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Kozai Cycles and Tidal Friction

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ABSTRACT

Several studies in the last three years indicate that *close* binaries, i.e. those with periods of $\lesssim 3\,\mathrm{d}$, are very commonly found to have a third body in attendance. We argue that this proves that the third body is necessary in order to make the inner period so short, and further argue that the only reasonable explanation is that the third body causes shrinkage of the inner period, from perhaps a week or more to the current short period, by means of the combination of Kozai cycles and tidal friction (KCTF). In addition, once KCTF has produced a rather close binary, magnetic braking also combined with tidal friction (MBTF) can decrease the inner orbit further, to the formation of a contact binary or even a merged single star.

Some of the the products of KCTF that have been suggested, either by others or by us, are W UMa binaries, Blue Stragglers, X-ray active BY Dra stars, and short-period Algols. We also argue that some components of *wide* binaries are actually merged remnants of former *close* inner pairs. This may include such objects as rapidly rotating dwarfs (AB Dor, BO Mic) and some (but not all) Be stars.

Subject headings: stars: activity — stars: individual (AB Dor, BO Mic) — binaries (including multiple): close

1. Introduction

The main predictions of a combined KCTF/MBTF model for close binaries are supported by a variety of astronomical observations:

- Tokovinin et al. (2006) looked at 165 known spectroscopic binaries with $P < 30\,\mathrm{d}$. Some of these already had known third (or more) companions, but they also found 13 new ones by NACO adaptive optics. Making allowance by a maximum-likelihood algorithm for observational incompleteness, they found that the shortest-period SBs, those with $P < 2.9\,\mathrm{d}$, were almost always (96% likelihood) in triples, while the longest-period SBs, those with $12 - 30\,\mathrm{d}$, were substantially less likely (34%).

- Pribulla & Rucinski (2006) found that for all (88) known contact binaries in the Northern sky down to $V = 10$, 52 (59%) are in triples; Rucinski et al (2007) increased that to 54 (61%) with two new adaptive-optics discoveries. This is a much higher proportion of triples than in a broad sample of binaries not confined to periods as short as in contact binaries ($< 1\,\mathrm{d}$). Given the many selection effects that make the discovery of faint companions difficult, this result (61%) is not inconsistent with 100% in practice.

- Eggleton & Tokovinin (2008) considered the multiplicities of the 4559 stellar systems brighter than Hipparcos magnitude 6.0. They found that 1841 were at least binary, and of these 404 were at least triple, i.e. about 22% of binaries have a further companion. However, among the 1841 that were at least binary, the 89 that had a period $< 3\,\mathrm{d}$ contained 55 (62%) that were at least triple.

- Makarov (2002) noted that among the nearest X-ray sources, Solar-type stars within 25 pc, several are in wide binaries. Although it is reasonably clear why Solar-type stars in *close* binaries are X-ray binaries, there is no compelling reason why they should be in *wide* binaries unless they are either (i) also in close sub-binaries that have not yet been detected or (ii) in former close binaries that have been driven to a merger and a rapidly-rotating single star (except that there is still the distant third star as a wide binary companion). Either possibility argues for a KCTF/MBTF origin (Makarov & Eggleton 2009), as was hypothesised for AB Dor by Eggleton & Kisseleva-Eggleton (2006).

- Torres et al. (2003) examined 10 stars suspected to be members of the pre-main-sequence TW Hya association (TWA). The candidate members were selected by high X-ray luminosities and kinematic or positional similarity to known TWA members. Despite this pre-selection, upon spectroscopic and radial velocity measurement none of the examined objects turned out to be young, but no less than six of them were confirmed as binaries. Even more strikingly, all binaries whose orbits could be determined had periods of less than 3 days. This result perhaps indicates that the overwhelming majority of bright X-ray sources in the field are short-period binaries, though most of them are yet to be discovered.

- Fabrycky & Tremaine (2007) applied the KCTF equations to a distribution of triples, and found that indeed the periods of inner pairs were often shortened into the range

$1-6\,\mathrm{d}$ from longer initial periods. In addition the mutual inclination of the two orbits was modified from a random inclination (by supposition) to one with peaks at inclinations of $\sim 40°$ and $\sim 140°$.

- Perets & Fabrycky (2009) have noted that a KCTF origin for Blue Straggler Stars (BSSs) is supported by (a) the large fraction of BSSs that are long-period binaries (b) the period–eccentricity distribution (with $P \gtrsim 700\,\mathrm{d}$, usually), and (c) the typical location of BSSs far from the cluster turnoff in the HRD.

The essential points about Kozai cycling, tidal friction and magnetic braking, are:

(a) If the inner orbit (with period $P_{\rm in}$) of a triple is inclined at an angle η to the outer orbit (period $P_{\rm out}$), and if $\sin\eta \geq \sqrt{2/5}$ ($39° < \eta < 141°$), then the inner orbit is forced to cycle in eccentricity and in inclination, but *not* in period or semimajor axis, on a Kozai-cycling period

$$P_{\rm KC} \sim P_{\rm out}^2/P_{\rm in} \cdot (m_1+m_2+m_3)/m_3\,.$$

The amplitude of the eccentricity cycle depends *only* on (i) the minimum eccentricty, and (ii) the inclination η. For instance if $\eta = 60°$or $120°$ the eccentricity can range between zero and 0.764, or between 0.5 and 0.863.

(b) However, pure Kozai cycling can be modified by (i) General Relativity, and (ii) the quadrupole moment of an extended star, due to rotation or a close companion. Very loosely, if

$$0.01 P_{\rm in}({\rm dys}) \lesssim P_{\rm out}({\rm yrs}) \lesssim [P_{\rm in}({\rm dys})]^{1.4}\,,$$

Kozai cycling can occur.

(d) To a good degree of approximation the outer orbit is not affected at all by Kozai cycling.

(e) Because the eccentricity $e_{\rm in}$ can become large during a cycle while the semimajor axis $a_{\rm in}$ is constant, the periastron separation $p \equiv a_{\rm in}(1-e_{\rm in})$ can become small, and as a result tidal friction can become an important dissipative agent. The dissipation of energy reduces $a_{\rm in}$ and $e_{\rm in}$.

(f) The timescale $t_{\rm TF}$ of tidal friction can be estimated (Zahn 1977) as $t_{\rm TF} \sim t_{\rm visc}\,(p/R)^8$, where R is the radius of the larger star; $t_{\rm visc}$ is a viscous timescale inherent in the structure of the star, and is $\sim 1\,\mathrm{yr}$. A better estimate, we believe, is given by Eggleton (2006).

(g) If the components of the close pair are of spectral type F – M, and if its period becomes short ($\lesssim 10\,\mathrm{d}$) as a result of KCTF, then orbital shrinkage will continue under the influence of magnetic braking, also in association with tidal friction – MBTF. F/G/K/M stars that rotate in $P_{\rm rot} \lesssim 10\,\mathrm{d}$ are usually very X-ray active, and this is normally attributed to dynamo activity driven by the combination of relatively rapid rotation and a turbulent surface convective zone. The dynamo activity means both that a stellar wind is driven off by the dissipation of magnetic field as it emerges just outside the stellar surface, and that this wind carries off further magnetic field. The magnetic field causes the wind to corotate with the star out to an Alfvén radius of possibly several stellar radii (about $10\,R_\odot$ in case of the Sun itself), and thus carries off a great deal of angular momentum which, beyond the the Alfvén radius, is lost to the star, and the binary.

(h) KCTF can spin the close sub-binary up to $P_{\rm in} \lesssim 6\,{\rm d}$, and then MBTF can spin it up further, by way of a very close but detached binary to Roche-lobe overflow (RLOF). This can lead first to a semi-detached 'reverse Algol', where the loser is still the more massive component, and then probably either (i) to a normal (but very short-period) Algol or (ii) to a contact binary. Contact binaries are likely to evolve by net mass transfer from the less to the more massive component, until the less massive component is merged into its companion (Webbink 1976). Such a process is likely to be quite slow, however, since contact binaries are by no means uncommon. But a further possibility (iii) is a *rapid* merger, on something like a timescale of years, and at its peak, days. Such a merger is to be expected if the mass ratio at the onset of RLOF is fairly extreme, like 2:1, 3:1 or even more; only if the mass ratio is rather mild, say $\lesssim 1.5:1$, is there likely to be a settling-down to a relatively long-lived semi-detached or contact state as in (i) or (ii). These evolutionary possibilities were discussed at some length by Yakut & Eggleton (2005).

The effect of KCTF and MBTF can be illustrated with an example that might be relevant to the AB Dor AC system (Nielsen et al. 2005). Consider a triple whose initial parameters, in an obvious notation, are

$$((\text{K5V+M7V};\ 0.65 + 0.15\,M_\odot;\ P_{\rm in} = 16\,{\rm d},\ e_{\rm in} = 0)$$
$$+\ \text{M8V};\ 0.8 + 0.09\,M_\odot;\ P_{\rm out} = 11.74\,{\rm yr},\ e = 0.61;\ \eta = 84.3^\circ)\ .$$

Since $\cos\eta = 0.1$, the probability is 10% that the inclination will be this large or larger, if the inclination is selected randomly because of some random collision of two primordial binaries. The initial rotational period of both components in the inner pair was set arbitrarily at 5 d. We computed the subsequent evolution according to the prescriptions of Eggleton (2006) for KCTF and MBTF. Kozai cycling lasted for about 1 Myr, until the eccentricity reached about 0.8, after which $e_{\rm in}$ and $P_{\rm in}$ decreased steadily to ~ 0 and $\sim 1.6\,{\rm d}$ at about 10 Myr. Then MBTF decreased the period to $\sim 0.3\,{\rm d}$ at about $\sim 60\,{\rm Myr}$. Very shortly after that the system would probably merge (because of the large mass ratio assumed) and the result would be a very rapidly rotating K dwarf of about $0.75\,M_\odot$, some mass having been lost by stellar wind. This dwarf would spin down rather rapidly, but is presumably being seen before the period has decreased very much.

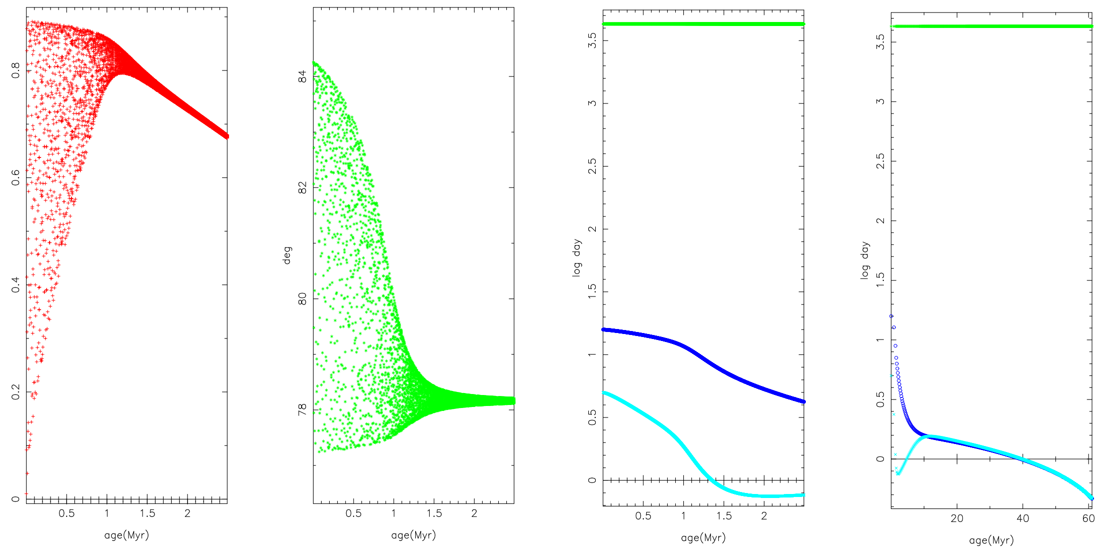

Fig 1 – Behaviour of eccentricty, inclination and period for the inner binary of a triple proto-AB-Dor system. Left-hand panel: eccentricity as a function of time. The periodic (Kozai cycling) behaviour at early times is severely undersampled. Second panel: mutual inclination as a function of time. Third panel: $P_{\rm in}$, dark blue; $P_{\rm rot}$, pale blue; $P_{\rm out}$, green. See text for details. Right-hand panel: as third panel, but on a longer timescale, so that the effect of MBTF leading to a merger at very short period is now visible.

The ultrafast rotator Speedy Mic (BO Mic, HIP 102626) is another example of an active isolated star in the solar neighborhood, whose origin remains a mystery. This early K dwarf has a rotational period of 0.38 d. There is no documented evidence, to our knowledge, of spectroscopic binarity. It has been known, however, since the publication of the Hipparcos catalog, as an astrometric binary with changing proper motion (ESA 1997). The invisible companion may be responsible for the outstanding properties of BO Mic, if it caused the original inner pair to merge recently, similar to the scenario discussed above for AB Dor. Makarov & Eggleton (2009) suggested an orbit with period $P = 1146$ d, inclination (to the line of sight) $i = 78°$, eccentricity $e = 0.63$, apparent semimajor axis $a_0 = 24.0$ mas, and parallax $\Pi = 25.0$ mas.

While the inner binary is still unmerged, it will be quite active because its period is $\lesssim 10$ d. But after the merger its rotational period will be ~ 0.25 d, and now *increasing* as a result of magnetic braking without tidal friction. The timescale for doubling the period will be about 20 Myr – the code used did not simulate either the merger or the later evolution.

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