226. Heartbeat stars

Heartbeat stars are a class of detached binary with eccentric orbits, ($e \gtrsim 0.3$), and short periods, typically in the range 1–100 d. They generally display very small amplitude variations, 1–2 mmag, which are driven by tidal distortion, reflection and Doppler beaming.

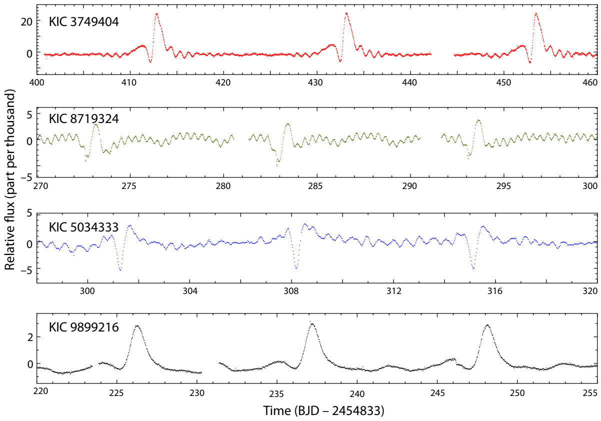
These effects are most prominent near periastron, where they combine to generate the characteristic electrocardiogram-like ‘heartbeat’ signature which gives them their name (Thompson et al., 2012). Many continue to oscillate after periastron and throughout the entire orbit, behaviour attributed to the tidal excitation of oscillation modes within one or both stars.

They are attracting considerable theoretical interest, as probes of tidal dissipation, internal stellar structure, orbit circularisation, and short-period binary formation (e.g. Shporer et al., 2016; Moe & Kratter, 2018; Toonen et al., 2020). Gaia is starting to contribute to their understanding. I will start with a pre-Gaia synopsis.

Early discoveries, some tentatively attributed to the effects of tidal distortion but without a full picture, included the well-studied but enigmatic ϵ Per (Frost & Adams, 1904; Tarasov et al., 1995; De Cat et al., 2000b), the eccentric binary HD 209295 (Handler et al., 2002), the SPB (slowly-pulsating B) star HD 177863 (De Cat et al., 2000a; Willems & Aerts, 2002), the eccentric CoRoT discovery HD 174884 (Maceroni et al., 2009), and the δ Scu variable HD 51844 (Hareter et al., 2014).

More than 100 with asymmetric light curves, attributed to large eccentricities and tidal distortions, were identified in the OGLE catalogue of ellipsoidal variables (Soszyński et al., 2004), of which they are a subset.

As a result of their small amplitude variations and characteristic time scales of order days, they were only found in larger numbers, and with better light curve characterisation, with Kepler (Welsh et al., 2011; Thompson et al., 2012; Hambleton et al., 2013; Beck et al., 2014; Kirk et al., 2016); and more recently with TESS (Murphy et al., 2020; Jayasinghe et al., 2021; Kołaczek-Szymański et al., 2021; Li et al., 2024; Solanki et al., 2024; Uronen et al., 2024). Many others have since been found in the OGLE data (Wrona et al., 2022a; Wrona et al., 2022b).



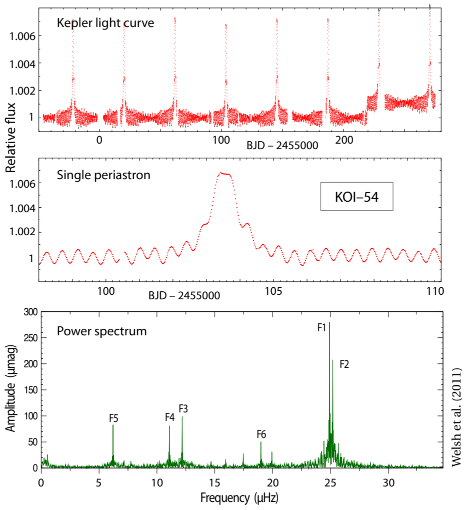
Thompson et al. (2012)

Of some 300 known today, four example light curves from the Kepler mission, are shown here. The ellipsoidal distortion, increasing towards periastron, results in part of the observed brightness changes (in common with other ellipsoidal variables, essay 133). But the strong tidal forces cause more rapid changes, resulting in the heartbeat-like fluctuations. Under certain conditions, tidal oscillations are also resonantly excited.

Orbital parameters are derived from the light curves, accounting for ellipsoidal variability, Doppler beaming, reflection effects, and eclipses (Kumar et al., 1995). Available codes for this include `eBEER` (Engel et al., 2020), and `PHOEBE` (Horvat et al., 2018).

Out of 180 heartbeat stars identified from 240 short-period ($P < 10$ d) binaries from TESS, Solanki et al. (2024) found 133 with eclipses. Some 30 with both primary and secondary eclipses show a secular change in inter-eclipse timing and relative eclipse depth over a multi-year baseline, attributable to orbital precession.

The physics gets more interesting in systems in which ‘tidally excited oscillations’ have been seen in their light curves, a phenomenon predicted by Kumar et al. (1995). One of the most-studied exemplars is the fourth heartbeat system discovered, the high eccentricity ($e = 0.83$, $P = 41.8$ d) Kepler discovery, KOI–54 (Welsh et al., 2011).

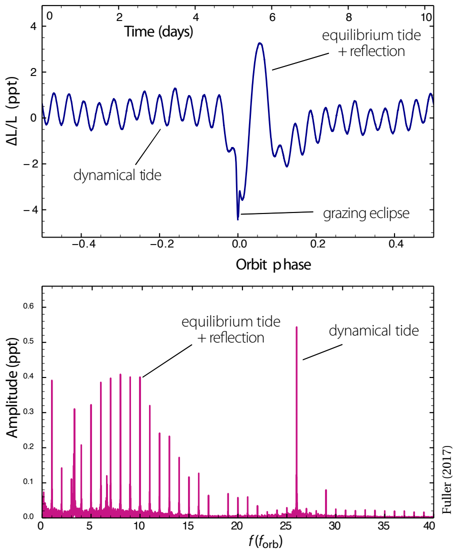


Welsh et al. (2011)

This, in turn, provides valuable constraints on the theories of dynamic tidal forces on stellar binaries (e.g. Willems, 2003; Burkart et al., 2012; Fuller & Lai, 2012; Cheng et al., 2020; Guo et al., 2020).

A key signature of tidally excited oscillations is their occurrence at integer multiples of the orbit frequency (Fuller, 2017), the largest corresponding to resonances between harmonics of the orbit frequency and the star's normal modes. For KOI–54, two dominant oscillations, responsible for the beating pattern, are at the 90th and 91st harmonic of the orbit frequency (Welsh et al., 2011).

The response comprises two components (Fuller, 2017): the equilibrium tide (the steady-state hydrostatic deformation due to the companion in the absence of orbital motion), and the dynamical tide (the oscillation due to the time-varying nature of the tidal forcing). The former contributes to the 'heartbeat' signature near periastron, while the dynamical tide results in tidally excited oscillations visible at all orbital phases.



Fuller (2017)

I HAVE MENTIONED that typical oscillation amplitudes of heartbeat stars are of order 1–2 mmag. In this context, particularly noteworthy is the system with the 'loudest' heartbeat: the 13 mag MACHO 80.7443.1718 in the Large Magellanic Cloud. This shows peak-to-peak variability of 40% near periastron (Jayasinghe et al., 2021). Its high-mass components, a $35M_\odot$ supergiant and a $16M_\odot$ O9.5 secondary, are in a 32.8 d, $e = 0.51$ orbit, and the system shows tidally excited oscillations at the 25th and 41st orbital harmonics.

Another peculiarity is the 'single-sided pulsator' HD 74423, discovered in the TESS data (Handler et al., 2020). It is inferred to have a 'teardrop' shape, with the star pulsating on only one side. More formally, it is interpreted as an obliquely pulsating distorted dipole, with a pulsation axis aligned with the tidal axis.

THE FIRST study of heartbeat stars that makes substantive use of Gaia data is for the 180 TESS systems identified by Solanki et al. (2024). Their fits to the phase curves, using `eBEER`, revealed that there is a potential degeneracy in constraining the stellar masses, radii, and temperatures using photometry alone. These were improved using the Gaia magnitudes and distances to estimate the absolute magnitudes, and improved (black-body) estimates of $T_{\rm eff}$ and $R_\star$. Gaia strongly constrains upper limits on the masses, radii, and temperatures, and yields masses in good agreement with main-sequence predictions based on the Gaia temperatures.

They also found good agreement between their estimates of eccentricity, e, and argument of periastron, ω, compared with those derived on the basis of supplementary radial velocity data (Shporer et al., 2016).

Finally, by examining the Gaia 'renormalised unit weight error' (RUWE, where large values might suggest the presence of a tertiary), they confirmed that the orbital precession measured for a number of systems (which reaches 9° / yr in the case of TIC 451708707) is indeed most likely driven by tides and not, for example, by Kozai–Lidov oscillations from a tertiary companion.

STUDIES OF THE rich complexities of heartbeat stars is still in its infancy. Searches to date suggest that many more systems will be discovered even in the TESS data alone (Solanki et al., 2024). And the use of the Gaia data to assist determination of improved orbits and stellar properties will surely be picked up in future studies.

Given their high eccentricities, short-period heartbeat systems represent a particular subset of all close binaries. The formation of close binaries with orbital periods $P \lesssim 10$ d ($a \lesssim 0.1$ au) is a subject of ongoing study (e.g. Moe & Kratter, 2018; Meyer et al., 2018; Hwang & Zakamska, 2020). Whether heartbeat binaries originate from the same formation channels as other circularised short-period binaries is, today, still an open question.