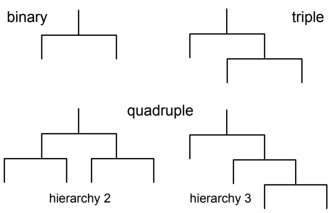
139. Quadruple star systems

I GAVE A SUMMARY of Gaia's ongoing contributions to *resolved* binary systems in essay #134, and followed this with some recent Gaia insights into triple systems in essay #135. I will look here at some interesting developments in the higher-multiplicity quadruple systems.

Compared with binary or even triples, quadruple (and higher-order) systems are relatively uncommon. For example, from a Hipparcos sample of F and G dwarfs within 67 pc, Tokovinin (2014) found the fractions with $n = 1,2,3,4,5$ components were $54:33:8:4:1$.

TWO STABLE configurations of quadruple systems can exist, as conveniently illustrated by the 'mobile' diagrams introduced by Evans (1968), and shown here for a binary system, a triple, and the two different (potentially) stable configurations for a quadruple system.



Hiererachy 2 corresponds to two binaries which orbit their common centre of mass. Hiererachy 3 corresponds to a triple system itself orbited by a fourth component. Unstable and short-lived trapezium systems are also observed in star-forming regions.

It is the great range of geometries, separations, and mass and magnitude differences, demanding a range of observational methods, that underlies the great difficulties in achieving any degree of survey completeness. For example, the inner binaries may be spectroscopic, eclipsing, or resolved; and the binary pairs may be very compact, or in wide orbits that are essentially unbound.

This range of properties also substantially complicates their measurement with Gaia: while a single star's motion can be characterised with just 5 astrometric parameters (two position and two proper motion components, and the parallax; or 6 including the radial velocity), and in principle over just 3–4 years, multiple systems require many more observations for their characterisation, and a more extended temporal baseline, crucially depending on the relevant orbital periods.

AMONGST KNOWN quadruple systems are the bright stars Capella, actually a pair of giants orbited by a pair of red dwarfs, and Mizar, a visual binary whose resolved components are themselves both binaries.

Others include Kepler–64, with the first exoplanet in a quadruple system orbiting two of the stars (Schwamb et al., 2013); ξ Tau, a spectroscopic and eclipsing 'hierarchy 3' system, with periods 7 d, 145 d, and 50 yr (Nemravová et al., 2013); GJ 867, at 8.8 pc, whose components are all M dwarfs (Davison et al., 2014); HD 98800, a young (10 Myr) nearby (45 pc) system composed of two spectroscopic binaries, with a gas-rich polar disk around one (Zúñiga-Fernández et al., 2021); and VW LMi, a particularly compact system including a contact eclipsing binary (Pribulla et al., 2020).

LET ME touch briefly on the complexities in understanding multiple star formation, and refer the interested reader to a recent review of the current theories by Clarke (2019). Her review also emphasises the role that Gaia can be expected to play in distinguishing rival hypotheses, for example (as will become clearer below) by constraining eccentricity distributions.

There are two main mechanisms considered responsible for multiple systems: fragmentation and capture. Formation by fragmentation of bound gas into multiple components includes 'turbulent fragmentation' during the initial large-amplitude perturbations, or 'disk fragmentation' during the later stages, usually associated with the growing importance of centrifugal effects. Formation may also occur through the mutual capture of initially unbound stars, either in cases where the excess kinetic energy of an initially unbound pair is transferred to a third star, and others where it is dissipated either via tides in the stellar envelope or in extended star–disk interactions. 'Fission', resulting from the spin-up and eventual rupture of a single star due to the accretion of high angular momentum material, is today disfavoured.

Further complications arise as a result of gas accretion, star–disk dynamical interactions, interactions within higher-multiplicity systems, and tidal interaction for the closest binaries.

AMONGST STATISTICAL studies pre-Gaia, Tokovinin (2008) compared the orbits of 81 binary–binary quadruples with those of 724 triple systems. Amongst his many findings were (a) that the distributions of the inner periods in triple and quadruple stars are similar and bimodal, while the outer periods and mass ratios are different; (b) in the systems with small period ratios the directions of the orbital spins are correlated, while in the systems with large ratios they are not.

Theories of the formation of triple and quadruple systems have become more interesting, and much more complex, with the advance of N-body dynamical simulations, and with the appreciation of the importance of the Kozai–Lidov resonance. In this curious 3-body gravitational phenomenon, the orbit of an inner binary is perturbed by a distant third body (on timescales much longer than the orbital periods), leading to a periodic exchange between the inner orbit's eccentricity and inclination. It can drive orbits to high eccentricity, and 'flip' a moderately inclined orbit from prograde to retrograde.

In a quadruple with two binaries on a long mutual orbit, each binary acts as a Kozai–Lidov perturber on the other (Pejcha et al., 2013). The binaries can then experience eccentricity oscillations, and be driven to high eccentricity (for a ratio of outer to inner semi-major axes of 10–20, some 30–50% reach an eccentricity $1-e<10^{-3}$ in one of the binaries). Orbital 'flips' and collisions are similarly enhanced in quadruples, with quadruples perhaps being a source of some triple systems. Further simulations were carried out by Hamers (2019).

Such a mechanism has been suggested as operating in the μ Ori system (Muterspaugh et al., 2008), but detailed tests of these ideas is complicated both by the small number of systems suitable for study, and by the difficulties in determining the relevant parameters of the 3-dimensional orbits (Tokovinin, 2020; Han et al., 2022).

GAIA IS contributing by discovering more such quadruple systems, and by helping to characterise their orbits. An effort to identify *resolved* systems was made by Tokovinin (2022), who started with the EDR3-derived Gaia Catalogue of Nearby Stars within 100 pc (essay #33). From common proper motions and other criteria, he identified 392 hierarchical triple systems, along with 30 quadruples and one quintuple, ξ Sco.

Also using EDR3, Fezenko et al. (2022) searched for comoving pairs where both are eclipsing binaries, and found eight new 2+2 systems with inner periods < 0.4 d, and outer separations > 1000 au, 7 times more than for random pairings. They concluded that the enhancement of short-period binaries in such wide-separation pairs suggests a close-binary formation mechanism enhanced by the presence of wide companions.

A number of other studies along similar lines are making use of the Gaia data, including those by Yousef et al. (2023), and Tokovinin (2023).

I WILL FINISH with two specific Gaia results on quadruple star systems that are arguably of particularly illuminating astrophysical interest.

For the first, simulations have failed to replicate the observed supernovae type Ia rates arising from collisions of two white dwarfs in dense stellar environments, or from binary mergers (Wang & Han, 2012). Even with Lidov–Kozai oscillations, white dwarf–white dwarf collisions in triples are too infrequent to explain observed rates (Hamers et al., 2013). But Lidov–Kozai oscillations in compact quadruple systems could play a key role.

Merle et al. (2022) studied the young, nearby short-period spectroscopic 2+2 quadruple HD 744384, in the open cluster IC 2391. The eccentricity of the 6-yr outer period is 0.46, and the two inner orbits ($P = 20.6$ d and 4.4 d, and $e = 0.36$ and 0.15) are not coplanar.

From a combination of ground-based spectroscopy, and Gaia/Hipparcos EDR3 astrometry, they showed that the system is undergoing secular (long time-scale) interaction, which may have pumped the eccentricity of one of the inner orbits to values far higher than expected for their spectral types. By modelling its future dynamical evolution, they showed that the HD 74438 system is an excellent candidate progenitor of sub-Chandrasekhar type Ia supernovae through white dwarf mergers.

I HAVE ALREADY looked at the crystallisation of white dwarfs, as they cool, in essays 42 and 108. The first evidence for this, from Gaia, was based on the white dwarf sequence in the Hertzsprung–Russell diagram. But later theoretical work (e.g. Cheng et al., 2019; Blouin et al., 2020) has found that the cooling delay required to match observations is larger than model predictions, requiring additional energy sources in their interiors.

In addition to considering the crystallisation process in a statistical sense, the observation of individual objects may provide further insight. In this context, Venner et al. (2023) reported that a recent Gaia discovery, HD 190412 C, at just 32 pc, identified in EDR3, is bound to the triple system HD 190412, thus representing a new Sirius-like system in the solar neighbourhood. Its location in the $T_{\rm eff}$–mass diagram implies that it is undergoing crystallisation, and makes it the first confirmed crystallising white dwarf whose total age can be externally constrained from the properties of the bound triple.

While their empirical age anomaly of 3.1 ± 1.9 Gyr is too imprecise to be statistically significant, preventing them from placing strong constraints on more detailed crystallisation models, their results *are* compatible with the hypothesis that ^{22}Ne phase separation is responsible for the excess cooling delay (e.g., Isern et al., 1991; Isern et al., 1997; Blouin et al., 2021). Their inference that similar systems are likely to be common, combined with future Gaia data releases, suggests that more stringent tests for models of white dwarf crystallisation should be possible in the near future.