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Evolutionary Processes in Multiple Systems

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Summary. There are several ways in which triple stars can evolve in somewhat unusual ways. We discuss two: situations where Case A Roche-lobe overflow, followed by a merger, can produce anomalous wide binaries such as γ Per; and Kozai cycles in triples with non-parallel orbits, which can produce merged rapidly-rotating stars like (we suggest) AB Dor, and which can also lead to the delayed ejection of one component of a multiple, as may have been observed in T Tau in 1998.

1 Introduction

We identify two classes of triple system that are likely to be of particular interest regarding their evolutionary history, past or future. These are
(a) those in which the *outer* orbit has a period less than $\sim$ 30 yr, because evolution in such systems might bring about Roche-lobe overflow (RLOF) in *both* orbits, presumably at different times
(b) those in which the outer orbit, which might be of much longer period than in (a), is highly inclined ($\eta > \sin^{-1}\sqrt{2/5} \sim 39°$) to the inner orbit, because in such systems Kozai cycles (in combination with tidal friction) can severely modify the inner orbit.

These two classes can overlap substantially. For instance β Per has an outer orbit of less than two years, and a mutual inclination $\eta \sim 100°$ [9].

The statistics of these classes are not well known, but we can make some reasonable estimates. Binary systems constitute probably $\sim$ 50% of stellar systems, and triple or higher-multiple systems may be $\sim$ 10% in addition, leaving perhaps 40% single, but with wide error bars on each percentage. By 'system' in this context we mean single and binary stars as well as multiples. Among the 60 systems nearer than $\sim$ 5.5 pc (61 including the Sun), about 20 are binary (including three with massive planets) and 8 are triple, but the census of multiples continues to increase slowly, e.g. [11]. Nearby stars are usually of low mass, and massive stars appear to be even more likely to be binary or multiple.

Something like 4540 systems have a (combined) Hipparcos magnitude $Hp < 6.0$. About 3050 are currently not known to be other than single, about 1130 double, and the rest (about 360) appear to be higher multiples. Of the last group, about 40 fall in category (a) above. This is only about 1%, but it is likely that this is a *severe* underestimate. If we restrict ourselves to the much smaller sample of about 450 systems brighter than $Hp = 4.0$, singles, doubles and higher multiples are about 240, 140 and 70. These proportions of binaries and multiples are substantially higher, and suggest that there is a considerable degree of incompleteness regarding the larger sample. Eleven of the smaller sample fall in category (a), i.e. about 2.5%. Thus it is reasonable to suppose that even 2.5% is only a lower limit, at best.

The sample of ~ 4500 bright stars is of course not very representative of stars as a whole; for example it lacks M dwarfs (except as low-mass companions), and M dwarfs are much the greater part of stars as a whole. But the sample is fairly representative of those stars in the Galaxy which are massive enough to undergo significant evolution in a Hubble time.

The statistics of mutual inclinations are harder to come by, because even if the inclinations to the line-of-sight of both orbits (in a triple) are known, the mutual inclination is somewhat indeterminate (see Sterzik & Tokovinin 2002 [17]). The mutual inclination of 100° in β Per, referred to above, was the result of VLBI astrometry, which has been applied so far to only a handful of systems ([12]).

From a theoretical point of view, one might arrive at either of two fairly contradictory conclusions regarding the distribution of inclinations. On the one hand, successive fragmentation of a proto-stellar gas cloud might be seen to imply that typically multiple systems would have roughly coplanar orbits. On the other hand, dynamical interactions between systems while they are still in the fairly small confines of a star-forming region might randomise the relative orientations in multiples, before they get scattered out into the general Galactic environment where such interactions would become rare. Randomisation might imply that the mean inclination is $\sim 60^\circ$, which is more than enough to put systems in category (b) above. For the purposes of the present article, we will attach more weight to the second possibility.

Muterspraugh et al (2005) [12] list six systems with unambiguously known mutual inclinations, including Algol; the results are marginally inconsistent with randomisation, but two exceed the Kozai limit (39°) considerably, two by small amounts, and two are below it. Our subjective impression is that the distribution is totally inconsistent with the hypothesis of near-coplanarity.

2 Multiples with two periods less than 30 years

In a triple where the outer period is sufficiently short we can anticipate two distinct episodes of RLOF. Which occurs first probably depends most on which of the three components is the most massive. We [2] have already discussed some of the wealth of possibilities that might arise. Consequently we discuss here only one possibility, since it has ramifications beyond what was perceived in 1996.

Suppose that the most massive component is in the close pair. RLOF has a quite high probability of producing a merger. Nelson & Eggleton [13] considered a large sample of theoretical models undergoing RLOF in Case A. If the initial mass ratio was fairly large ($\gtrsim 1.5 - 2$), evolution into contact was almost certain. And evolution into contact was also almost certain if the initial period was short – even by the standards of Case A. Although evolution once contact is established is uncertain, the most likely outcome seems to be a merger. The net result is that the system changes from triple to binary. In many cases it will be difficult to know that a particular observed binary is a merged former triple, rather than a system that has always been binary. But in some cases it may be fairly evident, because the binary might have some remarkable properties.

R. E. M. Griffin (1996, private communication) has drawn attention to the fact that several 'ζ Aur' systems have components that seem to violate what we would expect from simple binary evolution. She refers to the problem as 'oversized secondaries'. These binaries consist typically of a G/K giant or supergiant paired with a B/A main sequence (MS) star, in a fairly wide orbit, sufficiently wide that no RLOF is to be expected (yet). If in such a system the mass ratio is greater than about 1.2 (giant/dwarf) we would expect the dwarf to be rather little evolved, since rate of evolution is very sensitive to mass. Yet several ζ Aur systems have quite highly evolved secondaries, at least to the extent that the B/A dwarf is near the upper edge of the MS band rather than the lower edge.

A good example of an oversized secondary is γ Per [15]. The observed parameters are (G8III + A3V, $2.5 + 1.86\ M_{\odot}$, $21 + 4\ R_{\odot}$, 5350 d, $e = .79$). The mass ratio is about 1.34, and yet the radius of the A dwarf is more than 2.5 times what we expect for an unevolved star of its mass. It is *very* difficult to account for these parameters with conventional evolution. We suspect that the G8III component was once a close binary, with parameters guessed as $(1.9 + 0.6\ M_{\odot}, 1 - 10\ \mathrm{d})$. This would allow it to reach RLOF when the A dwarf was close to or slightly beyond the end of its MS life, and the RLOF, whether in Case A or Case B, would be likely to end up (fairly quickly) with a merger because of the rather large mass ratio. The merger remnant would either already be a red giant (in Case B) or else would very quickly become one (in Case A).

A system somewhat similar to our suggested initial system is β Cap, with parameters (B8V + ?; 8.68 d) + K0II-III; 3.76 yr and (3.3 + 0.9) + 3.7 $M_{\odot}$ [3]. This is actually part of a sextuple system, but the other three components are rather far away. The close pair is single-lined, so that there is an element of guesswork in the masses. The masses are a little on the large side to produce γ Per, and the two highest masses would have to be interchanged, but it is gratifying that even in the small number of triples that are of comparable brightness to γ Per there is one at least with parameters not grossly different from what we require.

We might expect the G giant in γ Per to be rapidly rotating as a result of its merger, and unfortunately it is not. However rapidly rotating G/K giants are likely to be very active, through dynamo activity, and can be expected to spin down to normal speeds quite quickly. We therefore feel that this is not a major problem for our theoretical interpretation.

How prevalent is the problem of oversized secondaries? Among the ~ 4500 bright stars, we identify about 15 ζ Aur systems which have been sufficiently analysed for a reasonably reliable estimate of the masses and radii. There are many more which have not yet been sufficiently analysed. Of these 15, 4 [16] have secondaries which we judge to be substantially oversized: γ Per, δ Sge, QS Vul (HR 7741) and ζ Aur itself. The remaining 11 agree reasonably well with the theoretical expectation that the size of the the secondary relative to the ZAMS radius appropriate to its mass should correlate in a particular way with the mass ratio: anticorrelate, if we define the mass ratio as giant/dwarf.

Although 4 out of 15 may seem an awkwardly large proportion, we suggest that a selection effect may render these systems particularly conspicuous. Secondaries that are oversized will also tend to be overluminous: if the A star in γ Per had the 'right' size for its mass, it would be about 5 times less luminous, and in that case it might be barely measurable at all. It will be necessary to do a population synthesis that takes account of the distribution of *triple*-star parameters, and that also takes account of selection effects, in order to see whether our proposed solution can work. We (X. Dearborn and P.P.Eggleton) are currently undertaking such a study.

A former triple might show up in other ways. V471 Tau is a well-known white dwarf/red dwarf binary in the Hyades. Its period is short (0.5 d), and the system is likely to be a remnant of common-envelope evolution in an earlier (and wider) red giant/red dwarf pair. The white dwarf is hot and luminous, and so is expected to be 'young'. It should therefore be less massive than the other white dwarfs in the Hyades, which are cooler, fainter and therefore 'older'. But in fact it is the most massive (O'Brien et al 2001 [14]). These authors have suggested that the white dwarf was a blue straggler previously, and that the blue straggler was the merged remnant of a previous *close* binary, a sub-component of the previous *wide* binary.

3 Multiples with highly inclined orbits

In the discussion of the previous Section it was taken for granted that the orbital periods for the two binaries that make up a triple do not change in time, except in response to RLOF. However in systems with highly inclined orbits the eccentricity in the shorter-period subsystem will fluctuate substantially, due to the Kozai effect [8] of the third star; and tidal friction, which will operate most strongly when the eccentricity is temporarily at a maximum, may lead the inner orbit to shrink, perhaps by a considerable factor.

If the outer orbit of a triple is inclined at more than 39° to the inner, some parameters of the inner orbit, in particular the eccentricity and angular momentum but *not* the period or semimajor axis, are forced to cycle between two values. The larger value of eccentricity can be quite close to unity and is given by

$$1-\frac{1-e_{\rm min}^2}{1-e_{\rm max}^2}\cos^2\eta \;=\; \frac{2(e_{\rm max}^2-e_{\rm min}^2)}{5e_{\rm max}^2}, \tag{1}$$

where η is the angle between the two orbits and $e_{\rm min}$ is the minimum eccentricity. The maximum is unity if the orbits are exactly perpendicular. An analysis of the Kozai mechanism, in the quadrupole approximation, was given by Kiseleva et al. [7].

Table 1 gives some values for $e_{\rm max}$ as a function of η and $e_{\rm min}$. *If* the mutual inclination of the two orbits is random, as we hypothesised in the Introduction, then the cumulative probability of η is given in Col.2. The median inclination should be 60°, and this is quite enough to drive the eccentricity, at the peak of the cycle, to 0.764, even if the orbit is circular to start with. Further, 17% will have an inclination of over 80° and then the peak eccentricity is in excess of 0.974. Thus it is by no means improbable that the periastron separation may decrease by a factor of 40 in the course of a Kozai cycle.

Table 1. Limits of Kozai Cycles

η	prob.	$e_{\rm min}$	$e_{\rm max}$	$e_{\rm min}$	$e_{\rm max}$	$e_{\rm min}$	$e_{\rm max}$
0	.000	0	0	.3	.3	.5	.5
10	.015	0	0	.3	.309	.5	.510
20	.060	0	0	.3	.341	.5	.543
30	.124	0	0	.3	.407	.5	.600
40	.224	0	.149	.3	.521	.5	.679
50	.357	0	.558	.3	.669	.5	.772
60	.500	0	.764	.3	.808	.5	.863
70	.658	0	.897	.3	.914	.5	.937
80	.826	0	.974	.3	.978	.5	.984
90	1.00	0	1.00	.3	1.00	.5	1.00

It is noteworthy that the amplitude of the eccentricity fluctuation depends only on the inclination and eccentricity. It does not depend on the period of either orbit, for example. However the cycle time $P_{\rm K}$ depends on the periods in a very simple way:

$$P_{\rm K} \;\sim\; \frac{M_1+M_2+M_3}{M_3}\,\frac{3P_{\rm out}^2}{2\pi P_{\rm in}}\,(1-e_{\rm out}^2)^{3/2}. \tag{2}$$

This is much the same period as for precession and apsidal motion. Even a brown dwarf, or a major planet, might cause a Kozai cycle of large amplitude, with a period of $\lesssim 10$ Myr if the outer period is $\lesssim 100$ yr.

Three physical processes may, however serve to reduce the maximum eccentricity that is predicted by Table 1. They are (a) general relativity (GR), (b) quadrupolar distortion, due to rotation, in each of the inner pair, and (c) quadrupolar distortion of each star by the other in the inner pair. All three of these processes produce apsidal motion, and if this is comparable to the apsidal motion produced by the third body then they interfere with the Kozai cycle. The eccentricity still cycles (because all these processes are time-reversible) but over a range which may be much more limited.

In a particular case, we took all three masses to be equal (and solar), and $P_{\rm in} = 10$ d, $P_{\rm out} = 10$ yr. We started with both orbits circular, and with a mutual inclination of 80°. Introducing each of processes (a) – (c) in turn, the peak eccentricity was successively reduced, the biggest reduction being for mutual distortion (c); and when all three perturbations are included together the peak is reduced from 0.974 to 0.78. Thus the periastron separation is reduced by a factor of 4.5 rather than 40, but this is still enough to give tidal friction a good chance to operate on a reasonably short timescale; whereas in a 10 d near-circular orbit it would be very slow (several Gyr). Since tidal friction depends mainly on periastron separation, we can say that the *effective* period is as short as $10/4.5^{1.5} \sim 1$ d, and this is indeed the actual period which tends to be reached after several Kozai cycles, each taking $\sim 4 \times 10^3$ yrs.

If we attempted detailed modeling we would have to take into account the fact that it would be difficult for such a binary to dissipate as much orbital energy as is necessary in only a few Kyr. What we expect happens is that the orbital energy, being released by friction inside each star, will tend to expand the stars, increase their quadrupole moments, and so cause the eccentricity cycle to peak at a less extreme value still, so that the process is somewhat self-limiting. It will take many more Kozai cycles, but still the process can only stop when the orbit is circularised at much the same terminal period.

Figure 1 illustrates the region in $(P_{\rm in}, P_{\rm out})$ space where Kozai cycles and tidal friction are important. The whole of the shaded area is where Kozai cycles can occur. The lower boundary is caused by the fact that very close triples are dynamically unstable. The upper boundary is where processes (a), (b) and/or (c) prevent the Kozai cycles. The darkly shaded area is where tidal friction can shrink and circularise the orbit on a timescale of ~ 1 Gyr. This figure assumed a mutual inclination of 80°. The combined effect of Kozai cycles and tidal friction (KCTF) should be to move a system from its initial point within the darly shaded area horizontally towards the left-hand boundary, where it should ultimately settle.

We might note that if KCTF does reduce the inner orbit to a shorter-period circular orbit, it also modifies the mutual inclination towards the Kozai limit (39°, or 141° for retrograde orbits). In the six systems listed by [12],

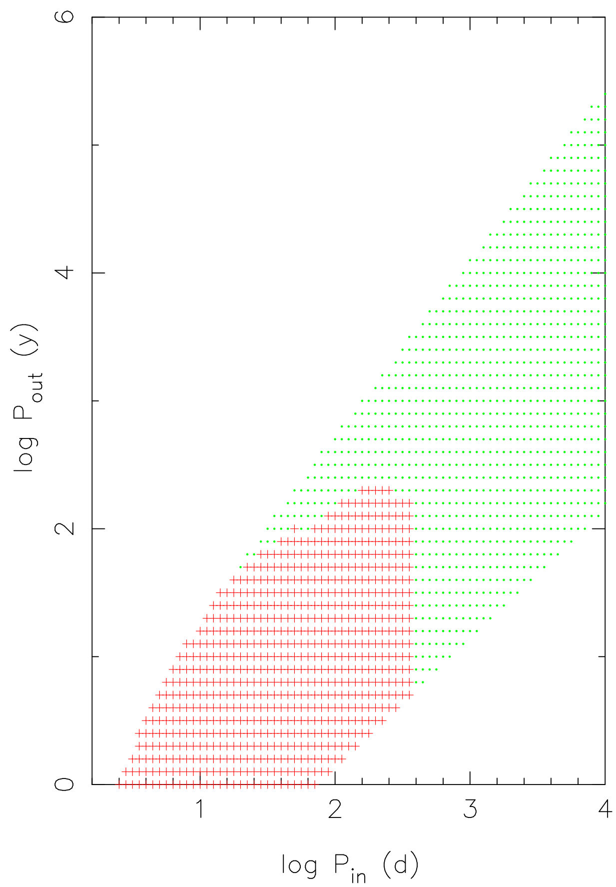

Fig. 1. The entire shaded area is where Kozai cycles, starting from $e = 0.01$ and $\eta = 80°$, are able to increase e to above 0.5 cyclically. The darkly shaded area is where the timescale of tidal friction at the peak of eccentricity is enough to reduce the eccentricity on a timescale of $\lesssim 1$ Gyr. The three masses were all 1 $M_\odot$.

two are within a few degrees of this limit, and may be the remnants of this process, having started with more perpendicular orbits.

Since the final $P_{\rm in}$ may be only a few days, or even less than a day if we consider M dwarfs rather than G dwarfs, it is possible for further shrinkage to take place by the mechanism of magnetic braking. Fairly low-mass (F/G/K/M) dwarfs are known to show anomalously strong activity (flares, spots etc.) when they are rapidly rotating, i.e. with periods under $\sim 5-10$ d. Usually this activity causes them to spin more slowly, by magnetic braking, and thus the activity is self-limiting. But in a close binary tidal friction can prevent the star from spinning down below the orbital period. The angular momentum is drained from the orbit rather than the stellar spin, and this causes the orbit and star to spin *up* rather than down. The process can therefore run away, although the 'runaway' is likely to be on a timescale of Myrs rather than days or years.

AB Dor is an unusually rapidly rotating K dwarf ($P_{\rm rot} \sim 0.5$ d). One might attribute its rapid rotation to youth. However (i) it is not in, or even particularly close to, any star-forming region, and (ii) Zuckerman et al. [19] identify it is a member of a rather loose moving group aged about 50 Myr. Its $V \sin i$ is 80 km/s, against an average of 11 km/s for 11 other K dwarfs in the group. We suggest that AB Dor is the result of a recent merger of the two components of a former close binary, perhaps of two early-M dwarfs, or a K dwarf and an L/T dwarf. There is a third (well, currently second) body, an object on the borderline of red/brown dwarfs, in an 11.75 yr, 0.032″ orbit [1, 5]. In fact there is also a further companion, AB Dor B, an M4e dwarf at 9.1″, which Close et al. [1] find also to be double (0.07″). The 9.1″ separation corresponds to a likely period of $10^3 - 10^4$ yr.

Perhaps the KCTF mechanism worked within the 11.75 yr orbit, on a primordial sub-binary that no longer exists, to produce an unusually close binary, and then the magnetic breaking mechanism shrank this binary to RLOF. We hypothesise a rather severe mass ratio, which makes it likely that RLOF will lead to a rapid merger, with the formation of a single rapidly-rotating star as observed. Probably the merger would be accompanied by rather substantial but temporary mass ejection. We imagine that this merger might have taken place only 1 or 2 Myr ago, so that the merger remnant is still rapidly rotating.

A very different possible outcome of Kozai cycling may be illustrated by another young system, the prototype young star T Tau. Loinard et al. [10] and Furlan et al. [4] suggested that a remarkable event occurred there in about 1998: one component of the multiple system was ejected from a bound orbit into an unbound orbit. This picture has been questioned more recently (Tamazian [18], Johnston et al. [6]), but until the picture settles down we shall follow the analysis of Furlan et al.

Furlan et al. followed the motion of 3 components that are part of the overall quadruple system. T Tau N is the most conspicuous and longest-known component. T Tau S, 0.73″ to the south, apparently consists of three components, two of them infrared sources (Sa, Sb) and one a radio source (Sc). As shown in Furlan et al.'s Fig. 3, Sc appeared to move round Sa in part of an elliptical orbit, over about 15 years, before passing close to Sb and then moving off at a tangent to one side. A possible interpretation is that Sa and Sb are in a somewhat wide orbit, with a period of decades, and that Sa and Sc were in a tighter orbit, with a period of ~ 20 yr, that was rendered unstable when a periastron of the larger orbit roughly coincided with an apastron of the smaller orbit.

It may seem odd that the system should take a Megayear or so to become unstable, when it might have been expected to become unstable in only a few decades. But this could be a natural consequence of Kozai cycling. The NS orbit is likely to be of order $10^3 - 10^4$ yr, and if well inclined to the (Sab +Sc) orbit might induce the latter to Kozai-cycle on a timescale of $10^5 - 10^6$ yr. This might cause the smallest orbit (Sa + Sb) to become unstable at a periastron of the intermediate orbit when its eccentricity was maximal. Thus it is not impossible that the breakup was considerably delayed, and only occurred recently.

4 Summary

Evolutionary effects within triple-star, or former triple-star, systems can take place which can produce effects that would be hard to understand in terms of conventional binary-star evolution.

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