On the formation of close binaries – an interferometric look on Algol(s)

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Abstract. Both theoretical and indirect observational evidences suggest that most of the closest binary stars with orbital periods of a few days (as well as hot Jupiter-type exoplanets) formed with an original separation larger by 1-2 orders of magnitude than the present one. Consequently, an orbital shrinking mechanism(s) must be present that extracts the angular momentum from a primordial binary. From the possible mechanisms studied in the literature we describe the so-called 'Kozai cycles combined with tidal friction' (KCTF), which gives some definite predictions for the statistical properties of the orbital elements in such close binaries. Due to the recent powerful observing techniques, such as optical and radio (VLBI) interferometry, we can already peer inside such close binaries, so we have some opportunity to check these predictions. We examine the practical details, constraints, restrictions about the inquiring of the necessary information from specific triple systems by interferometric (as well as polarimetric) observations. Finally, to illustrate this we give a brief description of our recent combined optical and radio interferometric measurements of Algol.

1. Introduction

Ternary stellar systems are common in the Galaxy. If \( n \) denotes the number of components in a stellar system then the expected relative frequency of \( n \)-body systems is proportional to \( 1/n! \) (Batten 1973) and therefore the relative frequency of ternary systems compared to the binary ones is about \( 2!/3! = 1/3 \) which shows that we can expect many (mainly) hierarchical triple systems in the sky. The continuously updated catalog of Tokovinin (1997) lists about 1000 such systems, many of them containing very close binaries with a characteristic orbital period of days or even hours.

Although the statistics of triple and multiple stellar systems (i. e., the number of the components, period distributions, mass ratios, orbital properties) are very poorly known, and are far from the completeness even in the case of the brightest systems (e. f. Eggleton and Tokovinin 2008), some systematic surveys suggest that most of the shortest period binaries have at least one additional stellar component. For example, Tokovinin et al. 2006 surveying a representative sample of 165 solar-type spectroscopic binaries concluded that the fraction of the (solar type) spectroscopic binaries with additional companions is about 63% ± 5%; this ratio reaches 96% for \( P < 3 \) d. This result has a great importance from the point of view of the
stellar or (more strictly) of the binary formation theories. According to our recent knowledge about stellar formation the minimal initial orbital separation of primordial binaries are strongly limited due to the large size of a protostar. For example, a proto-star with solar mass has a radius of \(\sim 6R_\odot\) at an age of \(7 \times 10^4\) yr (D’Antona and Mazzitelli 1994); which limits the minimal period of a marginally contact binary formed by two such proto-stars at \(P = 3.4\) d. Thus, the theory strongly suggests that many of the binary stars underwent a very strong orbital shrinkage (even by 1-2 orders of magnitude) during their lifetime. (Note, it is also thought that hot-Jupiters found in several exoplanetary systems should also have been the subject of some orbital shrinking mechanisms.) Different mechanisms are described in the literature. A short list of them, can be found e. g. in Tokovinin et al. (2006) and Fabrycky and Tremaine (2007).

In the next section we give a more detailed description about one of them, the so-called 'Kozai cycles combined with tidal friction' (KCTF).

2. Kozai cycles

The Kozai resonance (or recently it is frequently mentioned as Kozai cycle[s]) first was described by Kozai (1962) investigating secular perturbations of asteroids. The first (theoretical) study of this phenomenon with respect to multiple stellar systems can be found in the work of Mazeh and Shaham (1979), while a higher, third order theory was given by Ford et al. (2000). Briefly, the essence of this effect is as follows: In a hierarchical triple system, where most of the total angular momentum is concentrated in the outer orbit, the eccentricity \((e_1)\), the argument of periastron \((g_1)\) and the inclination \((i_1)\) of the inner orbit are subjects of secular cyclic variations depending upon only one independent variable (one degree of freedom system), namely, the above mentioned argument of periastron \((g_1)\). The mutual inclination of the two orbits is a critical parameter in the equations. If the cosine of the mutual inclination is less than \(\sqrt{3/5}(1 - e_{10}^2)\), where \(e_{10}\) is the minimal eccentricity of the inner orbit (belonging to \(g_1 = 0^\circ\) or \(180^\circ\) in case of circulation, or \(g_1 = 90^\circ\) or \(270^\circ\) in case of libration in \(g_1\), depending upon the initial conditions), then at some values of \(g_1\) its time-derivative becomes zero, and consequently, the time derivative of \(e_1\) becomes constant. Consequently, the eccentricity, \(e_1\) will tend to grow almost linearly in time. (Note, the above value of the critical inclination very weakly depends on other parameters, such as e. g. masses, and the ratio of the separations.) The eccentricity maximum mainly depends on the initial mutual inclination, but very weakly on the initial eccentricity, which means, that in the case of an almost perpendicular initial configuration, the eccentricity of even an originally circular orbit can reach almost 1. After such an eccentricity 'spike', the system returns back to its initial configuration, and a new cycle begins. As it was mentioned, the initial separations and masses hardly affect the eccentricity maximum, only the period of the cycles depends on these quantities. (Note, that according to Ford et al. 2000, including the aforementioned higher order formulae, the cycles are not strictly periodic and similar ones, some bifurcations occur in the \(e_1 - \cos g_1\) space, in accordance with the numerical integrations, nevertheless, the chaotic area is usually weak.) Söderhjelm (1984) was the first who showed that other perturbations of the apsidal line (i. e. \(g_1\)), like the stellar oblateness forced apsidal motion and/or the relativistic apsidal motion can completely eliminate the Kozai cycles. The possibly important role of Kozai cycles in formation of close binaries first was suggested by Kiseleva et al. (1998). According to this theory the close binaries originally should have had a significantly larger separation, and a distant, inclined third companion. Due to the third star induced Kozai oscillation, the inner eccentricity cyclically becomes so large, that around the periastron passages, the two stars approach each other so closely, that tidal friction may be effective, which then during one ore more Kozai cycles, and some additional circularization after the last cycle, may produce close binaries in their recent forms. Recently Fabrycky and Tremaine (2007) carried out a thorough study on the possibility of the orbital shrinkage by the combined effects of secular perturbations from an inclined distant companion star (Kozai cycles) and tidal
friction. They found that „binary stars with orbital periods of 0.1 to 10 days, with a median of \( \sim 2 \) d, are produced from binaries with much longer periods (10 d to \( \sim 10^5 \) d), consistent with observations indicating that most or all short-period binaries have distant companions.” What is extraordinarily important in their work is, that they provide some predictions which can be tested by observations. From our point of view the most important one is that in those binaries, where this combined effect could have been effective (namely, for recent periods between 3 and 10 d), the distributions of mutual inclinations of the close and the wide orbits should peak strongly near 40° and 140° (this arises from that feature of Kozai phenomenon, that during the maximum eccentricity phase of the cycle the mutual inclination reaches its minimum which is close to the critical inclination; furthermore, as the tidal friction becomes effective during this period, when the tidal friction cancels the Kozai cycles, it can be expected - and numerical integrations really show this behavior - that this inclination would freeze in the system). Consequently, it is important to determine the mutual inclinations in those triple stars, where the inner period is small enough for the predominancy of tidal forces.

In this context, in the next section we give a short overview of the methods of the determination of the spatial configuration i.e. the mutual inclination of triple stellar systems.

3. Observational aspects of mutual inclination determination

In order to make a distinction between the alternative evolution models on the formation of close binary systems, it is necessary to calculate the relative spatial orientation of the orbits of the close binary and of the tertiary component in as many systems as it is possible. This requires the determination of the spatial orbital elements, namely inclinations \((i_1, i_2)\) and longitude of the nodes \((\Omega_1, \Omega_2)\) for both the inner and the outer orbits. There are different methods to determine these elements.

(i) The classical one is the astrometric determination. From the sky-projected orbit of a star around its companion all of the six orbital elements can be determined, although the node and the argument of periastron only with an ambiguity of 180°. (Note, that in the case of most interesting small period systems, long-baseline optical and/or radio interferometric observations are required.)

(ii) If the binary is an eclipsing system, then the inclination can be calculated from its light-curve (with the ambiguity, that \( i \), and 180° – \( i \) give the same solution), but nothing can be said about \( \Omega \).

(iii) Finally, a rarely used method comes from polarimetry. If there are some sources of polarized light in the system which revolves together with either of the components, then the phase dependent variation of the polarization could give information both on \( i \) and \( \Omega \) (with the above mentioned ambiguity in this latter).

The ambiguity in the node can be resolved with additional information on the sign of the radial component of the motion (i.e. which component is closer to the observer in a given moment). There are at least three possibilities to get information about the radial component.

(i) The most usual way to get this information arise from radial velocity measurements. Observation of the radial motion of one binary member is already satisfactory for this purpose (single line binaries, SB1). Nevertheless, radial velocity measurements can be used to resolve the node ambiguity only if the two components astrometrically distinguishable, which is not the case at the simplest long-baseline optical interferometry, where in the absence of phase-information, the two components are interchangeable.

(ii) In the case of an eclipsing binary, the eclipses itself give the most easily observable information about the sign of the (relative) radial coordinate of the two stars. (This is especially true, when the two stars significantly differ which makes perfectly clear that
which star is the eclipser and which is the eclipsed.) Nevertheless, the same restriction
mentioned above also stands here.

(iii) While the previous two possibilities are mainly applicable for close binaries, in the case of the
wide orbit of the third companion, detection of the so-called light-time effect (LITE) could
be an easy way to determine the true radial configuration. If the close binary produces any
(almost) strictly periodic signal (for example, eclipses, pulsations, ellipsoidal light variations,
etc.) while orbiting around the common centre of mass of the triple system, this signal is
modulated by the third body, from which the sign of the relative radial coordinate could be
easily determined. (Supposing, of course, that the motion has significant radial component.)

Theoretically, the first, astrometric method seems to be the most usable. Unfortunately, the
small characteristic size of systems in which we are interested in gives a very strong limit.
In the case of a few day-long period binary consisting of two typical stars, the separation
of the components is of the order of 0.01 – 0.1 AU, and consequently, even for a relatively
close system with a trigonometric parallax of some 0′01, the angular size of the orbit is of the
order of milliarcseconds (mas). Furthermore, even for the tertiary the typical separation is in
the subarcsecond regime. Nevertheless, this latter separation being above the diffraction limit
of even smaller, submeter telescopes, by the use of speckle-interferometry or Lucky-imaging,
the positions of tertiary companions in several triple systems can be measured with sufficient
accuracy for the orbit determination. Turning back to close binaries, the mas, or sub-mas
separation gives a very strong practical limit. Such a resolution can be reached only with
very long baseline radio interferometry, or the recent, most powerful optical, near-IR long-
baseline interferometric equipments, e. g. CHARA array, Palomar Testbed Interferometer and
others. Above this direct observational limit, the use of these kind of special instruments gives
a further, indirect constraint, which of course, somewhat overlaps with the previous one. Only
the brightest close binaries can be reached by such methods. This latter limitation is more
expressed in the sense of the radio VLBI measurements narrowing our radio sample only for
the nearest chromospherically active binaries. Due to these reasons, the spatial orientation
(i.e. the longitude of the node) is known only for very few, approximately a dozen close
binaries (see, e.g. Muterspaugh et al. 2006, 2008; Zhao et al. 2008, and further references
therein), most of these results were obtained in the last years by optical devices. The first use
of VLBI technique in the radio domain for this purpose was carried out for the Algol system
by Lestrade et al. (1993). Recently we made a new analysis on the spatial orientation of the
Algol system combining the radio (European VLBI Network, EVN) and optical (CHARA array)
interferometric measurements (Csizmadia et al. 2009). According to our knowledge, this was
the first occasion, when such techniques were applied simultaneously (see next section).

Up to now, we concentrated on the first, astrometric method. Nevertheless, as was mentioned
earlier, polarimetric measurements could also reveal information about the spatial orbital
elements of close binaries. The method has been known for a long time. It was first described by
Shakhovskoi (1965). An improved method was applied for Algol by Rudy and Kemp (1978) and
Kemp et al. (1981). Their results are in excellent agreement with the recent CHARA and EVN
results (Csizmadia et al. 2009). The great advantage of polarimetry as opposed to long-baseline
interferometry is that, it does not require high-tech devices, these measurements could be carried
out by significantly smaller, cheaper, and easily reachable instruments. On the other hand, these
measurements require some intrinsic, phase-locked polarization in the systems, which condition
strongly limits the number of systems measurable by this manner. Although, there are close
systems whose spatial orbital elements were determined by this method (for example, some of
the most recent measurements are about CQ and CX Cepheis – Villar-Sbaffi et al. 2005, 2006),
we are not aware of any systematic surveys to determine spatial orientation of close binaries
orbiting in close triple systems by polarimetry.
Determination of the orbital elements of close binaries is only half of the work. The accurate measurements of the wide companion’s position is equally important. In most cases this can be done relatively easily even with smaller telescopes by speckle-interferometry. Nevertheless, in most of the cases the orbital period of the third star is of the order of decades (if not centuries). Accordingly, for most of the known systems (listed in the continuously refreshed on-line version of Tokovinin 1997) only a small part of the total orbital arc have been covered, and, consequently, the calculated orbital elements (if they exist) sould be considered only as very preliminary ones. (There are several cases, where elements calculated by different authors within a few years differ completely.) This means that continuous, long-term, accurate observations have essential importance. Furthermore, as it was mentioned, these observations leave a 180° ambiguity in the position of the node, which can be eliminated by the continuous, accurate photometric observations of the eclipsing minima times (supposing that the inner binary is an eclipsing one). In the next section we give a short overview about our new CHARA and EVN measurements about the Algol-system, which was the first step of our intended systematic survey.

4. Interferometric Observations of Algol

4.1. Previous results
Algol consists of a semi-detached eclipsing binary with an orbital period of 2.87 days (B8V + K2IV) with an F1IV spectral type star revolving around the binary every 680 days. The third component was succesfully observed by speckle interferometry, and its orbit was precisely determined by Bonneau (1979). This result was refined by using the Mark III optical stellar interferometer (Pan et al. 1993).

Considering the spatial orientation of the close binary, the polarimetric measurements of Rudy (1979) yielded Ω1 = 47° ± 7°. (Note, that the Ω-ambiguity was also resolved in that work, with the help of the eclipsing phase information.) In the radio regime, Lestrade et al. (1993) detected positional displacement during the orbital revolution of the AB pair using the VLBI technique, and identified the K-subgiant as the source of radio emission. From their measurements Kiseleva et al. (1998) calculated im = 100° for the mutual inclination of the close and wide orbital planes. This value has been widely accepted since then. However, this mutual inclination value cannot be correct due to dynamical considerations, because it would produce a fast variation in the observable inclination of the eclipsing subsystem (see e.g. Borkovits et al. 2004), resulting in a fast eclipse depth variation which contradicts to the more than century-long photometric observations (Söderhjelm 1980).

4.2. Observations and results
We carried out interferometric observations both in the optical/near-infrared, and in the radio regime. The optical interferometry observations were done by the CHARA Array on three nights (2, 3 and 4 December, 2006) in the Ks band. The radio measurements were carried out with a subset of the European VLBI Network (EVN) on 14-15 December 2006 at 5 GHz. The participating telescopes were Cambridge and Jodrell Bank (UK), Medicina (Italy), Onsala (Sweden), Toruń (Poland) and the Westerbork phased array (the Netherlands). The measurements and the data reductions were carried out according to the standard procedures (for details see Csizmadia et al. 2009).

From the analysis of the CHARA visibilities we determined the angular size of the binary’s semi-major axis (a1), the surface brightness ratio in Ks band (JKs), and the angle Ω1, as follows a1 = 2.28 ± 0.02mas, JKs = 0.330 ± 0.01, and Ω1 = (48° + k·180°) ± 2° (k = 0, 1), respectively.

The VLBI data were gained during a secondary minimum, which, according to our simultaneous optical photometry, occurred at t0 = 2 454 084.360 ± 0.003 (Biró et al. 2007). The measurements lasted 9 hours, i.e. ≈ 13% of the orbital period, but as the projected movement of the source is maximal around the minima, the covered projected orbital arc is significantly
larger. Due to the large inclination, this projected arc is almost a straight line parallel to the nodal line, which makes the determination of the longitude of the node easier. Our best fit gave $\Omega_1 = 52^\circ \pm 3^\circ$, resolving the node-ambiguity of the CHARA observations. However, the $\Omega$ value itself is likely less reliable, because the source flared during our observations, in which case structural variations (not reflecting orbital motion) are likely to happen. (Note, that the displacement of the source during our observation as almost twice of what was expected from Keplerian revolution.)

Due to the above mentioned facts, here we concentrate mainly on the CHARA results. The true size of the obtained semi-major axis and surface brightness ratio are in very good agreement with previous results, which makes our nodal result also plausible. The obtained $\Omega_1 = 48^\circ \pm 2^\circ$ is in excellent agreement with the value determined from polarimetric measurements mentioned above, indicating that polarimetry is an efficient tool to determine the spatial orientation of the orbits.

At this point, using the well-known cosine theorem of spherical triangles

$$\cos i_m = \cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos(\Omega_1 - \Omega_2)$$

we can determine the mutual inclination $i_m$, and we get $i_m = 95^\circ \pm 3^\circ$. This value is, however, closer to the exact perpendicularity than the $100^\circ$ which was based on the measurements of Lestrade et al. (1993). Note, that for the first sight, the difference by $5^\circ$ does not seem to be crucial, nevertheless, because the period of the precession of the orbital plane is approximately proportional to $\cos^{-1} i_m$ (see e. g. Söderhjelm, 1975; or for both the dynamical and the observable node in Borkovits et al. 2007), consequently, this new result gives a longer period by a factor of two which is already consistent with the observations.

5. Conclusions
The recent spatial configuration of close binary systems might be accurate tracers of the evolution and formation of such systems in the past, and indirectly of the stellar formation theories. Nowadays we already have the possibility to see inside of such systems. In this paper we gave a short overview about some of the practical, technical, strategic questions of acquiring such results, as well as some aspects of the theoretical predictions behind them. Considering the actually studied system, Algol, we found that results yielded with different technics can support each other. Nevertheless, we note, that the triple system of Algol itself is not the most ideal subject for the investigation of the consequences of the Kozai mechanism. This is the case at least for two reasons. (i) The secondary component of Algol is an evolved star, consequently, the system had passed on the Case A mass-transfer phase in the past which should have changed the configuration, including the separation of the binary dramatically. (ii) Furthermore, the third companion is too close to the binary (at least from this specific point of view) with respect to the typical triple stellar systems, and consequently, the general statistical considerations applied in Fabrycky and Tremaine (2007) might be not perfectly valid.

In the following we plan a systematic survey of hierarchical triple stellar systems to determine the mutual spatial configurations, in order to be able to make a statistical investigation of the relative orbits.

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