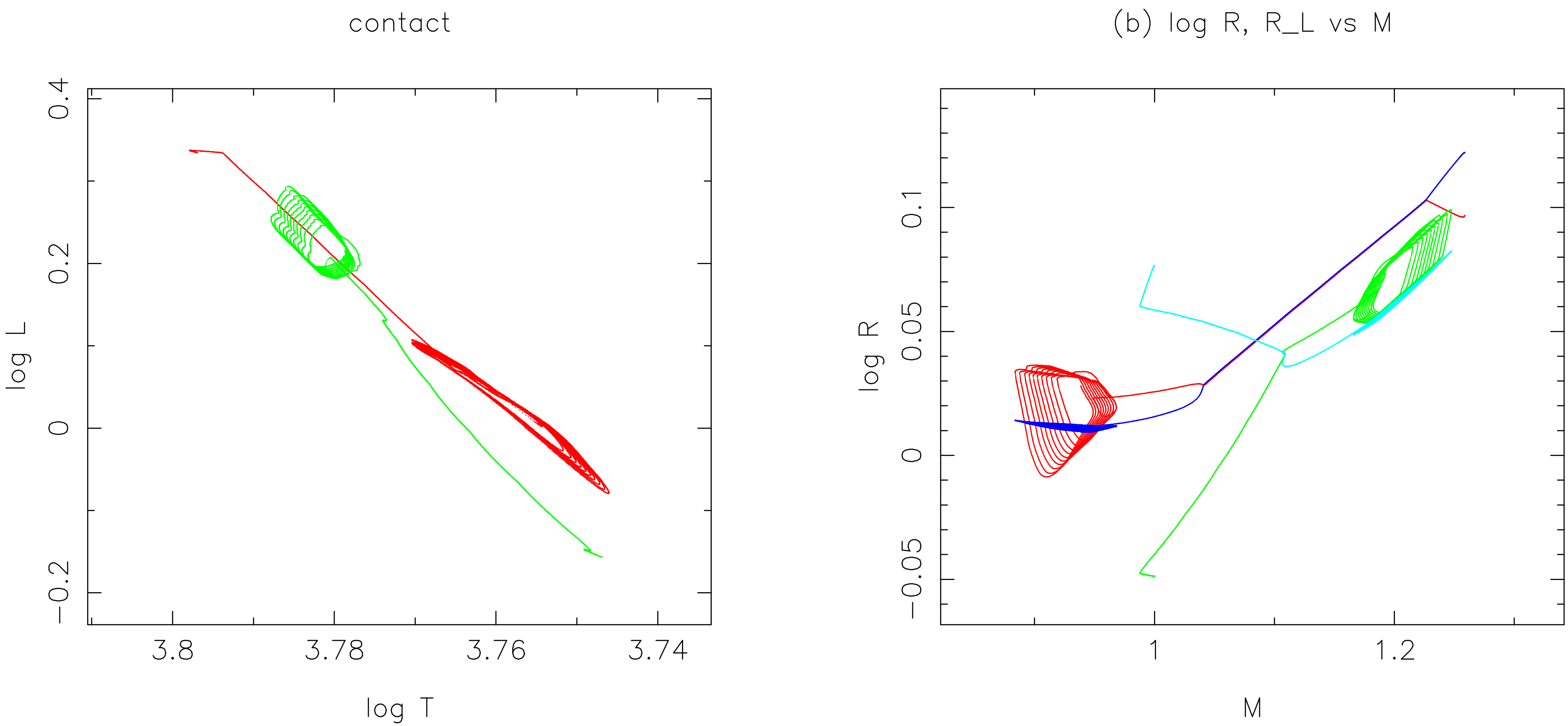

Figure 1: Spaghetti Diagram: Cyclic Evolution of a Binary on Reaching Contact.

NCBs are not as rare as once thought; there are at least several dozen. Some have been claimed to be 'contact but with unequal temperatures', e.g. W Crv, but this was shown to be more probably a semidetached system. Possibly W Crv is *not* in the semidetached phase of a TRO, but is instead a 'legitimate' Algol that has missed coming into contact, at least so far.

W Crv is very much in that area which I find uncomfortable: where NCEV and MBTF are so competitive that it is a toss-up which wins. However several NCBs, such as CN And, having once been seen as contact binaries, are now seen to be semidetached, and to fit quite well the concept of TROs.

Contact systems evolve on balance – despite TROs in the short term – towards very unequal masses, say $q \sim 10 - 15$. The limit of this must be a merger, probably triggered by the Darwin instability. This may be what happened to the binary V1309 Sco, which was observed to: (a) have been a contact binary with period 1.4 d before 2008 (b) to have had a 10 mag. eruption lasting ~ 2 yr; and (c) to be subsequently a *single* star. Except it will actually be a *wide* binary, since it was triple to start with. This binary's components will seem to be of different ages.

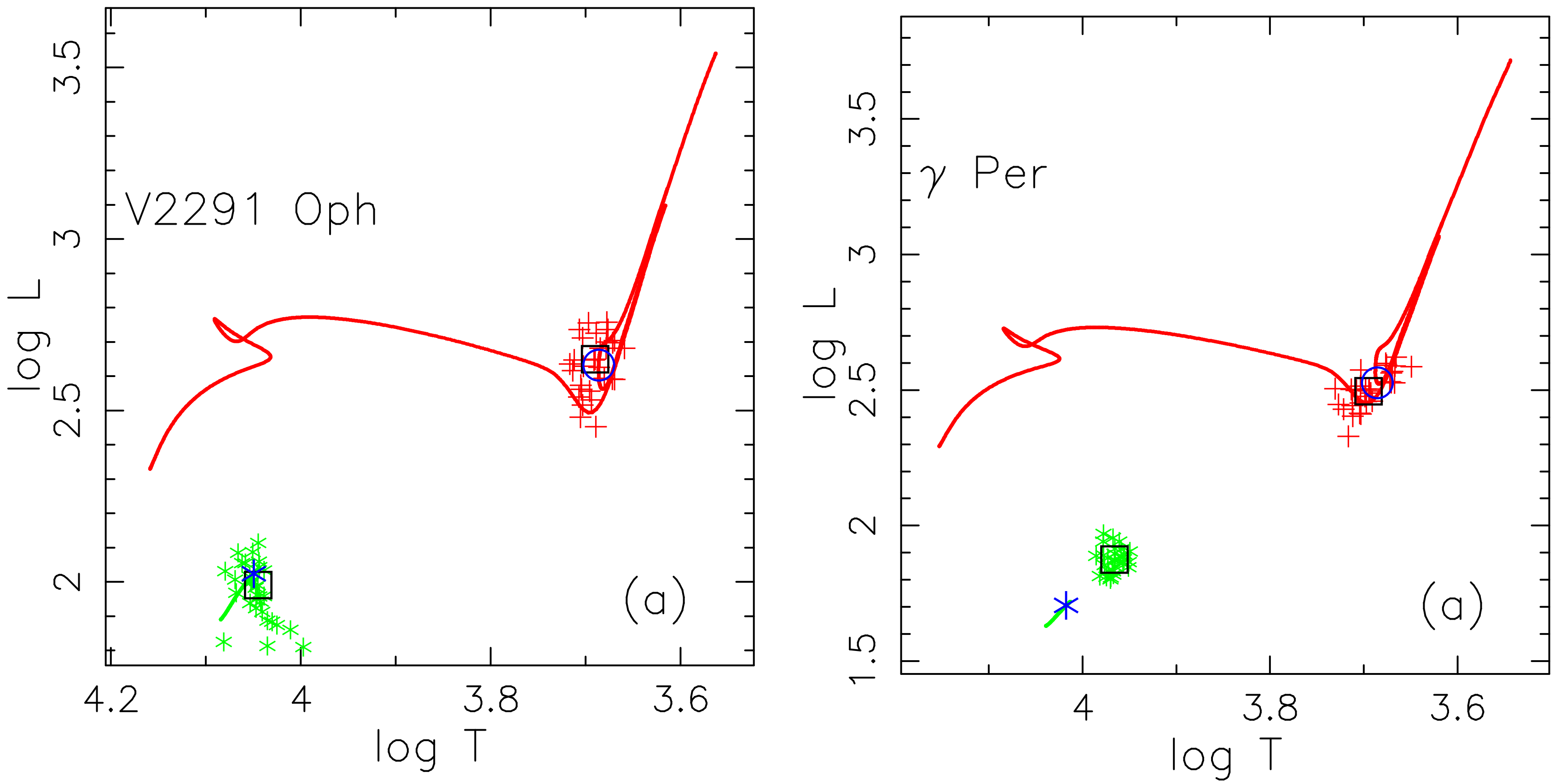

Figure 2: HRDs for V2291 Oph and γ Per

CONCLUSIONS

The formation and evolution of contact binaries seem to require a considerable variety of astrophysical processes, ranging from gravitational interactions to tidal friction and finally the Darwin instability and a merger.

A triple system may be a necessary stage, involving Kozai cycles and tidal friction. The pre-contact phase may involve a few Megayears to a Gigayear or more, and the contact phase may be of similar duration. The merger needs only a couple of years, but perhaps a further few Megayears to settle down. The longer-term product may be a 'non-coæval' wide binary, like γ Per.

There are more dramatic non-coæval systems:

OW Gem: G8IIb + F2Ib-II; 4 + 6 $M_\odot$, 3.5 yr

V643 Ori: K7III + K2III; 1.9 + 3.3 $M_\odot$, 52 dy (!)