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The Formation of Contact and Very Close Binaries

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Abstract. We explore the possibility that *all* close binaries, i.e. those with periods $\lesssim 3\,\mathrm{d}$, including contact (W UMa) binaries, are produced from initially wider binaries (periods of say 10's of days) by the action of a triple companion through the medium of Kozai Cycles with Tidal Friction (KCTF).

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Contact binaries are short-period, usually eclipsing, binaries that make up $\sim 0.2\%$ of F/G/K stars in the solar neighborhood. The components are so close that they touch, and even overlap (by about $1-5\%$ in radius), so that it is a semantic question whether they are really two stars, or one star with two cores. Periods are mainly in the range $0.2-0.5\,\mathrm{d}$. In fact contact binaries are also found at OB spectral types, with longer periods, but we put them outside the scope of the present discussion.

Pribulla & Rucinski (2006) noted that in a reasonably complete sample of 88 northern contact binaries, 52 ($59\% \pm 8\%$) show evidence of a third body. Given the difficulty of determining the presence of a third body except in favorable circumstances, this argues for the likelihood that *all* contact binaries are in triples, and hence that 'triplicity' is *necessary* for the formation of a contact binary.

Tokovinin et al. (2007) considered a sample of 161 stellar systems containing spectroscopic binaries (SBs) with periods $<30\,$d, and looked (by adaptive optics) for companions, for those for which companions were not already known. They found that among those with period $<3\,$d, 32 out of 41 were triple; and making allowance, by a maximum-likelihood procedure, for incompleteness they concluded that the fraction of triples must be $\sim 96\%$. For SBs with periods $>12\,$d the figure was lower (34%). We therefore feel that there is a good case for the hypothesis that very close binaries form as a consequence of the presence of a third body. The mechanism seems likely to be a combination of Kozai cycles with tidal friction (KCTF hereafter, following Eggleton & Kisseleva-Eggleton 2006). For the closest binaries, i.e. the contact binaries, we have to add another mechanism, magnetic braking also combined with tidal friction (MBTF hereafter).

For a recent discussion of Kozai cycles, and the KCTF mechanism, see Fabrycky & Tremaine (2007). Earlier discussions have been by Mazeh & Shaham (1979) and Kiseleva, Eggleton & Mikkola (1998; hereafter KEM98), for instance. The orbit of the third body has to be inclined by at least 39° to the orbit of the close pair and at most 141°; for present purposes it is adequate to assume that the behavior is symmetric about 90°. If third-body orbits are assumed to be randomly oriented relative to the inner pair then the distribution of $\cos\eta$, where η is the mutual inclination, should be uniform. Thus the probability is 50% that $\eta > 60°$, and at this inclination Kozai cycles can already be quite large, with the eccentricity cycling between zero and 0.76 (or between 0.3 and 0.81; see Eggleton 2006, Table 4.9).

Although determining the inclination of each orbit to the line of sight is not difficult in favorable cases, determination of the mutual inclination is rather difficult. Muterspaugh et al. (2006) list just six systems for which η has been determined. These inclinations range from 24° to 132°; two are retrograde and four prograde. A simple test excludes the likelihood that the distribution is uniform over $\cos\eta$, but with only six systems there is a considerable margin of uncertainty. There is in addition the likelihood that the distribution is itself already modified by Kozai cycling, which will tend, on average, to increase the observed $|\cos\eta|$.

The duration of a Kozai cycle is

$$T_{\rm KC} \sim \frac{P_{\rm out}^2}{P_{\rm in}} \cdot \frac{M_1 + M_2 + M_3}{M_3}$$

This can be as short as a thousand years, e.g. for Algol (β Per) with inner and outer periods 2.87 d and 1.86 y. Algol is one of the six systems with known η: $\eta = 99 \pm 5^\circ$. Algol should *not* now be undergoing Kozai cycles, because the quadrupolar distortions of the stars in this semidetached binary are sufficiently large as to quench the small but persistent effect of the third body on the orbit. However it is quite likely that Algol *did* suffer KCTF in its youth (KEM98), when both components were close to the ZAMS.

To determine the capacity of KCTF to produce short-period inner systems, we need to include the modifications to the inverse-square-law gravity that come from

1. the quadrupolar distortion of each component due to the other
2. the quadrupolar distortion of each component due to its intrinsic spin
3. General Relativity.

All three effects produce apsidal motion, and if this apsidal motion is comparable to the apsidal motion driven by Kozai cycles then the cycles are liable to be quenched. The effect of tidal friction has to include spin-orbit interaction for arbitrary inclination of the intrinsic stellar spin to the orbit. This was first worked out by Eggleton, Kiseleva & Hut (1998), but as that treatment contained some typographical errors the reader is referred to Eggleton (2006), in which (so far!) none have been detected, at least where the tidal-friction analysis is concerned.

We deal with tidal friction only in the 'Equilibrium Tide' (ET) approximation (Darwin 1880; Hut 1981). It can be argued that this is too simple an approximation in systems where the eccentricity may approach or exceed 0.99. However, alternatives appear to be very costly in terms of computational time, and cannot be considered as necessarily more accurate in the extremes that can arise. At some stage it will be desirable to model a close, extreme periastron passage using a fully 3D treatment such as the code `Djehuty`, which has modeled successfully the helium flash in 3D (Dearborn, Lattanzio & Eggleton 2006).

The ET theory gives definite prescriptions for the equations governing the dynamical effect of tidal friction, but leaves somewhat uncertain a numerical factor multiplying the strength of the dissipation. It is usual to assume that the viscosity which determines the dissipation is 'turbulent viscosity', and also to use some rather crude average of the mixing-length theory over the convective core or envelope. We use an improvement to this average, which comes from an exact (to first order) solution for the tidal velocity field within the star (Eggleton 2006).

We therefore integrate, by a stepwise procedure, equations which govern the rate of change of the inner orbit, and also of the spins of the two inner components; all these are treated vectorially so that spins are not necessarily parallel to the orbit. We include a simplistic treatment of stellar evolution, and also of mass-loss and angular-momentum loss by stellar winds. The latter are only important on timescales of Gigayears, but then so quite often is KCTF.

Figs 1 – 3 illustrate those portions of the $\log P_{\rm out}\,({\rm yr})$, $\log P_{\rm in}\,({\rm dy})$ plane where different physical processes predominate. The blank region in the upper left is where Kozai cycles do not occur, because either GR or quadrupolar distortion quenches them. The blank region to the lower right is where $P_{\rm in}$ and $P_{\rm out}$ are sufficiently close together that the system is dynamically unstable: we approximate this by $P_{\rm in} \geq 0.2 P_{\rm out}$. The intermediate shaded region has three textures: dots indicate a region where Kozai cycles operate but tidal friction is too slow to modify the orbit significantly in 3 Gyr; circles indicate a region where tidal friction is so significant that dissipational luminosities are in excess of the stellar luminosities; and plusses are a region where KCTF operates in a relatively straightforward fashion, reducing the inner orbit to a short-period circular one in less than 3 Gyr but not so quickly that the dissipation contributes substantially to the stellar luminosities.

In Figs 1 – 3 the three masses are $((1.0{+}0.6){+}0.9)\,M_\odot$. The inclination is $\cos\eta = 0.1, 0.3, 0.5$ successively in the three Figures. The effect of KCTF on systems marked by plusses is to move them horizontally towards (and usually somewhat beyond) the left-hand edge of the dotted region. This is illustrated in Fig. 4, where we plot the eccentricity, inclination and inner period as functions of time. This system started with $P_{\rm out} = 100\,{\rm yr}$, $P_{\rm in} = 100\,{\rm dy}$ and $\cos\eta = 0.1$. Individual Kozai cycles are about $3.10^4\,{\rm yr}$ to start with; they are severely undersampled by the plotting routine, at less than one point per cycle. The whole process is almost over in about 30 Myr. The final period of the circular orbit is about 2.3 dy.

It is a curious feature of KCTF that as TF starts to work it makes the *minimum* eccentricity (in the course of a cycle) *larger*, whereas one might rather expect that it would make the maximum eccentricity smaller while also shrinking the orbit. The orbit remains almost as large as it was initially, as the cycles in e diminish in size, and only when the eccentricity has become almost constantly large does the orbit as a whole shrink substantially.

Fig. 4 shows only the first 50 Myr. But if the code is run to well over a Gyr the effect of MBTF can be seen on $P_{\rm in}$. By $\sim 2\,{\rm Gyr}$ the inner system should come into contact.

Our work has not yet clarified the issue of what happens to the systems marked by circles in Figs 1 and 2. These have quite short Kozai cycles, in which our estimate of tidal friction leads, if followed naively, to rates of change of (inner) orbital energy that are comparable to the rate at which the components are losing energy by nuclear reactions. One possible answer is that tidal friction simply cannot work that fast, which probably means as a consequence that the stars crash into each other, and merge. But we intend to explore the possibility that there is an escape route, at least for some of these systems: as the inner orbit becomes more eccentric and tidal friction begins to contribute to the stars' luminosities, the stars may swell, and this could increase the quadrupolar distortion to the point where further progress along the Kozai cycle ceases, and the situation stabilises itself at a modest rate of dissipation.

Acknowledgments

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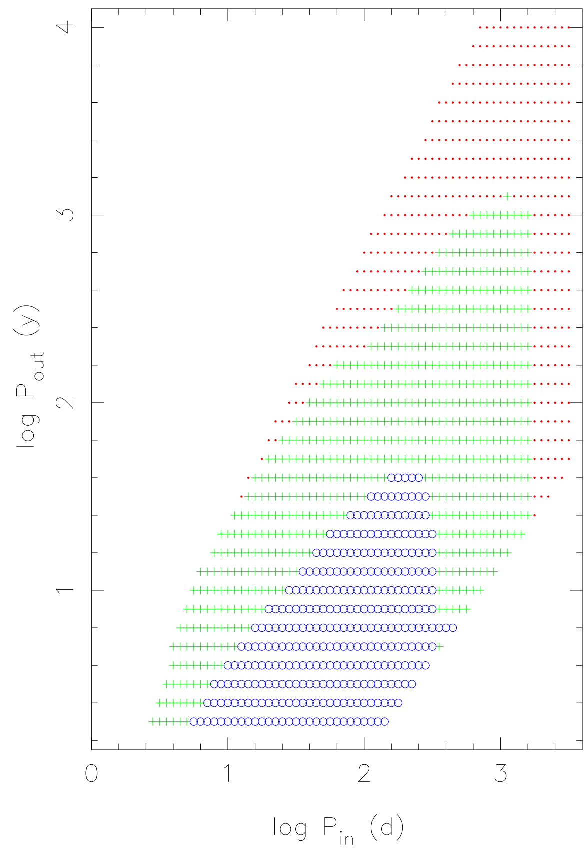

Fig. 1 – The oucome of KCTF on triples with a range of $P_{\rm in}$, $P_{\rm out}$. Initial masses were ((1.0+0.6)+0.9) $M_\odot$, and the initial inclination was $\cos\eta = 0.1$ ($\eta = 84.3°$). Dots: systems where KCTF was too slight to make much difference in 3.10^9 yrs. Plusses: systems where KCTF decreased $P_{\rm in}$ at constant $P_{\rm out}$ from the position indicated to a final position near and somewhat beyond the left-hand boundary of the shaded region. Circles: as plusses, but the KCTF was so intense that significant luminosity would have been added to the members of the inner pair; the outcome of these systems is unclear.

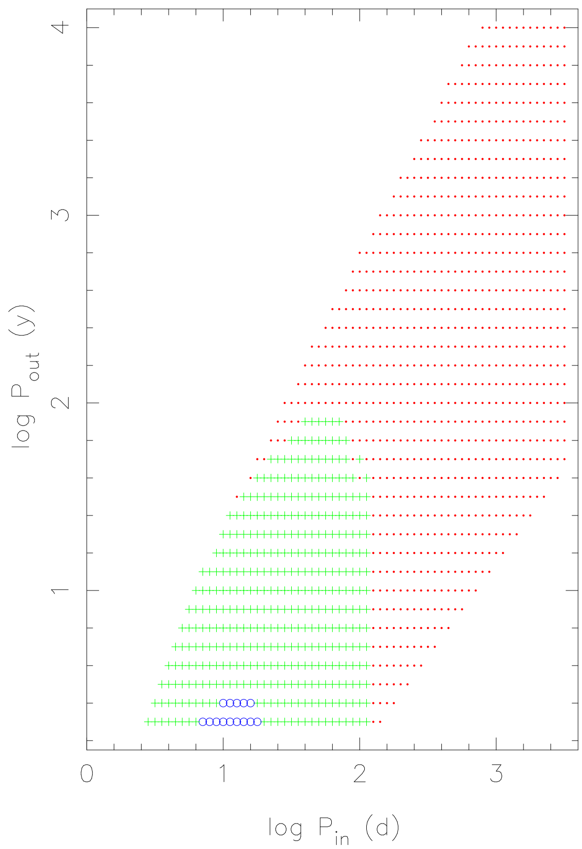

Fig. 2 – As Fig. 1, but with initial inclination $\cos\eta = 0.3$ ($\eta = 72.5°$).

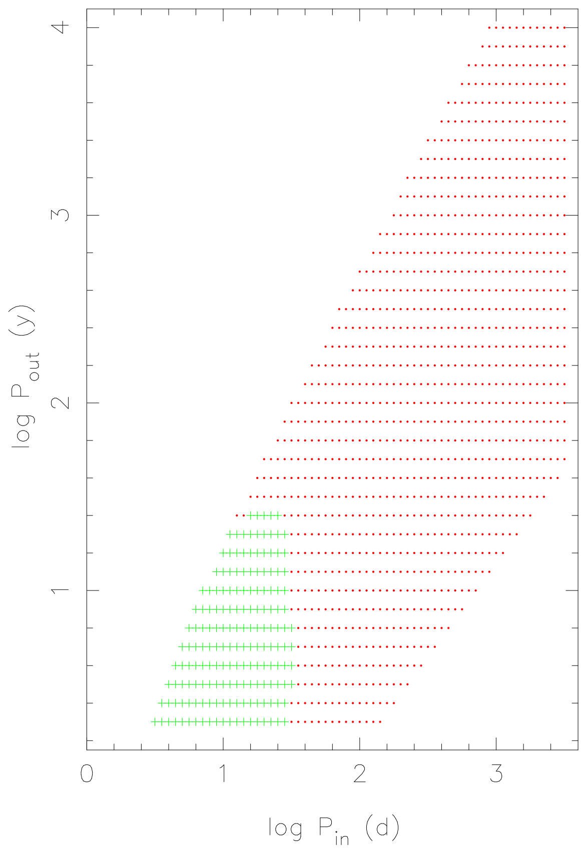

Fig. 3 – As Fig. 1, but with initial inclination $\cos\eta = 0.5$ ($\eta = 60°$). On a statistical model, a half of all triples would have mutual inclination η as large as this or larger (Figs 1, 2).

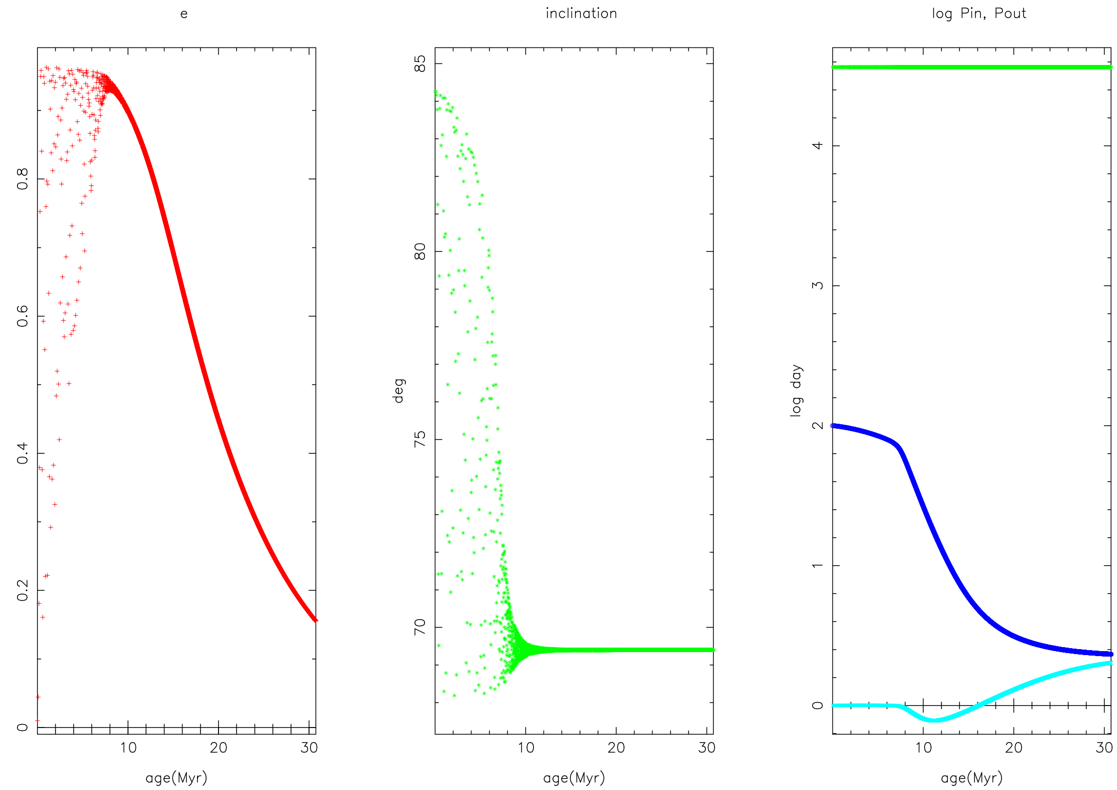

Fig. 4 – The evolution under KCTF of a single system from Fig. 1: $P_{\rm out} = 100\,{\rm yr}$, $P_{\rm in} = 100\,{\rm d}$. The first panel shows the eccentricity; the Kozai cycles are severely undersampled by the plotting process. The system cycled powerfully for about 8 Myr, then settled to a steady diminution of e for about 40 Myr. The second panel shows the mutual inclination, which also cycled strongly for the first 8 Myr, before settling at $\sim 69°$. The third panel shows the periods: $P_{\rm out}$, top line; $P_{\rm in}$, middle line; $P_{\rm rot}$, lowest line.