138. Twin binaries – and our Sun

In essay 134, on resolved binary systems, I touched on the topic of 'twin binaries', the excess numbers of equal brightness (and presumably equal mass) binary systems. Recent Gaia results have unambiguously confirmed the existence of this curious property of the binary star population. In turn, this has stimulated new investigations into their origin, the consequences for models of star formation, and indeed for the origin of our own Sun. I will expand on this topic here.

Although several studies of the distribution of the mass ratio in binary systems ($q = M_2/M_1$) had been carried out previously, Trimble (1974) examined the distribution of the 826 binary systems listed in Batten's *Sixth Catalogue of the Orbital Elements of Spectroscopic Binary Systems* (both single-lined, SB1, and double-lined, SB2), and concluded that the distribution was bimodal, with peaks near mass ratios of 0.3 and 1.0. The latter correspond to components of equal mass.

A similar study, but restricted to just 178 single-lined systems, was carried out by Lucy & Ricco (1979), based on the semi-amplitudes of the radial velocity curves. They identified a narrow peak at $q \simeq 0.97$ which they attributed to some underlying formation mechanism, as opposed to the effects of evolution or selection.

Of the formation mechanisms discussed at the time, they dismissed 'fission'. Simulations had shown that fission during the final phase of a rotating protostar's contraction to the main sequence produces binaries with $q \sim 0.2$ (a result consistent with classical models in which breakup results from a third-harmonic instability of an elongated triaxial ellipsoid). Instead, they favoured formation via 'fragmentation' of the toroidal structure that can appear during a rotating star's dynamical collapse. Later models, I should add, largely exclude formation by such a fragmentation process.

Tokovinin (2000) revisited the distribution for some 100 double-lined systems (the SB2s being less dependent on selection effects). He confirmed that solar-type binaries have a statistically significant excess of systems with $q > 0.95$ at $P < 40$ d, and which he designated as 'twins'. He found no such population at longer periods.

Tokovinin favoured the formation of 'twins' as arising in binaries that had evolved to become relatively close, possibly through dynamical interaction in multiple systems. If this occurred while the system was still surrounded by a massive envelope, their formation by subsequent accretion might follow. That many twins have tertiary components might, he argued, be further circumstantial evidence for such a mechanism.

Independently of the spectroscopic binary statistics, the frequent occurrence of binary stars with nearly equal components had also been invoked to explain the existence of the so-called 'binary sequence' in the colour–magnitude diagrams of open clusters, some 0.75 mag above the main sequence, such as in Praesepe (Mermilliod & Mayor, 1999) and the Pleiades (Kähler, 1999).

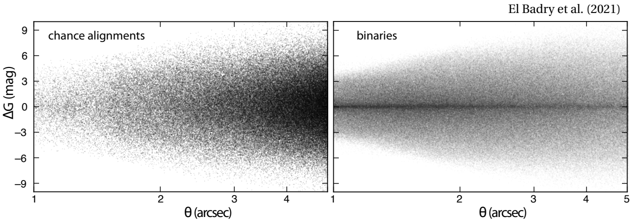
Extending these studies to *resolved* binaries has been complicated by the various selection effects that plague the construction of complete binary star samples. Gaia's uniform astrometric survey provides a new opportunity for further insights.

El-Badry et al. (2019) used Gaia EDR3 to define a sample of 42 000 wide main-sequence binaries, and identified a sharp excess of equal-mass 'twins', now statistically significant out to separations of 1000–10 000 au. The excess is narrow, with a steep increase between mass ratios 0.95–1.

In a later paper, also using EDR3, El-Badry et al. (2021) defined a larger sample of 1.26 million resolved binaries within 1000 pc with more than a 90% probability of being bound. The figure below shows the magnitude difference, ΔG, as a function of separation, for both true binaries (for which both components have consistent parallaxes and proper motions) and chance alignments. The excess population with $\Delta G \simeq 0$ is clearly apparent. They inferred a contrast limit of $\Delta G \simeq 4$ mag at 1 arcsec separations, and $\Delta G \simeq 7$ mag at 2 arcsec.

In the remainder of this essay, I will look in more detail at the properties of this population of 'twin binaries', at subsequent work on the possible formation mechanisms, and what some authors have concluded it might be informing us about our own Sun.

El Badry et al. (2021)



It is worth emphasising the huge advance in statistical weight provided by the Gaia EDR3 sample. Compared with the few hundred systems in the early spectroscopic binary studies, the 42 000 main-sequence binaries defined by El-Badry et al. (2019) were assigned to 35 independent bins, sub-divided according to primary mass and component separation, with hundreds or even thousands of binaries in each!

This allowed them to measure the mass ratios of binaries with primary masses M_1 in the range $0.1-2.5M_\odot$, mass ratios in the range $0.1 < q < 1$, and separations in the range 50–50 000 au. The excess of equal mass twins remains significant out to 1000–10 000 au, depending on the primary star mass. The excess is narrow, with a steep increase in the range $q = 0.95-1$, but with no obvious excess for $q \lesssim 0.95$. The twin excess decreases with increasing separation, but its width (for $q \gtrsim 0.95$) is constant over separations ranging from 0.01–10 000 au.

The results have clarified several aspects of the twin binary enigma. For example, both Lucy & Ricco (1979) and Tokovinin (2000) found a fall-off for $P > 40$ d ($a \lesssim 0.2$ au), although this was not confirmed by Tokovinin (2014), nor by Moe & Di Stefano (2017). Neither is the twin phenomenon a selection effect, as suggested by Mazeh et al. (2003) and Cantrell & Dougan (2014).

There is a substantial literature on binary star formation, with different mechanisms invoked to explain their formation over a wide range of separations. Putting twin binaries to one side, it has often been hypothesised that the components of binaries wider than a few hundred au formed nearly independently of one another during turbulent core fragmentation or, for the widest separations, by becoming bound at later times.

But clearly, twin binaries pose a specific challenge to formation models. At the smallest separations, their formation through accretion in circumbinary disks has been suggested (e.g. Bate, 2000). Adams et al. (2020) showed that a binary's lowest energy state corresponds to equal mass stars on a circular orbit, with the stellar spins both synchronised and aligned with the orbit.

At wider separations, out to 100–200 au, competitive accretion within a circumbinary disk seems to provide an intuitive, albeit not a consensus, explanation, with several studies finding that the accretion rate is usually higher for the secondary than the primary (e.g., Bate, 2000; Young & Clarke, 2015). This is because the secondary's orbit around the barycentre is larger than the primary's, so it sweeps out a larger radius, and accretes more rapidly, driving the mass ratio towards unity.

For separations more than 100–200 au, viz. beyond the typical maximum sizes of observed circumstellar and circumbinary gas disks, the most plausible scenario is that twin binaries formed at closer separations, and their orbits were subsequently widened by dynamical interactions in their cluster environments (e.g. El-Badry et al., 2019, Section 5.2).

Further insight could come from knowledge of the alignment of their spin vectors, and how this varies with separation (e.g. Justesen & Albrecht, 2020). If twins indeed formed in circumbinary disks at closer separations, their spins should be more aligned than non-twins at the same separation (El-Badry et al., 2021, Section 6.1).

A further development, following on from these Gaia results, was the examination of the eccentricity distribution of wide twins by Hwang et al. (2022). From the angle between the component separation and relative velocity vectors, they found that essentially all wide twins must be on extremely eccentric orbits.

For the excess-twin population at 400–1000 au, they inferred eccentricities almost exclusively in the range $e = 0.95-1$, in turn implying pericentre distances of order 10 au. This is consistent with a scenario in which twins are born in circumbinary disks, and are subsequently widened via dynamical interactions, either in their birth environments, or subsequently by tidal torques from the Galactic disk, or scattering by passing stars and molecular clouds (Modak & Hamilton, 2023).

I will finish with what might seem to be an unrelated topic! Amongst the puzzles in our understanding of the solar system are the origin of the outer Oort Cloud and its relation to the scattered disk (e.g. Brasser & Morbidelli, 2013), and the clustering of trans-Neptunian objects suggesting a hypothetical 'Planet Nine' at some 500 au from the Sun (e.g. Batygin et al., 2019).

Siraj & Loeb (2020) showed that an equal-mass companion to our Sun in the solar birth cluster at a separation of 1000 au would have increased the likelihood both of forming the observed population of outer Oort Cloud objects, and of capturing Planet Nine.

This rests on the findings that stellar binaries can capture background objects via three-body processes, with capture rates enhanced relative to single stars. Close companions to the Sun had been considered previously, but ruled out observationally (Luhman, 2014).

But their models of an equal-mass binary companion to the Sun, which existed only in the birth cluster and was subsequently ejected, indeed predicts an overabundance of dwarf planets, and with similar orbits to Planet Nine. Such objects could, they conclude, soon be discoverable with the Vera Rubin Observatory.