145. Spectroscopic binaries

BINARY STARS span a wide range of angular separation, magnitude difference, and orbital period and inclination to the line-of-sight.

They are often only detectable by specific observations, according to their phenomenological classification as visual (with angular separations that can be resolved spatially), eclipsing (where the orbit plane is closely aligned to the line-of-sight), astrometric (where the photocentre shows periodic motion in the plane of the sky), or spectroscopic (compact systems manifested by the Doppler motion of their spectral lines).

Let me also recall that for spectroscopic binaries, systems are further subdivided into single-lined systems in which the spectrum is populated by the lines of one of the two binary components (SB1), and double-lined systems in which lines of both components are detected and observed to vary (SB2).

Some systems may be measurable by more than one technique. And as I noted in essay #79, on some non-single star results, Gaia's combination of astrometric, photometric, and radial velocity accuracy, and its angular resolution, equips it to discover and characterise all of these binary types (although not all binaries!), simultaneously and uniformly, and in substantial numbers.

I looked at some of the general results on *resolved* binaries in essay #134. I will focus here on some of the bottom-line numbers, and just one of the many scientific insights, that Gaia is advancing in the case of *spectroscopic* binaries.

MY STARTING POINT is the first overview of stellar multiplicity (viz. 'non-single stars') derived from Gaia DR3 by Arenou et al., 2023. In their Section 2.2.3, they identify 181 327 SB1 spectroscopic binaries (and a further 5000 or so SB2), based on the radial velocities measured by Gaia's radial velocity spectrograph (RVS).

This is a huge advance simply in terms of numbers of systems compared with previous such catalogues, notably the SB9 catalogue which lists around 4000 orbits (Pourbaix et al., 2009), and the recent APOGEE compilation of some 1000 new orbits (Price-Whelan et al., 2020).

THIS INCREASE, by nearly two orders of magnitude, provides an unprecedented high-quality data set for examining the statistics of short-period binaries, including the binary frequency as a function of primary mass, the mass–ratio distribution, and the eccentricity–period relation. These are, in turn, of great importance in understanding binary formation and evolution.

A NEXT IMPORTANT step was the verification of this sample by Bashi et al. (2022). As they stressed, this Gaia DR3 catalogue of 181 327 spectroscopic binaries includes the Keplerian elements of each orbit (including period and eccentricity), and the robustness of the solution, but not the individual radial velocities and measurement epochs. Bashi et al. (2022) used two external radial velocity sources to validate the Gaia orbits: 17 563 stars from LAMOST DR6, and 6018 from GALAH DR3. They constructed a function that estimates the reliability of the Gaia orbits, eliminating some spurious systems, and resulting in a 'clean' (but still very large) Gaia sample of 91 740 single-lined spectroscopic binary orbits.

They noted two features evident in their resulting sample: a paucity of short-period binaries with low-mass primaries, which they considered might nevertheless be a result of observational bias, and a subsample of main-sequence binaries on *circular* orbits, taken as evidence for some significant circularisation process.

I WILL FOCUS on this specific question of orbit circularisation, and it is useful to emphasise why the problem is important. Firstly multiple systems, and in particular binary systems, are common, with some 35% of solar-type stars being in multiple systems, and as many as 70% in the case of O-type stars.

The companion often has a significant impact on the evolution of both stars, with the products including fast rotators, X-ray binaries, novae, and chemically peculiar objects (such as carbon-enhanced stars and barium stars), representing a major driver of the Galactic enrichment of heavy elements. As a result, understanding their detailed evolution is of considerable importance.

Given that an important physical process in binary star evolution is tidal friction and associated evolution, I will focus on this phenomenon in the following, and illustrate how Gaia's observations of spectroscopic binaries are advancing our understanding of it.

There are, not surprisingly, various complexities in modelling and interpreting tidal evolution. To give some flavour, tides in binary systems are divided into the so-called 'equilibrium' and 'dynamical' tides (e.g. Zahn, 2008; Ogilvie, 2014). The former results from the companion's gravitational attraction, and leads to a bulge rotating at the companion's orbital period. The latter results from tidally-excited, low-frequency gravity-driven oscillation modes near the core–boundary surface, with modal periods comparable to that of the orbit. Their relative importance depends on the form of the stellar (convective/radiative) radial profile.

Both extract energy from the orbit, resulting in a secular decrease of the orbital period, a decreasing eccentricity with time, and stellar rotation rates tending to spin–orbit synchronisation (Hut, 1981).

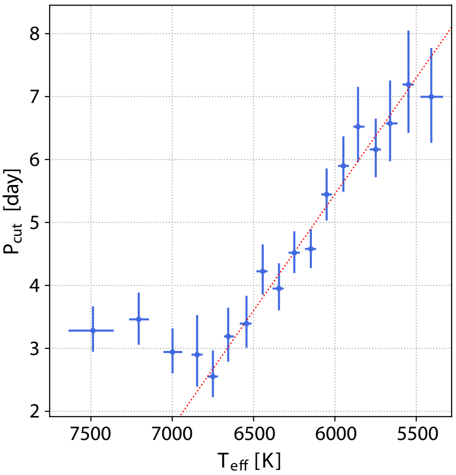
Observational evidence for tidal circularisation, based on small samples of spectroscopic binaries, was already presented by Mayor & Mermilliod (1984) and Mathieu & Mazeh (1988). Their samples showed circularisation 'cut-off periods', with short-period binaries having circular orbits, and longer period systems having more eccentric orbits. A straightforward explanation invokes the dependence of tidal interaction on binary separation, and therefore on binary period, with older samples showing longer cut-off periods (Witte & Savonije, 2002). In open clusters in which the age can be determined through main-sequence turn-off fitting, the cut-off period provides an observational measure of the tidal efficiency (Meibom & Mathieu, 2005).

The most recent studies of the fraction of circular orbits in coeval populations of open clusters of different ages has been based on the widespread inference that tidal circularisation operates predominantly during the main sequence evolutionary stage.

A new opportunity for studying the details of this physical process, enabled by the availability of the Gaia DR3 sample of spectroscopic binaries, has been presented by Bashi et al. (2023).

They selected 17 000 main sequence systems from the 'cleaned' sample of Bashi et al. (2022), focusing on A, F and G-type primaries, as inferred by their position in the Gaia colour–magnitude diagram.

From the resulting behaviour of period versus eccentricity, they found that the cut-off period does not depend on the stellar age but, instead, varies with stellar temperature (and therefore stellar mass), decreasing linearly from 6.5 d at $T_{\rm eff} \sim 5700$ K to around 2.5 d at 6800 K, as shown in the accompanying figure.



Bashi et al. (2023)

Following the detailed models reviewed by Zahn (2008), they assume that the circularisation timescale is determined by turbulent dissipation – in cool stars characterised by convective envelopes and radiative damping, and in hotter stars with radiative envelopes. But their findings on the cut-off period for F- and G-stars are inconsistent with such circularisation theory, if it is assumed that this circularisation took place during the star's *main-sequence* lifetime.

Their favoured explanation is that the eccentricity distribution was determined, instead, during their *pre-main-sequence* phase, when the stars were much larger, and the circularisation processes correspondingly much faster. Interestingly, this possibility had already been suggested by Mayor & Mermilliod (1984), and evaluated in detail by Zahn & Bouchet (1989), and subsequently by Khaliullin & Khaliullina (2011). They suggest that the weak dependence of the cut-off period with cluster age is of minor significance, perhaps instead related to the different temperatures of the samples.

A subsequent study by Mirouh et al. (2023) assessed the impact of tides on the orbit circularisation in eight open clusters. Their study confirmed the inefficiency of tides on the main sequence, and therefore provides additional circumstantial support for the suggestion that the major contribution to the orbit circularisation of close binaries indeed takes place in the pre-main sequence phase.

The conclusions by Bashi et al. (2023), that orbit circularisation occurs predominantly in the pre-main sequence phase, are potentially far-reaching.

As they emphasise, understanding tidal circularisation is important for modelling the evolution of short-period binaries, with implications for the understanding of close triple systems, cataclysmic binaries, X-ray binaries, black hole mergers, and also in the formation and evolution of exoplanets, and hot Jupiters in particular.