Stars and their variability observed from space
C. Neiner, W. W. Weiss, D. Baade, R. E. Griffin, C. C. Lovekin, A. F. J. Moffat (eds)

LISTENING TO THE HEARTBEAT: TIDAL ASTEROSEISMOLOGY IN ACTION

Z. Guo[1]

Abstract. We briefly review the current status of the study of tidally excited oscillations (TEOs) in heartbeat binary stars. Particular attention is paid to correctly extracting the TEOs when the Fourier spectrum also contains other types of pulsations and variabilities. We then focus on the theoretical modeling of the TEO amplitudes and phases. Pulsation amplitude can be modeled by a statistical approach, and pulsation phases can help to identify the azimuthal number m of pulsation modes. We verify the results by an ensemble study of ten systems. We discuss some future prospects, including the secular evolution and the non-linear effect of TEOs.

Keywords: Binary star, tide, oscillation

1 Introduction

More than half of all stars reside in binaries, and tides can have a significant effect on stellar oscillations. In the first version of the classical textbook *Nonradial oscillations of stars*, there is a whole chapter on tidal oscillations (Unno et al. 1979). However, it was removed in the second version (Unno et al. 1989), probably owing to the notion that such oscillations are difficult to be observed in practice.

The direct manifestation of equilibrium and dynamical tides can be seen in the light curves as flux variations. The theoretical foundations were laid out several decades ago, and Kumar et al. (1995) even derived an expression for the observed flux variations from the tidal response. However, it is only because of the *Kepler* satellite that we are able to observe unambiguously such tidally excited oscillations. The prototype system KOI-54 (Welsh et al. 2011), inspired lots of interest in observational (Hambleton et al. 2013, 2016, 2018; Guo et al. 2017, 2019a) and theoretical studies (Fuller & Lai 2012; Burkart et al. 2012; Fuller et al. 2013; O'Leary & Burkart 2014; Fuller 2017; Penoyre & Stone 2019). Thompson et al. (2012) presented tens of such so-called 'heartbeat' stars (HBs) and the Kepler Eclipsing Binary (EB) Catalog (Kirk et al. 2016) now consists of 173 such systems, flagged as 'HBs'. Out of these, about 24 systems show tidally excited oscillations (TEOs), flagged as 'TPs'. Spectroscopic follow-up observations are accumulating (Smullen & Kobulnicky 2015; Shporer et al. 2016). Other space missions such as BRITE revealed more-massive HBs with TEOs (Pigulski et al. 2018), including the O-type binary ι Ori (Pablo et al. 2017). The first sector data of the ongoing TESS mission already offered us a massive HB with TEOs (Jayasinghe et al. 2019).

2 Extracting Tidally Excited Oscillations from Binary Light Curves

To study TEOs, we usually first model the flux variations from the equilibrium tide. Dedicated light-curve synthesis codes are usually used, such as that by Wilson-Devinney (Wilson & Devinney 1971) and its further development in PHOEBE (Prša & Zwitter 2005). In Figure 1, we show sample binary light curve models as red lines. For low inclination systems, the light curves usually contain only one periastron brightening bump. If the binary orbit has a moderate inclination, both a hump and a dip are present. For high inclination systems, the light curves usually contain both a bump and an eclipse. The binary models presented here are either from the simplified light-curve model (Kumar model for KIC 9016693 and KIC 5034333) or from dedicated synthesis codes (KIC 4142768).

After subtracting the binary model, Fourier spectra of the residuals are presented in the right half of Fig 1. Both the low-frequency (g-mode) and high-frequency (p-mode) region can show variability.

[1] Department of Astronomy and Astrophysics, 525 Davey Lab, The Pennsylvania State University, USA

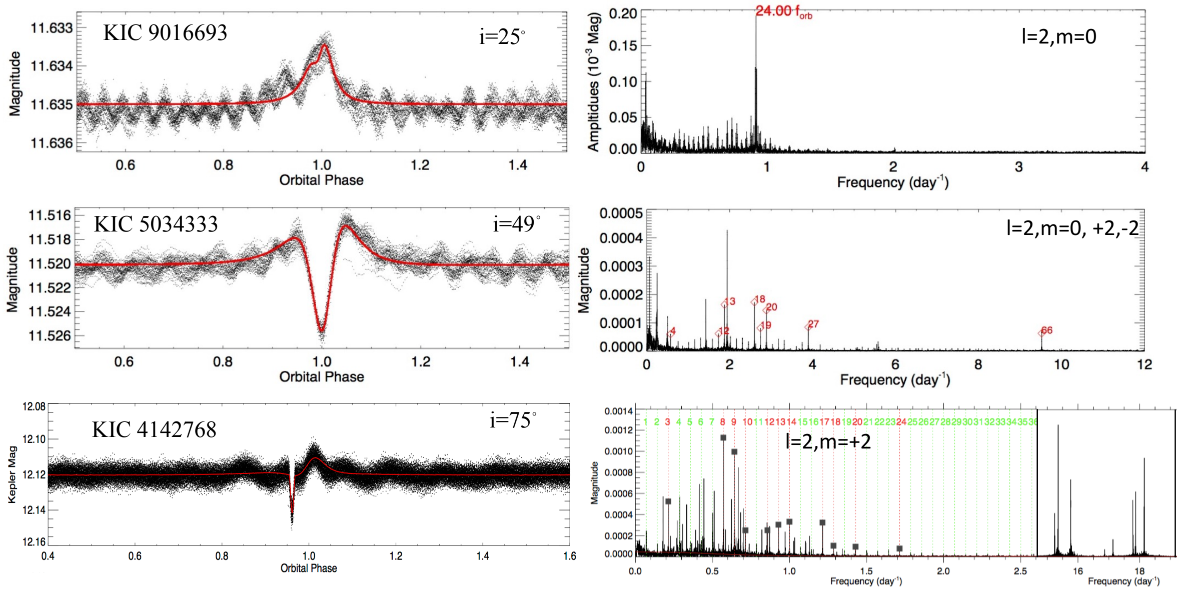

Fig. 1. Phase-folded Kepler light curves of sample heartbeat binaries and their Fourier spectra. Here we show three typical systems of low, moderate, and high orbital inclinations. From top to bottom, $i = 25.6°, 49.9°$, and $75.8°$. The tidally excited oscillations are labeled in the Fourier spectra.

2.1 Low-frequency Region

The tidal forcing frequencies from the companion star naturally fall within the low frequency regime. We thus expect the prominent TEOs are low-frequency g modes* with $l = 2$, which are almost always orbital harmonics†. However, in the low-frequency region of the Fourier spectrum, variabilities can also arise from imperfect binary light-curve removal (a series of orbital harmonic frequencies), rotational modulations (usually one or two times the orbital frequency), and γ Dor-type self-excited g modes (usually not orbital harmonics, but quasi-linearly spaced in period). Thus the analysis has to be performed with care. In the right panels of Fig 1, we show the three Fourier spectra. The TEOs have been labeled, and other variablities are mostly from the rotational signal and γ Dor type g modes.

2.2 High-frequency Region

Tidally excited oscillations can coexist with high-frequency p modes. These p-modes can be affected by tides. For instance, the δ Scuti type p modes in KIC 4544587 are coupled to the tidally excited g-modes, showing a regular pattern spaced by the orbital frequency (Hambleton et al. 2013). In the circular, close binary HD 74423, the p modes from the near-Roche-lobe filling primary star are magnified and trapped around the inner L1 point (Handler et al., submitted). The pulsation axis is aligned with the tidal force so that the observed p modes show amplitude and phase variations. In the Fourier spectrum, the perturbed p modes also appear as splittings with spacing of the orbital frequency.

3 Modeling the amplitudes and phases of TEOs

3.1 Pulsation Amplitude: the Statistical Approach by Fuller (2017)

Unlike self-excited oscillations, linear theory can predict the amplitude of the tidally forced oscillations. This can be achieved by directly solving the forced oscillation equations (Burkart et al. 2012; Valsecchi et al. 2013) or

*However, refer to Fuller et al. (2013) for tidally excited p modes in a triple system. In principle, Rossby modes can also be tidally excited.

†Non-linear effects can generate harmonic TEOs, e.g., those in KOI-54 and KIC 3230227.

by using the mode decomposition method (Schenk et al. 2002; Fuller & Lai 2012). The latter method has been used to calculate the amplitude and phases of TEOs with rotation, nonadiabaticity, and spin-orbit misalignment taken into account (Fuller 2017). The pulsation amplitude sensitively depends on the detuning parameter, i.e., the difference between the forcing frequency and the eigen-frequency of the star, which cannot be determined accurately. It is better to model the TEO amplitude by a statistical approach, treating the detuning as a random variable. Fig 2 shows the TEO amplitude modeling for KIC 4142768 (Guo et al. 2019a). The shaded region indicates the $\pm 2\sigma$ credible region, matching the observed amplitudes (gray squares) very well.

For the modeling of TEOs in resonance locking, special treatment is required: refer to section 5.1 of Fuller (2017). Practical applications can be found in Fuller et al. (2017) for KIC 8164262, and Cheng (2020, in prep.) for KIC 11494130.

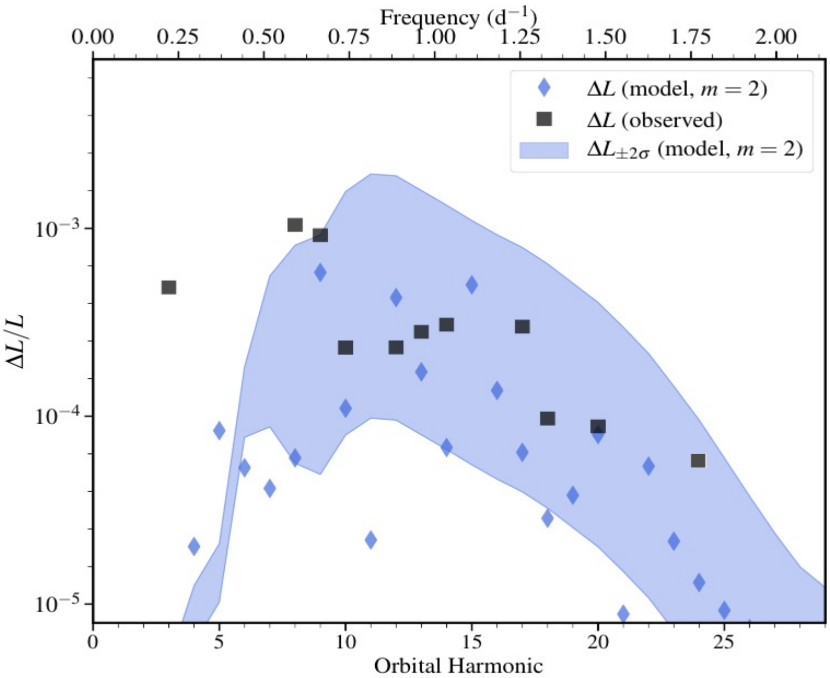

Fig. 2. TEO amplitude modeling of KIC 4142768 assuming a mode identification of $l = 2, m = 2$. See Guo et al. (2019a) for details.

3.2 Mode Identification from Pulsation Phases

Simply speaking, the theoretical adiabatic pulsation-phase of TEOs depends only on the argument of periastron passage ω_p by the relation $\phi_{l=2,m} = 0.25 + m[0.25 - \omega_p/(2\pi)]$. Fig 3 shows the observed TEO phases of six heartbeat binaries and the theoretical phases (vertical strips) with the corresponding azimuthal number m labeled. The diagrams of KOI-54 and KIC 3230227 are taken from O'Leary & Burkart (2014), and Guo et al. (2017), respectively. It is encouraging to see that they almost all agree within one sigma.

However, as shown in Fig. 4, we also find a large number of heartbeat systems that show significant deviations from the theoretical adiabatic phases (see Guo et al. 2019b for more details). A non-adiabaticity mode and spin-orbit misalignment are likely the reasons behind this. Guo et al. (2019a) considered the mode nonadiabaticity in the theoretical TEO phase calculations, and the theory seems to agree with observations.

We find that low-inclination systems favor the presence of $m = 0$ modes, and very high-inclination systems are more likely to show $|m| = 2$ modes. This is in agreement with the simple geometric interpretation.

4 Discussions and Future Prospects

Other than mode identification, variations of the amplitude and phase of TEOs can offer us information on mode damping and orbital evolution. For KOI-54, it was found that the TEO amplitudes decrease by about $2 - 3\%$ over three years, which cannot be explained solely by the radiative-mode damping (O'Leary & Burkart 2014). A careful observation of these TEOs can identify modes that are undergoing triple- or multi-mode coupling.

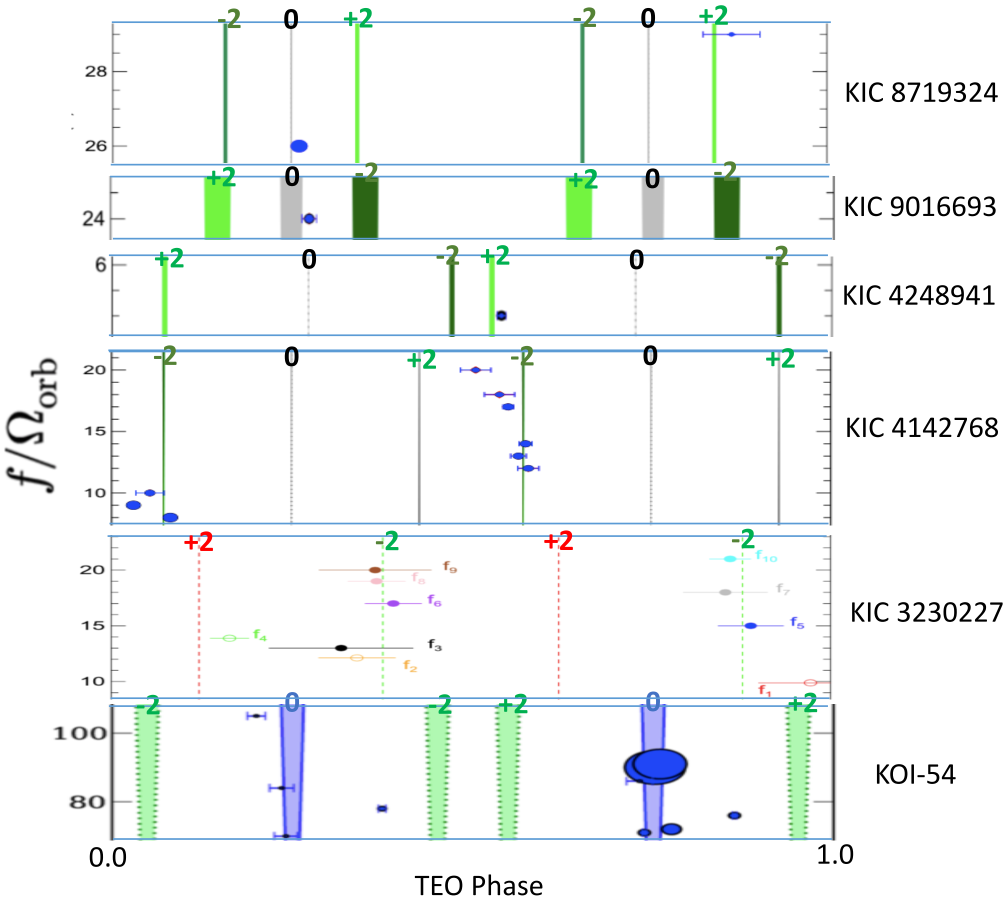

Fig. 3. Pulsation frequencies of TEOs in units of the orbital frequency ($N = f/\Omega_{\rm orb}$) as a function of TEO phases (in units of 2π). These are six heartbeat binaries showing a good match with theoretical predictions for TEO phases. The azimuthal number m is labeled.

Recently, Guo (2019, submitted) found that the non-linear mode coupling in KIC 3230227 has probably settled to the equilibrium state. By utilizing the amplitude equations, a detailed analysis of the non-linear mode coupling can be performed (Weinberg et al. 2012) and is highly desirable. Besides the tidal effect, heartbeat stars are also laboratories for physical processes such as high-eccentricity orbital migration and precession. Their potential has not yet been fully exploited.

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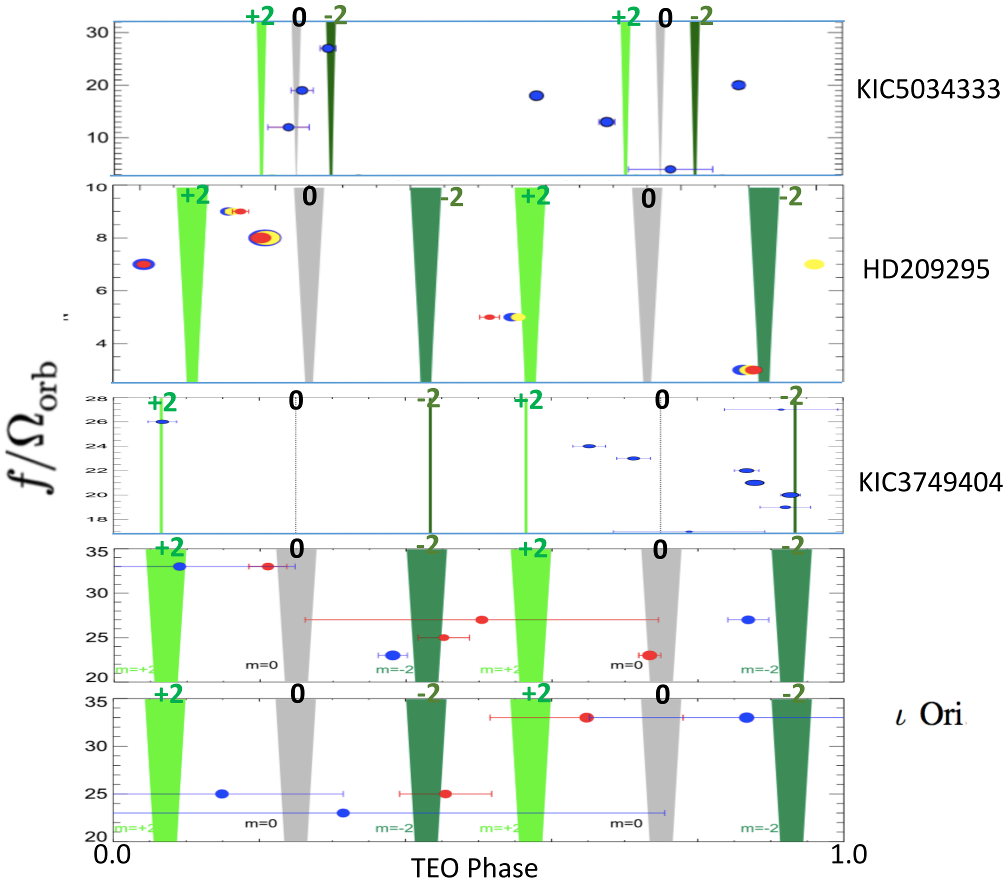

Fig. 4. Same as Fig. 3, but for four systems with significant deviations from theoretical adiabatic phases (vertical strips).

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