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Evolution of Very Close Binaries of Low Mass

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Evolution of Very Close Binaries of Low Mass

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ABSTRACT

Binaries of low total mass (say $1-3\,M_{\odot}$) and very short period (say $\lesssim 4\,\mathrm{d}$) are subject to a number of evolutionary processes, such as nuclear evolution, Roche-Lobe overflow, mass loss by stellar wind enhanced by rapid rotation, angular momentum loss by stellar wind with magnetic braking and tidal friction, mass transfer in contact (potentially in either direction), and heat transport from one component to the other during contact. Unfortunately all of these phenomena can be expected to occur on something like the same timescale. This makes it especially difficult to tie a particular system to a particular set of evolutionary processes.

Theory suggests that very close binaries should appear in four morphological forms: detached binaries, semidetached binaries in which the more massive component is the one that fills its Roche lobe (reverse Algols), semidetached binaries in which the less massive component is the one that fills its Roche lobe (normal Algols), and contact, or, as some would say, overcontact binaries, where both components overfill their Roche lobes up to the same equipotential surface. This is not to say that perhaps some other configuration may be important, but I am not sure that any has yet been put forward that is incontrovertible.

I have developed an evolutionary code in which the two components are solved *simultaneously*, and subject in principle to all six of the processes in the first paragraph. All four morphological forms are achievable by the code, as the physics demands. The code is still preliminary, partly at least because of the difficulty of quantifying all six processes. I will illustrate some possibly peculiar evolutionary scenarios that can emerge; but I will mainly argue, on the basis of observed data from a variety of systems, that it is indeed necessary to include all these processes, and not, for example, to ignore mass loss by stellar wind by claiming that it cannot be strong enough to be significant.

Subject headings: stars: activity — stars: binaries (including multiple): close

1. Introduction

It is well known that Solar-type stars, probably meaning stars of spectral type F or later, i.e. those with convective envelopes, are liable to be very active if they are in rapid rotation. The activity manifests itself as starspots, emission lines, radio and X-ray flux. Usually these are time-varying, with aperiodic as well as periodic behaviour. These aspects of activity are linked together by our concept of a rotationally-driven dynamo. Although dynamo theory is far from being quantitatively understood, there is an elementary picture which so far appears to be reasonably physical:

1. Rotation, in combination with a fairly deep surface convection zone (SCZ), produces differential rotation, with the base of the SCZ near the equator rotating somewhat faster than the stable zone immediately below it.

2. The differential rotation causes a seed poloidal magnetic field to be wound up and amplified, and thus generate buoyant, toroidal flux loops.

3. The combination of rotation, SCZ and buoyancy leads both to a cyclic variation of the poloidal magnetic field (an α, Ω dynamo), and to the expulsion and destruction of magnetic flux above the photosphere.

4. The destruction of magnetic flux leads to a hot corona and a stellar wind beyond it, of strength $\dot{M}$ say.

5. The stellar wind interacts with the poloidal magnetic field out to an Alfvénic radius $r_{\rm A}$ ($\sim 10\, R_{\odot}$, for the Sun), picking up angular momentum from the rotation

6. Beyond the Alfvén radius the wind expands freely, carrying off both mass and angular momentum.

7. In a binary of short period, tidal friction couples the rotation of each component to the orbit, and so magnetic braking with tidal friction (MBTF) causes the orbit to spin *up*, thus tending to amplify the effect in the long term; whereas in a single star magnetic braking causes the star to spin *down*, and thus tends to diminish the effect in the long term.

It is not difficult to think of some mathematical formulation that will link both $\dot{M}$ and $r_{\rm A}$ to the independent variables M, R, L, Ω. In addition we need a formulation of the couple due to tidal friction, which depends on the orbital period and eccentricity as well as on M, R, L, Ω. These formulae become extra differential equations and boundary conditions for the set of structure equations for a stellar interior. In addition there need to be equations for mass transfer in semidetached and contact binaries, and for luminosity transfer in contact binaries. The ensemble is best treated as a set of 2N simultaneous equations in 2N variables, where N is the number of variables in each component star.

I think the following processes, six in number, represent the best current simplification of the evolution of close, low-mass binaries:

(i) nuclear evolution (NE),

(ii) Roche-Lobe overflow (RLOF),

(iii) mass loss by stellar wind enhanced by rapid rotation (ML),

(iv) angular momentum loss by stellar wind, magnetic braking and tidal friction (MBTF),

(v) mass transfer in contact, potentially in either direction (MT), and

(vi) heat transport from one component to the other during contact (HT).

It seems to me that, unfortunately, at least the first four processes, and all six in the case of contact binaries, have comparable rates, when we consider specifically lowish-mass ($M_1 + M_2 \sim 1 - 3\,M_\odot$) and short-period ($\lesssim 4\,\mathrm{d}$) binaries. One would like to be able to say that at least in such and such a system ML is negligible, and in some other NE is, but I think that is dangerous. For example, we might see a system in which the masses seem to low for NE, and so be inclined to dismiss NE; but the masses might be that low because ML has operated for a Gyr or two, and in its earlier life NE was *not* neglible.

Standard understanding of the centrifugal-gravitational (Roche) potential of close binaries suggests that close binaries can be divided into four categories:

(D) detached binaries,

(SD1) semidetached binaries in which the more massive component is the one that fills its Roche lobe (reverse Algols),

(SD2) semidetached binaries in which the less massive component is the one that fills its Roche lobe (normal Algols), and

(C) contact, or, as some would say, overcontact binaries, where both components overfill their Roche lobes up to the same equipotential surface.

Analysis of observational data sometimes does unequivocally place a given system in just one of these four categories, but quite often there is some ambivalence, notably because in all of these systems there are liable to be starspots that distort the light curve. Although starspots can be modeled, it is not clear that such modeling is unique, particularly since there may be hot regions as well as cool regions. Given the great difficulty in practice, if not in principle, of distinguishing between these four geometries when the periods are very short, I am glad that the term 'near-contact binaries' has become fairly widespread. This term will probably include some binaries that in a really rigorous examination turn out to be genuinely in contact; but it is a convenient shorthand for SD1/SD2 binaries in which it is not clear which way the geometry goes.

Table 1 is a tiny selection of a few systems that illustrate, I hope, some of the points I wish to make. I believe that DV Psc is the shortest-period binary that is very plausibly detached, but there are several more, like XY UMa, that have periods of less than a day. What helps to make such stars 'very plausibly detached' is that both radii are about right for MS stars of those masses, in fact almost right even for ZAMS stars. For XY UMa, we might note that a $1.1\,M_{\odot}$ star at ZAMS has a radius slightly under $0.9\,R_{\odot}$, and so $*1$ must have undergone a Gyr or two of NE. This might be taken to mean that ML has not been significant in these systems, but actually one can only conclude that NE has not been very significant.

The strongest indications that ML *is* important, for at least some of these systems, come from Z Her, R CMa and TV Mus, which are D, SD2 and C systems respectively. The primary in Z Her has lost at least $0.3\,M_\odot$, and presumably more since (a) it would have had to be the more massive initially, and (b) the companion may well have lost some mass too. The *total* mass of R CMa is so low that one can hardly imagine an RLOF history that would get it to its present configuration without having started from a greater total mass. TZ Boo has, at present, a total mass of $0.83\,M_\odot$. It is hard to see how either component could be an evolved remnant, and yet *both* components are oversized for their masses. The easiest explanation of the present radii at the present masses is that $*1$ has lost mass, mostly by stellar wind but perhaps also slightly by mass transfer, and started at $\gtrsim 1\,M_\odot$ so that NE could have taken place on a reasonable timescale in the past. $*1$ is now $\sim 30\%$ oversized because of former NE, although $*1$ is now of such low mass that it is hardly capable of more NE. I believe that the SD2 system W Crv also in practice supports the likelihood of lost mass; although one can just about account for the system with conservative evolution, it would take more than a Hubble time to get to its present configuration through RLOF but without systemic mass loss.

There are many C and SD2 systems that indicate that at least $\sim 0.2\,M_\odot$ has been lost, and probably more. My experimental algorithm for ML usually gives values of $\sim -2 \times 10^{-11}\,M_\odot/\mathrm{yr}$ for stars of about $1\,M_\odot$ and rotation periods $\lesssim 2\,\mathrm{d}$.

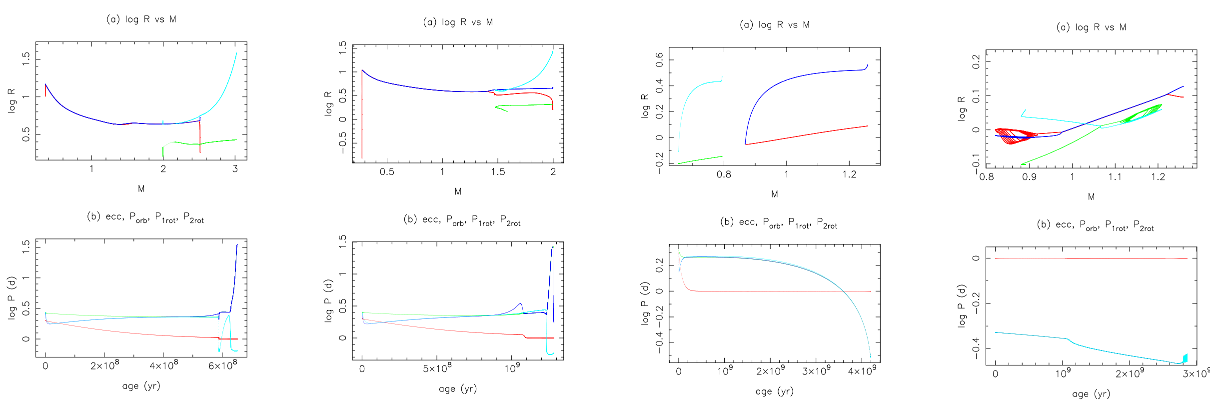


Fig 1 (left 2 panels) to Fig 4 (right two panels). (a) Top row: log(radius) versus mass for both components, and for both Roche lobes. (b) Bottom row: eccentricity, orbital period, and each stellar rotation period. See text for details.

Figs 1 to 4 are a very sparse selection of cases that I have computed in or near the mass and period range I concentrate on. Fig 1 is slightly on the massive side, and illustrates NE with rather insignificant ML or MBTF. The masses started at $2.5 + 2\,M_\odot$ and ended at $0.4 + 3.0\,M_\odot$, by which time $*2$ shrank to a WD. The period started at 2.7 d, and ended at

32 d. Although the amount of mass lost, at ~25%, was not trivial, it had only a modest effect on the evolution as compared with completely conservative evolution. Most of the wind mass loss occurred when $*1$ was already a red giant.

Fig. 2 is a somewhat less massive system: $(2.0 + 1.6\,M_\odot; 2.5\,\mathrm{d})$. The result is somewhat similar to Fig 1, but now with some quite substantial mass loss $(0.5\,M_\odot)$ *before* RLOF begins. The final parameters are $0.25 + 2.0\,M_\odot; 25\,\mathrm{d}$. One can say that NE and ML are very comparable here.

Fig. 3 shows a somewhat less massive and closer system still: $(1.25 + 0.8\,M_\odot; 2.1\,\mathrm{d})$. There is little NE in this system, but quite a lot of both ML and MBTF. The primary's mass drops by over 30%, while the period drops to 0.3 d. The evolution till RLOF took ~4 Gyr.

Fig. 4 is a case (rather rare, I'm afraid) where the code held together for some time after the system evolved into contact. The initial parameters were $(1.25 + 0.9\,M_\odot; 0.5\,\mathrm{d})$. The system came to RLOF in 1 Gyr, was semidetached (SD1 $\rightarrow$ equal masses $\rightarrow$ SD2) for 1.5 Gyr, and then oscillated between a contact state and an SD1 state. This would probably have gone on for a long while, but I let it do only 10000 timesteps.

It is clear that some systems can avoid contact, and others can not. It is rather less clear where the boundary is in the 3-dimensional initial M_1, M_2, P space, because the physics of ML and MBTF is not clear. If a system does indeed evolve into contact, then there is further uncertainty because a model is needed for both MT and HT. I believe that the details of a model for MT are not important, as long as it says that matter flows away from the component whose surface is at the higher Roche potential. I implement this by using a Bernoulli-like model for flow, as in the classic case of water flowing over a weir. I integrate this equation through the layers of both stars that are above the potential at the inner Lagrangian point.

HT is more uncertain, but I have become convinced that the essence of HT is *differential rotation*, of the sort observed in the Sun by helioseismology. Returning to the dynamo model I mentioned briefly at the beginning, it is reasonable to suppose that all stars with deep(ish) convective envelopes have faster rotation near the base of the envelope thasn elsewhere. In a frame that rotates with the *average* angular velocity of the Sun, a region extending to roughly $\pm 30°$ from the equator, and to a depth of 30% of the radius, is rotating about 5% faster. It is easy to confirm that this means that an *enormous* horizontal flux of heat is being advected: about $3000\,L_\odot$. This makes no difference to the Sun of course, because the Sun is roughly axisymmetric. But if the Sun were in contact with a star of half its mass, both components would be presumably driving differential rotation (in the same direction!). The contact envelope will not of course be 30% deep, but it may be 2 – 5% deep, and this could mean ‘only’ perhaps $30\,L_\odot$, which is still more than sufficient to bring the surface temperatures into rough agreement.

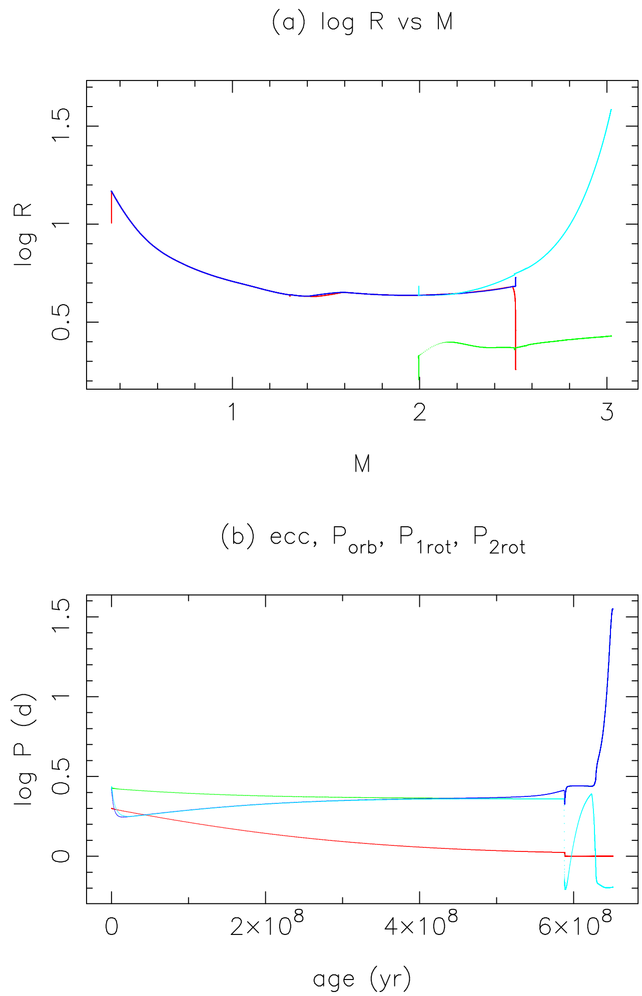
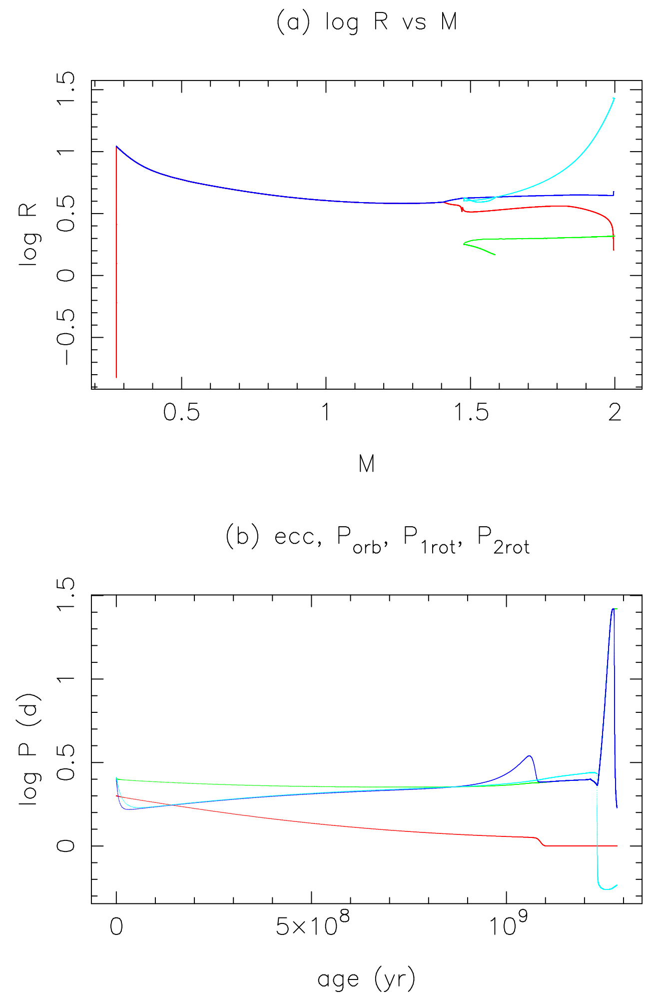


Fig. 1. A system which is slightly on the massive side, and illustrates NE with rather insignificant ML or MBTF. The masses started at $2.5 + 2\,M_\odot$ and ended at $0.4 + 3.0\,M_\odot$, by which time $*2$ shrank to a WD. The period started at 2.7 d, and ended at 32 d. Although the amount of mass lost, at $\sim 25\%$, was not trivial, it had only a modest effect on the evolution as compared with completely conservative evolution. Most of the wind mass loss occurred when $*1$ was already a red giant.



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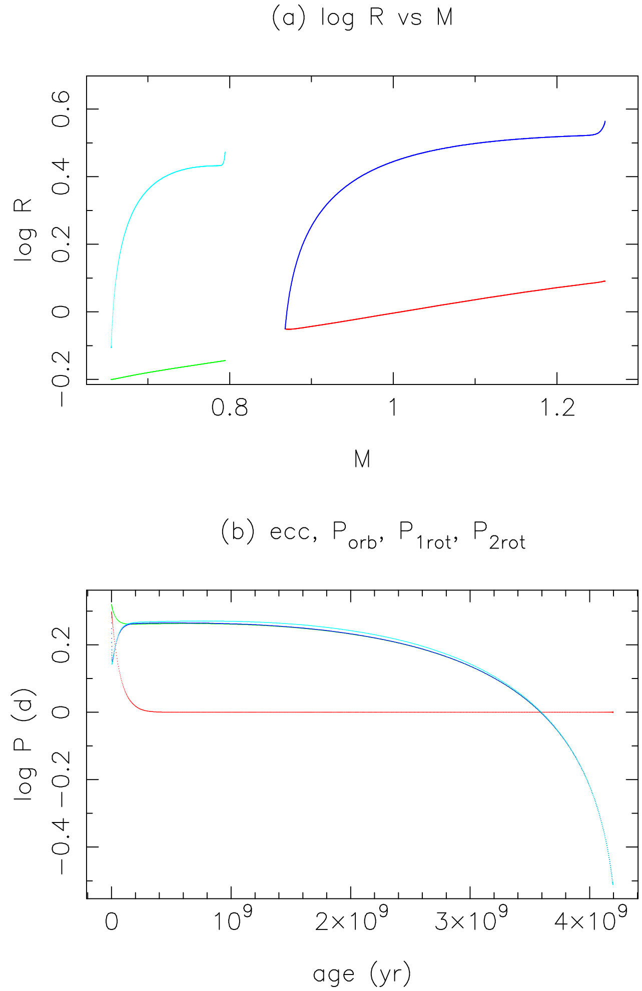

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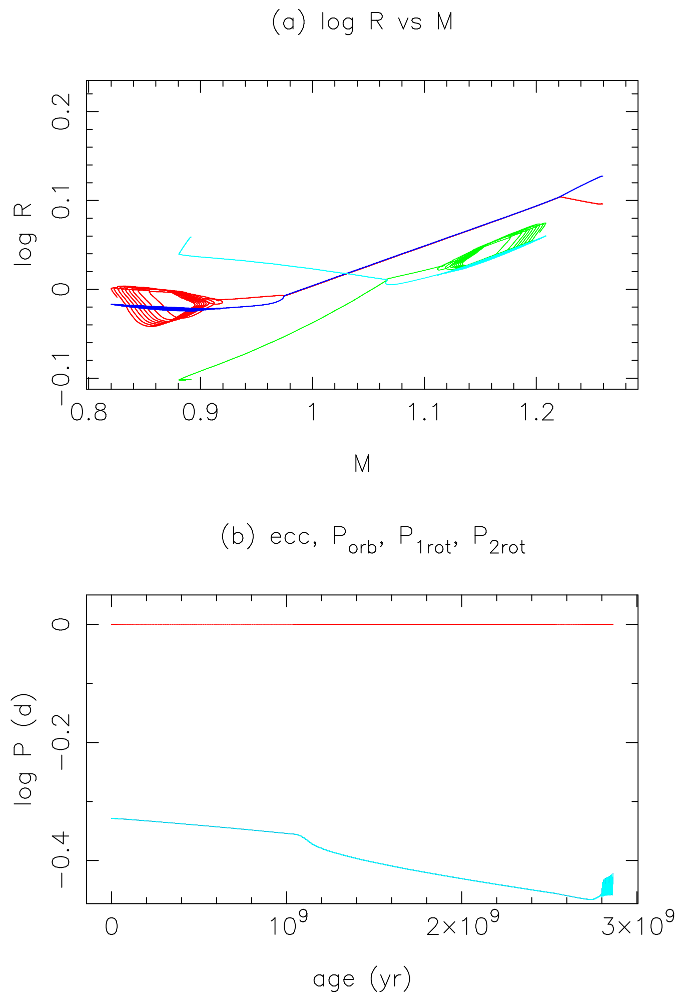

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Table 1. Some Very Close Binaries (VCBs).

Type	Name	V	T_1	T_2	P	M_1	M_2	R_1	R_2
D	XY UMa	10.2	5200G9V	4125K6V	.4790	1.10	0.66	1.16	0.63
D	DV Psc	10.6	4450K4V	3600M1:	.3085	0.70	0.49	0.68	0.51
D	Z Her	7.3	4980K0IV	6400F4	3.992	1.31	1.61	2.73	1.85
SD1	V 361 Lyr	13.7	6200F8	4500	.3096	1.26	0.87	1.02	0.72
SD1	[HH97]FS-79	13.6	4100K7Ve	3425M3Ve	.2508	0.59	0.31	0.67	0.48
SD2	R CMa	5.7	4300G/KIV	7300F1	1.136	0.17	1.07	1.13	1.48
SD2	W Crv	11.8	4900	5700G6	.3881	0.68	1.00	0.92	1.01
C	TZ Boo	10.4	5890G1	5754G5	.2976	0.72	0.11	0.97	0.43

Note. — XY UMa, Pribulla et al. (2003); DV Psc, Zhang & Zhang (2007); Z Her, Popper (1988); V 361 Lyr, Hilditch et al. (1997); [HH97]FS-79, Austin et al. (2007); R CMa, Sarma et al. (1996); W Crv, Rucinski & Lu (2000); TZ Boo, Hilditch et al. (1988)