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Populations of hierarchical stellar systems

A. Tokovinin[1]

Cerro Tololo Interamerican Observatory – NSFs NOIRlab, Casilla 603, La Serena, Chile (E-mail: andrei.tokovinin@noirlab.edu)

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Abstract. Triple and higher-order stellar systems are common products of star formation, and their frequency depends strongly on the mass. About 10 0000 hierarchies are expected within 100 pc, but only a quarter of those are presently catalogued. The diversity of their architectures is related to several processes responsible for formation and early evolution: pure N-body dynamics, dynamics with tides, fragmentation of disks and cores, and dissipative capture. Each mechanism leaves its characteristic imprints, illustrated by real systems matching the predicted features. Tentative classification of hierarchies into families assiciated with particular formation scenarios is a new emerging field. Large surveys play an increasing role in improving the multiplicity statistics and in finding rare systems. As an example, relative alignment of eclipsing binaries in triples with known inclinations of outer orbits is discussed, suggesting that only a quarter of such systems are aligned.

Key words: binaries: general – binaries: visual – binaries: close

1. Introduction

Statistics of binary stars in the field is known relatively well, starting from the best-studied group of solar-type stars and extending to smaller and larger masses (Offner et al., 2023). It became clear recently that the field binaries are a mixture of different populations. For example, the frequency of close pairs depends strongly on metallicity, while the frequency of wide pairs differs considerably between dense and sparse clusters (Deacon & Kraus, 2020) and also possibly depends on metallicity (Hwang et al., 2020). These differences are related to the formation mechanisms of binaries, but, unfortunately, their signatures are blurred in the statistics of the mixed field population.

Hierarchical stellar systems can be viewed as combinations of two or more elementary binaries. They are described by a larger number of parameters (periods P, mass ratios q, eccentricities e of each pair, mutual orbit orientation, period ratios). In this multi-parameter space, the signatures of formation processes might be more pronounced, compared to binaries. Hence the idea of classifying hierarchies into distinct families emerges (Tokovinin, 2021). Although such classification is still tentative or ambiguous, it might be a useful endeavor.

Remember that the empirical classification of biological species appeared well before its underpinning genetic roots were discovered.

Our current knowledge of hierarchies is still very incomplete. Using the estimated frequency of hierarchical systems plotted in Fig. 1 of Offner et al. (2023) and the number of Gaia stars in the 100-pc volume, I estimated a total of $\sim$10 000 hierarchies, while only 2225 are listed in the latest[1] update of the multiple star catalog, MSC (Tokovinin, 2018b). Hierarchies, like binaries, are discovered via combination of various observing techniques spanning the full range of periods. The Gaia DR3 catalog (Gaia Collaboration et al., 2021) has substantially improved the completeness by revealing all pairs wider than $\sim 1''$ and detecting their inner subsystems via astrometric accelerations, radial velocity (RV) variation, and other markers. Some of those nearby hierarchies were confirmed by directly resolving the inner pairs (Tokovinin, 2023b). As a result, the completeness of nearby hierarchies within 100 pc is substantially improved at wide separations (outer periods $P_{\rm out} > 10^5$ d), and it is very good when the inner pairs are also resolved by Gaia. Nevertheless, the plot of inner mass ratios and periods, $q_{\rm in}$ vs. $P_{\rm in}$, shows clear imprints of the observing techniques (see Fig. 7 in Tokovinin, 2023b). The discovery of the most interesting compact hierarchies is still largely dependent on the ground-based work and, so far, is barely helped by Gaia.

2. Formation mechanisms and families of hierarchies

The basic mechanisms producing binaries and hierarchies (Offner et al., 2023) are: (i) dynamical interactions, (ii) dynamics with tides, (iii) disk fragmentation, (iv) core or filament fragmentation, and (v) dissipative capture. These processes and their predictions regarding architecture of hierarchies are detailed below and illustrated by examples. However, association between formation mechanisms and real systems remains speculative; a given system can be possibly produced by alternative mechanisms. The sequence of events in formation and early evolution is called formation *scenario* — a term borrowed from binary evolution and cinema.

2.1. N-body dynamics

Originally, triple stars were studied as systems of gravitating point masses (Anosova, 1986). This approach established the criteria of dynamical stability (Mardling & Aarseth, 2001). The N-body dynamics makes clear predictions about architecture of triples: the orbits are randomly aligned, the period ratios are moderate (just above the stability limit), and the inner eccentricities are distributed thermally as $f(e_{\rm in}) \propto e_{\rm in}$ (e.g. Antognini & Thompson, 2016; Stone & Leigh, 2019).

[1]December 2023, https://www.ctio.noirlab.edu/~atokovin/stars/ and Vizier J/ApJS/235/6

One expects the N-body dynamics to dominate at large scales, on the order of distances between stars in the primordial clusters. Indeed, the properties of the relatively complete sample of wide low-mass Gaia hierarchies within 100 pc match the N-body predictions (Tokovinin, 2022a). The most intriguing member of this sample is the sextuple system V1311 Ori (Tokovinin, 2022b) composed of M-type dwarfs. It contains four Gaia sources in a non-hierarchical configuration with projected separations of $\sim 10^4$ au, and two of those sources are close resolved pairs. This system is still young ($\sim$24 Myr) and might disintegrate into triple, binary, and single stars in the future.

Dynamical interactions at much smaller scales occur in hierarchical systems that become unstable owing to shrinking outer orbits or internal dynamics. Violent interactions during close approaches result in ejections (usually of the lowest-mass member) and tightening of the inner binary that absorbs the binding energy of the ejected star. This mechanism is largely responsible for producing massive runaway stars (Fujii & Portegies Zwart, 2011). Their peculiar velocities above 30 $\mathrm{km\,s^{-1}}$ indicate the spatial scale of disintegrating multiple systems on the order of 1 au or less. The remaining close binaries are even more massive than the runaways, so this process is most relevant for large masses.

2.2. Dynamics and tides

When separation between stars in the inner binary is comparable to their radii, the point-mass approximation is no longer valid because tides in the inner binaries came into play. Close binaries can be formed within triples with misaligned or eccentric outer orbits via Lidov-Kozai (L-K) cycles and related mechanisms (Eggleton & Kisseleva-Eggleton, 2006; Naoz, 2016). The empirical fact that close binaries are often found within triples seems to support this scenario; however, Moe & Kratter (2018) show that this mechanism can produce only a fraction of close binaries, and it is most efficient at the pre-main sequence (PMS) stage when the stars are large.

While close binaries indeed like to be accompanied (Hwang, 2023), their tertiary companions are often too distant to exert any dynamical influence. However, these apparent triples might contain intermediate-level subsystems, i.e. be quadruples of 3+1 architecture. This offers an interesting possibility of cascade L-K cycles (Hamers et al., 2015). First, they slowly modify the orientation of the intermediate orbit to the point when the inner triple starts these cycles and eventually forms a close inner pair with the help of tides. This happens well after the stars have contracted from their large PMS size. Recently, Powell et al. (2023) searched for intermediate subsystems in wide pairs containing eclipsing binaries (EBs) and found 20 new 3+1 quadruples.

2.3. Disk fragmentation and migration

The gravitational instability starts on large spatial scales and proceeds to smaller scales, as the gas gets denser while remaining cold (Vázquez-Semadeni et al., 2019). During this isothermal collapse stage, the Jeans mass decreases, prompting fragmentation. The cooling becomes inefficient for optically thick gas at densities corresponding to a spatial scale of ∼10 au; this prevents formation of closer pairs (so-called opacity limit to fragmentation). Conservation of the angular momentum slows down the accretion on to protostars: the incoming gas is temporarily retained in disk-like structures (Tu et al., 2024) which can become unstable and form companions at separations >10 au. Continuing accretion on to a binary results in the preferential growth of the companion (increases the mass ratio), and, generally, in its inward migration (Lai & Muñoz, 2023; Siwek et al., 2023). Using several simplifying assumptions, Tokovinin & Moe (2020) developed a statistical model of companion formation and migration that matches reasonably well the statistics of short-period binaries.

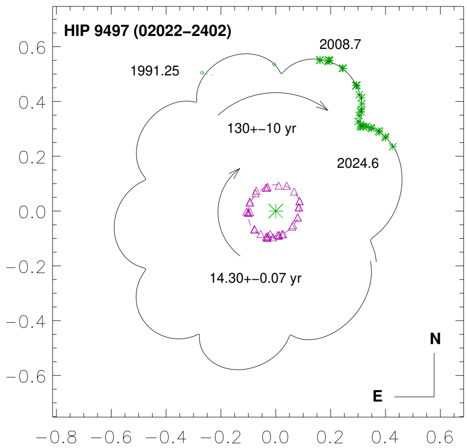

Figure 1. The double twin triple system HIP 9497 with recently updated orbits (Tokovinin, 2018a). The inner 14.3-yr orbit is well constrained, and the still uncertain outer period suggest a period ratio of 1:9, possibly in a mean motion resonance. Both orbits are quasi–circular. The masses of two stars in the inner pair are 0.6 $M_\odot$, the primary is of 1.2 $M_\odot$.

A tertiary companion can form by disk fragmentation. If the accretion continues, the companion can become as massive as the inner binary, and the system becomes a double twin where the inner and outer mass ratios are close to one. This mechanism implies dissipative interaction of stars with the disk, leading to quasi-circular and mutually aligned orbits. Many examples of such triples are known (Fig. 1). Quadruple systems of 3+1 architecture with roughly aligned orbits could also be formed inside-out by successive disk fragmentation and migration, especially the compact ones like HIP 41431 with periods of 2.9, 59 days, and 3.9 yr (Borkovits et al., 2019). Compact triple systems identified by eclipse time variations or by double eclipses (Borkovits et al., 2016; Rappaport et al., 2023) were plausibly formed by disk fragmentation and migration; their orbits are typically very well aligned. The shortest known outer periods in compact triples are about 33 days (examples in Tokovinin, 2021).

2.4. Core fragmentation

A filament or a density peak within it (core) can fragment into several protostars. These stellar embryos continue to accrete the surrounding gas and to interact dynamically with each other, as demonstrated in computer simulations (Bate, 2019; Lee et al., 2019). Bound hierarchical systems are frequently formed during core collapse, although some of them later become disrupted. Dynamical interactions with neighbors imply misaligned and eccentric orbits in such triples. Two young quintuple systems, ξ Sco and κ Tuc, could be formed in this way (Tokovinin, 2020). Their particularity is the absence of close inner binaries, suggesting that, for some reason, the migration was not strong, if any; the outer separations are around 8 kau, and both hierarchies are members of young moving groups, suggesting formation in a low-density environment.

Dynamical interactions between nascent protostars occur on the free-fall (crossing) time scale; however, the gas accretion can continue longer, fed by the large-scale hierarchical collapse (Vázquez-Semadeni et al., 2019). Some stars can be ejected from the cloud, becoming low-mass orphans (Reipurth, 2000), while the remaining stars continue to gain mass from the common gas reservoir. This circumstance can explain why stellar masses in multiple systems do not correspond to a random draw from the IMF, being much more similar. In the extreme case, hierarchies containing 3 or 4 stars of nearly equal masses (triplets and quadruplets) can be formed. One such example is ϵ Cha, the core of the young (5 Myr) association, hosting three similar 2.5 $M_\odot$ stars (Tokovinin, 2023a). Here, the inner 6.4-yr orbit has an eccentricity of 0.73, and it is not aligned with the outer orbit, suggesting a violent dynamical history (unlike the double twins discussed above). This system could be formed by core collapse followed by the dynamical interplay between the seeds and accretion. Alternatively, it could result from dynamical decay of a 2+2 quadruple, but in such a case the remaining triple would acquire a recoil velocity and would leave the association, which is not observed.

Collapse and fragmentation can be triggered by gas compression during collision between two clouds. Early simulations by Whitworth (2001) demonstrate formation of a 2+2 quadruple with comparable masses in such triggered event. Unfortunately, this idea was not developed further theoretically, while many wide 2+2 quadruples composed of comparable-mass stars are known in the field and among PMS stars (Reipurth et al., 2024).

Generally speaking, however, formation of hierarchical systems during core collapse is not an event, but rather a process where continuing gas accretion and the associated migration play a crucial role. Apart from equalizing stellar masses, it shrinks the orbits and, presumably, aligns them. Extreme products of such process are compact 2+2 quadruples where four stars of similar masses are packed in a small volume. Until recently, the shortest outer period of ∼1 yr was found in VW LMi (Pribulla et al., 2020). In 2023, this record was beaten by TIC 219006971 with an outer period of 168 days (Kostov et al., 2023) and by BU CMi with an outer period of 121 days (Pribulla et al., 2023). In all these 2+2 quadruples, the four stars have similar masses above 1 $M_\odot$, and all orbits are confined to one plane. If this reasoning is correct, there should be no compact 2+2 quadruples among low-mass M dwarfs because they have not accreted enough gas. Interestingly, among the 8 newly identified doubly eclipsing 2+2 quadruples containing contact pairs (Zasche et al., 2024), the least massive one is a K3 dwarf with an outer period of 22 yr (not compact).

2.5. Dissipative capture and close binaries

Close approaches of stars in a nascent mini-cluster can produce wide bound systems if the excessive kinetic energy is dissipated in their gas envelopes. At the same time, this causes a surge of accretion on to each star that can form close companions via disk fragmentation or shrink the orbit if the colliding star is already a binary. During such encounters, the accreted gas is not aligned with the original binary orbits or disks, which makes for a rapid orbit migration. Simulations of star formation show that dissipative collisions occur frequently (Bate, 2019; Kuruwita & Haugbølle, 2023) or may even be the dominant binary formation channel (Rozner et al., 2023). This mechanism can potentially explain the empirical relation between close (e.g. eclipsing) and wide binaries (Hwang, 2023) without evoking the L-K cycles.

3. The role of large surveys

Large surveys from ground and space dominate the current and future landscape of astronomical research and have profound impact in the area of stellar multiplicity. Yet, none of the existing surveys was designed for the study of binaries and multiples, and these detections are just by-products. Although a million of resolved Gaia binaries in El-Badry et al. (2021) greatly surpass the content of the WDS, many more binaries are missed by Gaia. Figure 2 represents various indicators of binarity available in DR3. One of those, for example, is the lack of astrometric solutions for pairs with separations from 0.1″ to 1″ and moderate magnitude differences, the so-called *Gaia hole* (Fig. 6 in Tokovinin, 2023b). Another non-trivial indicator is the variability of G-band fluxes in semi-resolved pairs (Holl et al., 2023). An excessive astrometric noise (large RUWE) can be caused not only by the motion of the photocenter, but also by blending with a faint semi-resolved companion. Surveys like Gaia become more productive when they are complemented by dedicated follow-up observations designed to overcome their limitations.

Statistical inferences from surveys must inevitably account for the selection biases. This can be achieved by two alternative strategies. The raw statistics

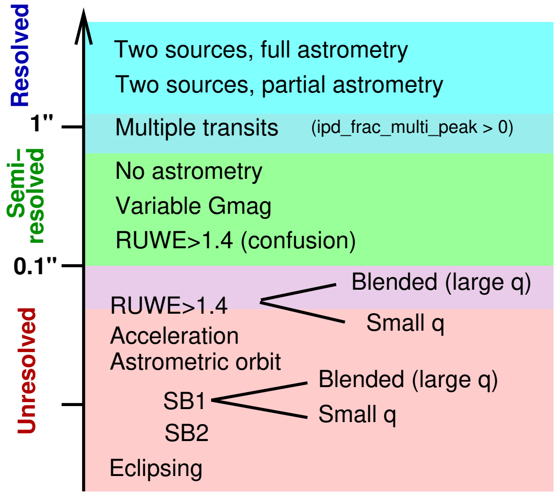

Figure 2. Schematic inventory of binarity indicators in Gaia. They are split into three broad groups: resolved (wide), semi-resolved, and unresolved (close) binaries. Each indicator has a complex and poorly known selection bias.

can be de-convolved from the selection and other effects. Alternatively, the true underlying statistics can be represented by a parametric model. The model is filtered by the selection function, and the result is compared to the observations to find the best-matching values of the parameters and their confidence intervals. Both approaches are found in the modern literature.

Apart from the statistics, large surveys find rare objects, like the two triply eclipsing sextuple systems discovered by TESS (Powell et al., 2021; Zasche et al., 2023). Existence of such objects challenges the theory and, thus, advances our understanding of the multiple-star formation.

Here is an example of my ongoing work based on surveys. Using the catalogs of EBs and the Gaia orbits, Czavalinga et al. (2023) identified 376 new compact hierarchies where astrometric or spectroscopic pairs contain inner short-period EBs (many of those are confirmed by the eclipse timing). Mutual alignment in such systems can be probed by the distribution of $x = |\cos i|$, where i is the inclination of the Gaia orbit. In aligned triples, one expects to find an excess of edge-on orbits with $x \approx 0$, while an isotropic orbit orientation corresponds to the uniform distribution of x. For all 1685 MSC triples with known outer inclinations (i.e. astrometric or visual orbits), x is indeed distributed uniformly. However, for the subset of 369 hierarchies containing EBs, a clear excess at $x < 0.3$ is seen, indicating mutual alignment within $\sim 20^\circ$ (Fig. 3). The excess, however, contains only 1/4 of such triples (the rest have uniform x), and this fraction does not depend on the outer period. So, the majority (3/4) of compact triples with short-period inner subsystems appear to be not mutually aligned. This result does not contradict the known misalignment of close inner pairs in some emblematic hierarchies like Algol or Castor (Torres et al., 2022). However, it is in tension with the strong alignment of compact hierarchies found by Borkovits et al. (2016). Resolved triples also show a strong alignment at outer separations

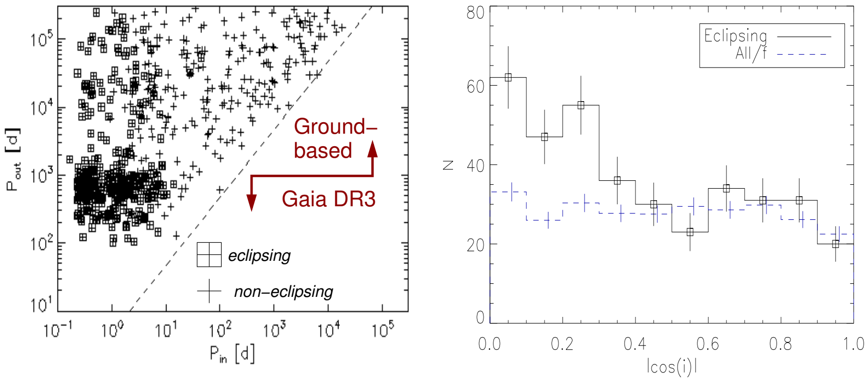

Figure 3. Mutual alignment in triple systems containing EBs. The left panel is a plot of outer and inner periods of all hierarchies with known outer inclinations. Outer periods below 1000 days are dominated by the Gaia sample of Czavalinga et al. (2023), longer periods result from ground-based observations. The dashed line is the dynamical stability limit; eclipsing subsystems are marked by squares. The right panel plots the histogram of $x = |\cos i|$ in the 369 hierarchies containing EBs and the scaled-down histogram for all hierarchies with known inclinations.

below ∼100 au (Tokovinin, 2017), but their inner subsystems are much wider than the EBs. The prevailing misalignment in the sample of Czavalinga et al. can be tested by dynamical analysis of compact hierarchies, e.g. a search for eclipse depth variations caused by precession (which, however, is slow).

A possible explanation of these findings might be related to the differences in the angular momentum of the accreted gas. When it is roughly constant, an aligned triple can form where the accretion of co-rotating gas does not shrink the orbits too much, like in the system shown in Fig. 1. If, on the other hand, a triple is formed by a dissipative capture, the accreted gas is strongly misaligned and efficiently shrinks the inner orbit, producing a close inner pair. More observational and theoretical work is needed to explore this scenario, and here the role of large surveys will be essential.

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