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Stars, Companions, and their Interactions: A Memorial to Robert H. Koch

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Formation and Evolution of Contact Binaries

Peter P. Eggleton†
Lawrence Livermore National Laboratory, CA 94551, USA

I describe a series of processes, including hierarchical fragmentation, gravitational scattering, Kozai cycles within triple systems, tidal friction and magnetic braking, that I believe are responsible for producing the modest but significant fraction of stars that are observed as contact binaries. I also discuss further processes, namely heat transport, mass transport, nuclear evolution, thermal relaxation oscillations, and further magnetic braking with tidal friction, that influence the evolution during contact. The endpoint, for contact, is that the two components merge into a single star, as recently was observed in the remarkable system V1309 Sco. The single star probably throws off some mass and rotates rapidly at first, and then slows by magnetic braking to become a rather inconspicuous but normal dwarf or subgiant. If however the contact binary was part of a triple system originally–as I suggested above was rather likely–then the result could be a *widish* binary with apparently non-coeval components. There are several such known.

Keywords: stars: binaries, stars: evolution

1. INTRODUCTION

Contact binaries can be variously described as two stars witha single envelope, or one star with two cores. Either way it is somewhat like a peanut. The larger component is usually something like an F or G dwarf, and the orbital periods are usually 0.3-0.5 d, although some inhabit the extremes of the wider range 0.2-1.0 d. The smaller component has much the same temperature as the larger, and yet usually has a much lower mass, more typical of a K or M dwarf.I believe that they are one of the two great unsolved problems of stellar astrophysics, the other being common envelope evolution.

At any rate I *used* to believe that. But I had a curious feeling while writing this talk that several things I had thought were problems might no longer be problems, and indeed perhaps there is now a logical series of processes that run all the way from the formation to the destruction of contact binaries. Probably this curious feeling was *hubris*–I dare say the logic apparent to me will be demolished by your questions following this talk.

Let us address the following four questions:

(A) How are 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 only justify them–to the extent that I can, and that time allows–after putting them all down.

(A1) Protostars condense within a star-forming region (SFR) by a process of hierarchical contraction and fragmentation into binaries and higher multiples. The shortest periods are ~1 yr, and periods range up to 10^4 yr or more.

(A2) Independent binaries and triples 'collide' gravitationally,and the shorter periods are shortened further, some to ~months; longer ones are lengthened. Triples are often formed from two binaries, with the fourth star ejected and the inner pair becoming rathert ight. Inner and outer orbit will be typically highly inclined to each other.

(A3) If P_{in}~months, and P_{out} ~10-1,000 yrs, and the relative orbital inclination is between 39° and 141°, then Kozai

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†**Corresponding Author**
E-mail: peter.eggleton@yahoo.com
Tel: +1-925-423-0660 Fax: +1-925-422-6594

cycles can cause the inner orbit to make large cycles in eccentricity, while keeping the semimajor axis a_{in} (and so P_{in}) constant. Thus inner periastron will at intervals be *much* closer than a_{in}.

(A4) During the close periastra tidal friction takes energy from the inner orbit, thus reducing a and P_{in}. The process (Kozai cycles with tidal friction [KCTF]) only ends when P_{in} ~2-3 d.

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

(A6) At P_{in}~0.25-0.4 d, star 1 fills and starts to overflow its Roche lobe (RLOF). It loses mass to star 2, which expands and usually fills *its* Roche lobe too. Thus the system comes into contact, and acquires a shallow common envelope.

(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 (NCEV) in star 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'). 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 aunique conclusion about the geometry.

(C) On a longish timescale, determined by NCEV 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 star 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 instability 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 brake 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 coeval, 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.

2. DISCUSSION

2.1 Evolution to Contact

Regarding process (A1), the issue is whether very close binaries (VCBs, say P< 3d) 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, Bodenheimer 1978). Note that VCBs are about 2% (Eggleton & Tokovinin 2008) of the stars in the Bright Star Catalogue. One requires that a subcloud of gas and dust that ends up as a *single* star should have rather 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. Perhaps viscous discs can extract enough angular momentum. Are viscous discs particularly common around young VCBs? I think not.

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. Tokovinin et al. (2006), Rucinski et al. (2007), and Eggleton & Tokovinin (2008) all 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% if P > 30 d. The numbers are quite consistent with 100%, given that M-dwarf triple companions are rather hard to recognize 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. It is not necessary that the *outer* orbit be particularly tight:100-1,000 yr will do. It is only necessary that the inner and outer orbits be fairly inclined to each other, and this is what is to be expected if process (A2) is largely responsible for the triples. Of course (A1) can also produce triples, though one might guess that these might be more nearly coplanar. Kozai cycles are discussed at some length by Eggleton (2006, ch. 4.7) and Fabrycky & Tremaine

(2007). As an example, suppose the inner masses and period are 2+1 $M_\odot$, 50 d, that the third mass and outer period are 0.3 $M_\odot$, 100 yr, and that the mutual inclination is 60˚. Then the Kozai cycle period is ~10^5 yr, and the eccentricity could oscillate between, say, a minimum of 0.3 and a maximum of 0.808. This makes the inner pair as close, at periastron, as if P_{in} were 4.5 d, which is close enough for tidal friction to be significant. Note that 60˚ is the *median* to be expected, since the distribution of inclination is to be generated by random collisions; and note further that the nature of the cycle is not determined by the outer period, but only by the inclination (though more strictly also by the magnitude and orientation of the two Laplace-Rung-Lenz vectors to each other and to the separation vector). It might take 100 or even a thousand cycles to do the trick, but this is still not a long time in the life of an A/F/G star. KCTF will stop only when the inner orbit is shrunk to about 2-3 d, because then the perturbing effect of quadruple distortion of the components, plus general-relativistic apsidal motion, becomes stronger than the third-body perturbation which drives the Kozai cycles.

We do not require KCTF to reduce the period below ~2 - 3 d, because even before that period is reached MBTF (process A5) is capable, for magnetically active stars, of reducing the period right down to the value, 0.25 - 0.4 d, at which RLOF sets in. Note that it is only necessary that *one* of the two close components be magnetically active. In δ Cap (A9m + G:; 1.023 d), which is an X-ray source probably on account of activity in the secondary (Lloyd & Wonnacott 1994), it may well be the secondary that has already made the period quite small.

That dynamical interactions–process (A2)–take place and produce remarkable results, unlikely to be produced directly by process (A1), is suggested by a few examples:

(i) in DI Her, a 10 d binary of two B5 stars, *both* components are rotating almost perpendicular to, rather than parallel to, the orbit (Albrecht et al. 2009)

(ii) in ι Ori, a quintuple or sextuple system, an 8 d subsystem has one component rotating four times faster, and the other rotating two times slower, than the orbit (De Mey et al. 1996)

(iii) ι Ori is a 29 d binary (e = 0.75) where the secondary is about half the mass of the primary, yet seems to be more evolved. Many degrees away from ι Ori in opposite directions are two runaway OB stars, AE Aur and μ Col. Gualandris et al. (2004) suggested that there was a collision 2.5 Myr ago between a 10 Myr binary and a 4 Myr binary, in which one component from each pair ended up together while the remaining two components escaped.

For me, a difficult issue is that with late-A/F/G stars (and F/G/K companions) having periods of 0.4 to 3 d it is very likely that NCEV on the one hand and activity-generated MBTF–process (A5)–on the other are very competitive in timescale. When I try to model such systems I get results that vary alarmingly depending on only modest changes in the formalism that I adopt for the dynamo model which generates the mass loss driven by magnetic dissipation, and angular momentum loss driven by the mass loss in collaboration with the overall magnetic field. Thus in an example like δ Cap mentioned above it is very unclear to me 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 d if NCEV is stronger and 0.4 d if MBTF is stronger. The systems XY Boo (0.37 d) at spectral type A9 and V2388 Oph (0.80 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.

2.2 Evolution in Contact

After the sequence of processes which leads to contact, we are still faced with the challenge of how stars evolve further, during contact. Several investigators in the 1970s (Flannery 1976, Robertson & Eggleton 1977, Lucy 1976) concluded that the evolution would have a non-linear, cyclic character, a relaxation cycle or thermal relaxation oscillation (TRO). In this process, the transfer of heat from the hotter to the cooler slightly contracts the hotter, and slightly expands the cooler, thus 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 of course lead to a breaking of contact; but once contact is broken the primary will swell up again, re-establishing RLOF and ultimately contact.

Yakut & Eggleton (2005) followed a binary through the detached phase, with orbit shrinking in response to MBTF, and through a few dozen TROs. The numerical modeling of heat transport in contact was somewhat ad hoc, but reasonably robust and reproducible. Shortly after RLOF began the system was rather like an Algol; that is, the initial primary, significantly more evolved nuclearly than the secondary, lost sufficient mass before coming into contact that it became the less massive star. The mass ratio was however not far from unity, which makes it somewhat unlike most contact binaries since these usually have mass ratios far from unity. But in the course of a few dozen TROs the mass ratio gradually moved further from unity, and so in the direction one would hope for.

My expectation is that as the mass ratio diverges further from unity, the TROs will become more asymmetric, with long contact portions and (relatively) short near-contact portions. This is what we need in order to agree with the fact that near-equal-temperature contact binaries are substantially more common than the so-called 'near-contact binaries' that presumably represent the semidetached part of the TRO. Long-term evolution, whether driven mainly by NCEV or MBTF, *must* tend towards more unequal masses, because if the converse were the case then there would be a big accumulation of systems at equal mass whereas in practice we see a big accumulation towards highly unequal masses.

However, near-contact binaries (NCBs) are not as rare as was once thought. Yakut & Eggleton (2005) listed 25 likely objects. Several of these have at some time been believed to be 'contact but with unequal temperatures'; for example W Crv (Lucy & Wilson 1979), but this was shown to be more probably an Algol-like semidetached system (Rucinski & Lu 2000). It is entirely possible that W Crv is *not* in the semidetached state of a TRO, but is instead a 'legitimate' semidetached binary that has missed coming into contact, at least so far. In fact I think it is very much in that area which, for me, is very uncomfortable: where NCEV and MBTF are so competitive that it is a toss-up which wins. However several other NCBs, such as CN And (van Hamme et al. 2001), having once been lumped in with contact binaries, are now seen to be semidetached by a slight margin, and seem to fit quite well into the concept of TROs.

A problem with determining the 'geometrical' status of a VCB is that such systems often have light curves distorted with spots. And even if no asymmetric distortion is particularly evident, it is quite feasible that there is a distortion which happens to be fairly symmetric. For instance, if I am right in believing that it is differential rotation which drives luminosity transfer, then there may well be an equatorial belt that is at a (slightly) different temperature from the polar regions of either star.

I have already argued that it seems inevitable that systems evolve on balance–and despite TROs in the short term–towards very unequal masses. The limit of this must be a merger, and it will probably be triggered by the Darwin instability. Enough has been said about this elsewhere; I summarise it in Eggleton (2006). The instability happens when the spin angular momentum of the more massive star (taking the less massive to be a point mass, for convenience) exceeds one third of the orbital angular momentum.This requires a mass ratio that may range between ~7 if the primary is a convective dwarf to 15 or 20 if the primary is radiative, and with a dense core as on the evolved side of the main sequence band. It can be even larger if the primary gets into the Hertzsprunggap, but it suddenly becomes much smaller again once the primary is a largely convective red subgiant.

This may be what happened to the binary V1309 Sco, which was observed (Tylenda et al. 2011) to:

(a) have been a contact binary with a period of 1.4 d before 2008

(b) to have undergone a 10 mag. eruption lasting ~ 2 yr starting in 2008; and

(c) to have subsequently appeared to be a *single* star.

I think this must have been a system with intense competition between NCEV and MBTF: enough NCEV for the primary to reach the end of the MS and a little beyond, yet enough MBTF to avoid the usual widening of the orbit that we expect in a legitimate Algol when its mass ratio becomes extreme.

2.3 Evolution after Contact

Some might see that as the end of the story. But I think there is still another chapter. How do we recognise a former contact binary that has merged? Not easily. Probably it is rapidly rotating, but it may lose mass and angular momentum sufficiently rapidly that it soon becomes 'normal.' However, I have already suggested that it probably–even dare I say certainly–was in a triple, and so after the merger it will be in a *wide* binary. With a little luck, it may be possible to recognise a wide binary where both stars are quite evolved: say, one is a red giant and the other, less massive, is near the end of the main sequence. But suppose the red giant is 1.5 times as massive as the companion. The latter should hardly have evolved at all. Yet we find just this combination in the 15 yr binary γ Per. The mass ratio is 1.5, and yet the secondary is an evolved A2IV star, with a radius nearly twice the radius of a zero age main sequence star of its mass (R. E. M. Griffin, p.c.). I suggest that the primary is in fact the remains of a merged contact binary.

3. 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 Mega years to a Giga year or more, and the contact phase may be of similar duration. The merger needs only a couple of years, but perhaps a further few Mega years to settle down. The long-term result may be a somewhat anomalous long-period binary.

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