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# Testing tidal theory for evolved stars by using red giant binaries observed by *Kepler*

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## ABSTRACT

Tidal interaction governs the redistribution of angular momentum in close binary stars and planetary systems and determines the systems evolution towards the possible equilibrium state. Turbulent friction acting on the equilibrium tide in the convective envelope of low-mass stars is known to have a strong impact on this exchange of angular momentum in binaries. Moreover, theoretical modelling in recent literature as well as presented in this paper suggests that the dissipation of the dynamical tide, constituted of tidal inertial waves propagating in the convective envelope, is weak compared to the dissipation of the equilibrium tide during the red giant phase. This prediction is confirmed when we apply the equilibrium-tide formalism developed by Zahn, Verbunt & Phinney, and Remus, Mathis & Zahn on to the sample of all known red giant binaries observed by the NASA *Kepler* mission. Moreover, the observations are adequately explained by only invoking the equilibrium tide dissipation. Such ensemble analysis also benefits from the seismic characterization of the oscillating components and surface rotation rates. Through asteroseismology, previous claims of the eccentricity as an evolutionary state diagnostic are discarded. This result is important for our understanding of the evolution of multiple star and planetary systems during advanced stages of stellar evolution.

**Key words:** Planet–star interactions – stars: binaries: spectroscopic – stars: evolution – stars: kinematics and dynamics – stars: late-type – stars: oscillations.

## 1 INTRODUCTION

A binary system has reached the state of minimum energy through tidal interactions when the orbit is circularized and the orbital and stellar spins are aligned and synchronized (e.g. Hut 1980; Zahn 2013). While for orbital periods shorter than  $\sim 10$  d nearly all systems are circularized, a large spread in eccentricity is found for longer orbital periods (e.g. Mazeh 2008). Consequently, for wider binaries the orbital period alone is not sufficient to characterize tidal interactions (hereafter VP95; Torres, Verbunt & Phinney 1995; Andersen & Giménez 2010). The efficiency of the physical processes that dissipate the kinetic and potential energies of tides into heat

depends on stellar structure (in particular, the respective size and mass of the radiative and convection zones), fundamental parameters, and rotation. This determines the evolutionary pace for an eccentric binary towards equilibrium (e.g. Zahn 1977; Ogilvie & Lin 2007; Mathis 2015; Gallet et al. 2017).

In stars, tides can be understood as the combination of an equilibrium/non-wave-like tide and of a dynamical/wave-like tide (e.g. Zahn 1977; Ogilvie 2013, 2014). The equilibrium tide is a large-scale flow driven by the hydrostatic adjustment of a star induced by the tidal gravitational perturbation due to the companion (e.g. Zahn 1966; Remus, Mathis & Zahn 2012; Ogilvie 2013). It is efficiently dissipated in the convective envelope of low-mass stars during their evolution (e.g. Verbunt & Phinney 1995; Zahn & Bouchet 1989) because of the friction applied on its velocity field by turbulent con-

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vection (e.g. Zahn 1966; Mathis et al. 2016). However, the equilibrium tide is not a solution of the complete equations of stellar hydrodynamics and it must be completed by the so-called dynamical tide introduced by Zahn (1975). In rotating stars, it is constituted by tidal inertial waves that propagate in convective regions and are driven by the Coriolis acceleration (e.g. Ogilvie & Lin 2007; Ogilvie 2013; Mathis 2015) and by tidal gravito-inertial waves that are excited in stably stratified radiative zones and driven by buoyancy and the Coriolis acceleration (e.g. Zahn 1975; Terquem et al. 1998; Ogilvie & Lin 2007; Barker & Ogilvie 2010). They are damped by the convective turbulent friction and thermal diffusion and breaking, respectively.

Because of the long tidal evolution time-scales compared to the existing time bases of observational data, such theoretical descriptions of tidal interactions within binary stars are difficult to probe empirically. VP95 however tested successfully their formalism for the dissipation of the equilibrium tide in evolving convective envelopes using a sample of spectroscopic red giant binary systems located in open clusters. Today, this test can be extended, thanks to the NASA *Kepler* space mission, originally designed for detecting planetary transits (Borucki et al. 2010) which has been very successful in finding binary systems. Among the 197 100 stars observed by *Kepler* (Mathur et al. 2017),  $\sim 3000$  binary stars are known (Kirk et al. 2016). Thirty-five of these systems contain a red giant component. Through combination of space photometry, asteroseismology, and ground-based spectroscopy, these systems are well characterized (Frandsen et al. 2013; Gaulme et al. 2014, 2016, Beck et al. 2014, 2018, Rawls et al. 2016, hereafter F13, G14, G16, B14 and B18, R16). The main catalogues were presented by G14 and G16 and B14 (Table C1). While G14 and G16 focused on eclipsing systems, B14 presented binary stars exhibiting photometric signatures of tidal interactions due to the non-adiabatic component of the equilibrium tide, as predicted theoretically by Kumar, Ao & Quataert (1995). We refer to them as heartbeat stars, a term coined by Thompson et al. (2012).

In this work, we constrain the relative strength of the dissipation of the equilibrium and dynamical tides in red giant stars. We use the formalisms developed by VP95 and Remus et al. (2012) for the equilibrium tide as well as Ogilvie (2013) and Mathis (2015) for the dynamical tide and confront their predictions to the observed orbital properties of the *Kepler* red giant binaries sample. We discuss tidal interactions in these systems in the light of surface rotation and seismology provided by *Kepler*.

## 2 TIDAL DISSIPATION IN RED GIANT STARS

### 2.1 Equilibrium tide

For stars with large convective envelopes such as red giant stars, the first of the main tidal dissipation mechanisms is the turbulent friction applied by convection on the equilibrium tide (e.g. Zahn 1966; Remus et al. 2012).

In the Appendix A, we provide the expression of this dissipation  $\mathcal{D}_{\text{eq}}$  as a function of the stellar structural properties and rotation and of the orbital period. It will be used to compare the respective strength of the equilibrium and dynamical tides on the red giant branch (RGB). In addition, we follow VP95 who rewrote the associated circularization time-scale  $\tau_{\text{circ}}$  derived by Zahn (1977) in the

following way:

$$\frac{1}{\tau_{\text{circ}}} = \frac{d \ln e}{dt} \simeq -1.7f \cdot \left( \frac{T_{\text{eff}}}{4500 \text{ K}} \right)^{4/3} \cdot \left( \frac{M_{\text{env}}}{M_{\odot}} \right)^{2/3} \cdot \frac{M_{\odot}}{M_1} \cdot \frac{M_2}{M_1} \cdot \frac{M_1 + M_2}{M_1} \cdot \left( \frac{R_1}{a} \right)^8 [\text{yr}^{-1}], \quad (1)$$

whereby the parameters of the primary and the secondary are the mass  $M$  and the radius  $R$ . The effective temperature and mass of the convective envelope of the giant component are given by  $T_{\text{eff}}$  and  $M_{\text{env}}$ , respectively. The dimensionless parameter  $f$  is of the order of unity and determined by the details of the convective turbulent friction. Finally,  $a$  is the system's semimajor axis.

To quantify the tidal dissipation within the giant component in detached close binary systems and classify them, VP95 isolate the terms of equation (1) that depend on the parameters of the primary component and introduce the circularization function

$$I(t) = \int_0^t \left( \frac{T_{\text{eff}}}{4500 \text{ K}} \right)^{4/3} \cdot \left( \frac{M_{\text{env}}(t')}{M_{\odot}} \right)^{2/3} \cdot \left( \frac{R_1(t')}{R_{\odot}} \right)^8 dt'. \quad (2)$$

By integrating equation (2) along the evolutionary tracks of representative stellar models, VP95 found that  $I(t)$  is a monotonic function of the stellar radius that can be well approximated by the analytical expression

$$I = 7.6 \cdot 10^8 \cdot \left( \frac{R_1}{R_{\odot}} \right)^{6.51} [\text{yr}]. \quad (3)$$

For stars in the red giant phase, the radius is the parameter that varies most drastically with time, more than two orders of magnitude, while the mass of the convective envelope and the effective temperature change only modestly. By using equations (1), (2), and Kepler's third law, VP95 derive the rate of eccentricity reduction,

$$\frac{\Delta \ln e}{f} = \frac{-1.7}{10^5} \cdot \left( \frac{M_1}{M_{\odot}} \right)^{-11/3} \cdot \frac{q}{(1+q)^{5/3}} \cdot I(t) \cdot \left( \frac{P_{\text{orb}}}{d} \right)^{-16/3}. \quad (4)$$

with  $q = M_2/M_1$  the components mass ratio. In their plots, VP95 use the logarithm of negative value of equation (4), which, for the convenience of the reader, we call in this work  $\epsilon_r$ .

$$\epsilon_r = \log \left[ - \left( \frac{\Delta \ln e}{f} \right) \right]. \quad (5)$$

This quantity represents the inverse time-scale of tidal circularization as a diagnostic of the strength of the dissipation. We will compute it for our sample in Section 3.

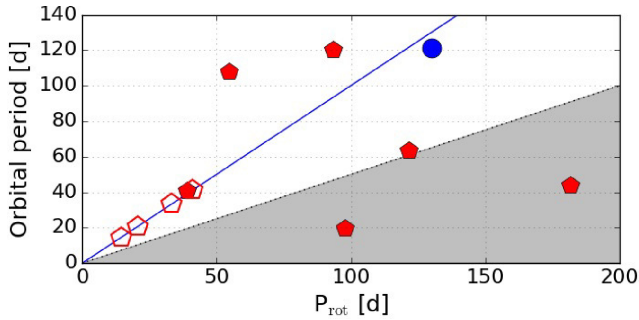
### 2.2 Dynamical tide

In the deep convective envelope of red giant stars, the dynamical tide is constituted by tidal inertial waves driven by the Coriolis acceleration<sup>1</sup> if  $P_{\text{orb}} > \frac{1}{2} P_{\text{rot}}$ , with  $P_{\text{orb}}$  and  $P_{\text{rot}}$  the periods of the orbital motion and stellar surface rotation, respectively (Ogilvie & Lin 2007).<sup>2</sup> As shown in Fig. 1, most of the 11 *Kepler* binary systems with known rotation periods (G14, G16, B14, B18, see Table C1) lie in the regime where tidal inertial waves can propagate.

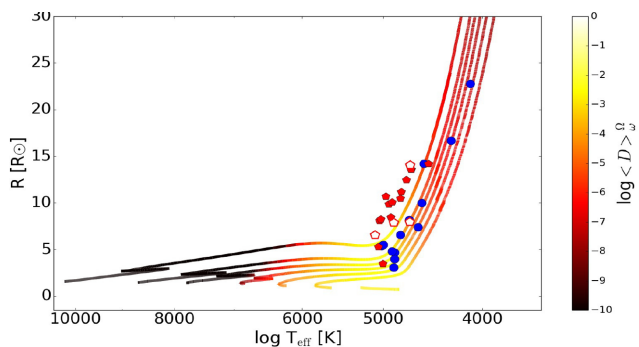
We compute the structural frequency-averaged dissipation  $\langle \mathcal{D} \rangle_{\text{struct}}$  (see equations B2 and 3 in Gallet et al. 2017), introduced

<sup>1</sup>As a first step, we do not take into account the tidal dissipation in the radiative stellar core.

<sup>2</sup>In the case of eccentric systems, other tidal frequencies will be excited (see Appendix B and Zahn 1977; Ogilvie 2014).



**Figure 1.** Orbital versus surface rotation period of *Kepler* red giant binaries. The grey shaded area depicts the prohibited region for the dynamical tide, i.e.  $P_{\text{orb}} < \frac{1}{2} P_{\text{rot}}$ . Red pentagons and blue dots mark eclipsing (G14, G16) and heartbeat systems (B14, B18) observed by *Kepler*, respectively. Open symbols denote non-oscillating primaries.



**Figure 2.** Dissipation of the dynamical tide as a function of stellar evolution. The colour-code reflects the intensity of the dissipation along the theoretical tracks starting at the zero-age main sequence in the  $R_* - T_{\text{eff}}$  plane, calculated for the sample mass range ( $Z_{\odot}$  tracks for 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, and  $2.2 M_{\odot}$ ). The same symbols as in Fig. 1 are used.

by Ogilvie (2013) and Mathis (2015) for standard (non-rotating) solar metallicity stellar models in the mass range  $0.8 \leq M/M_{\odot} \leq 2.2$  (covered by the sample of *Kepler* stars, see Table C1 in the Appendix) computed with the stellar evolution code STAREVOL (see Gallet et al. 2017, and references therein). As shown in Fig. 2, the dissipation varies by several orders of magnitude along the stellar evolution from the main-sequence to the RGB phase (see Ogilvie & Lin 2007, and Appendix B).

We see that for stars with solar-metallicity and masses above  $1.4 M_{\odot}$  the structural frequency-averaged tidal dissipation is most efficient at the end of the sub-giant branch, while for stars with  $0.8 \leq M/M_{\odot} \leq 1.4$  it is efficient throughout the main-sequence and sub-giant branch. However, the efficiency is reduced by several orders of magnitude, once the stars passed the bottom of the RGB. This diagram only shows the efficiency of dissipation due to the dynamical tide. From seismic analysis and comparison with the evolutionary tracks in the Hertzsprung–Russell diagram it is shown that all our sample stars are on the RGB (see Section 4), with half of them lying in or just above the region of maximum dissipation.

On the their way towards the RGB, stars experience a rapid expansion of their convective envelope in mass to maintain a surface hydrostatic equilibrium. This results in a drastic reduction of the efficiency of the dissipation of tidal inertial waves because the stellar structure configuration tends towards a full-sphere configuration. Here the viscous friction acting on sheared inertial waves attractors become less efficient because inertial waves become regular (we

refer to the detailed discussion in Mathis 2015). Simultaneously, the growing (in radius) envelope amplifies the strength of the dissipation of the equilibrium tide as shown by equation (A6).

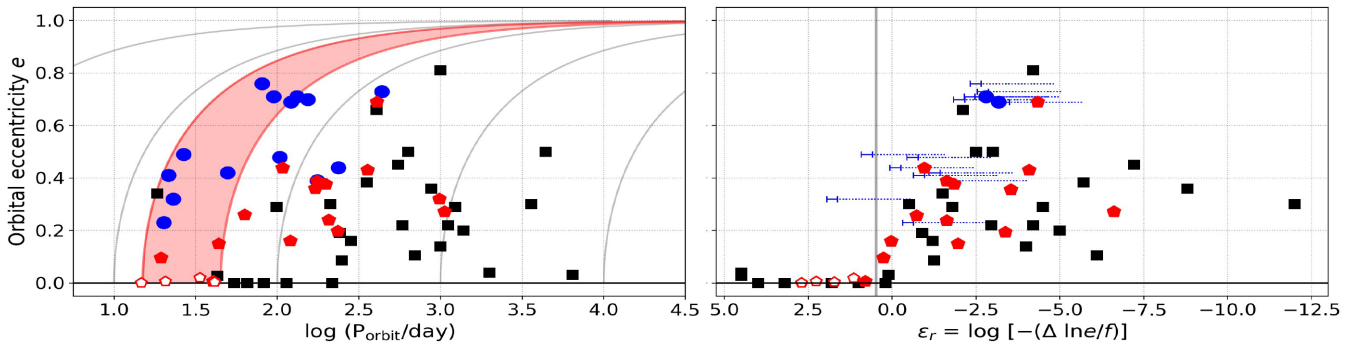
### 3 COMPARISON WITH VP95 AND *Kepler* SAMPLES

VP95 applied their formalism to 28 well-studied binaries with giant components with masses derived from cluster isochrones. In Fig. 3, the orbital eccentricity  $e$  of the systems in the cluster-sample is plotted as a function of the orbital period and  $\epsilon_r$  as black squares. While in the  $e$ – $P$  plane no convincing structure is found, plotting the eccentricity versus  $\epsilon_r$  separates efficiently the eccentric from the circularized systems. From their analysis, VP95 suggest that a value of  $[\Delta \ln e/f] \simeq 3$  marks the approximate transition limit between quasi- and non-circularized systems. Following equation (5), we refer to this value as  $\epsilon_{\text{crit}} \simeq 0.478$ , which is marked as a vertical line in the right-hand panel of Fig. 3. We note that  $\epsilon_{\text{crit}}$  is not indicating an exact dichotomy between circularized and eccentric systems, but can be understood as the entry line to the rapid circularization phase. Fig. 3 suggests that  $\epsilon_{\text{crit}}$  is lower for very eccentric systems.

The red giant binaries found by the *Kepler* mission now provide a key comparison data set. The masses of the components are determined from seismology and dynamical approaches, complementing mass determination through isochrone fitting as done for the cluster stars. The literature parameters of the stars in the *Kepler* sample are given in Table C1. In the left-hand panel of Fig. 3, eclipsing systems (F13, G14, G16) are depicted as red pentagons, while heartbeat stars (B14) are shown as blue dots.

From the full sample of *Kepler* red giant binary systems, a subset of 19 stars were found by various studies to be double-lined spectroscopic binary (SB2) systems (F13, G16, R16, B18), providing us with precise mass ratios of the system. By comparing the seismic and the dynamical masses of the SB2, G16 showed that masses and radii derived from seismic scaling relations are overestimated by  $\sim 15$  per cent and 5 per cent, respectively. Therefore, we use, whenever available, the dynamical or corrected seismically inferred masses. For 14 out of the 18 heartbeat stars, B14 reported orbital eccentricities, based on their spectroscopic radial velocity (RV) monitoring. For one heartbeat system, KIC 5006817, the mass ratio was constrained from a combined fit of the *Kepler* light and RV curve (B14). With the exception of KIC 913796 (B18), these systems have typically much fainter companions stars, making it observationally challenging to detect the secondary’s spectrum. For the 12 remaining heartbeat systems with known seismic masses but unknown mass ratio, we assumed a mass ratio  $1/5 \leq q \leq 1$  (values taken from B18 and B14). To explore the expected range of  $\epsilon_r$  for planetary systems, the mass ratio down to  $1/1000$  is depicted, representing an approximate mass ratio for a star hosting a giant planet. We note that in Fig. 2 systems from G16 are systematically hotter than those from B14. Such difference could overestimate the seismic masses and radii in G16 of a few per cent but does not explain the full 15 per cent.

The *Kepler* and the VP95-cluster samples are complementary in terms of primary mass and orbital periods, covered by each sample. With a mean primary mass of  $2.0 \pm 0.4 M_{\odot}$  the stars in the VP95 sample are substantially more massive than stars in the *Kepler* sample ( $1.3 \pm 0.3 M_{\odot}$ ), but are very similar in terms of the mass ratio,  $0.6 \pm 0.3$  and  $0.7 \pm 0.3$ , respectively. As shown in Fig. 3 (left-hand panel), all except two systems of VP95 have orbital periods  $P_{\text{orbit}} \gtrsim 45$  d, and most eccentric systems are found at even periods of several hundred or thousand of days. Such long periodic systems are



**Figure 3.** Eccentricity of red giant binaries in the *Kepler* sample and open clusters. Red pentagons and blue dots mark *Kepler* red giants in eclipsing (G14, G16) and heartbeat systems (B14, B18), respectively. Open symbols denote non-oscillating primaries. The sample of VP95 cluster stars is shown as black squares. *Left:*  $e$  versus orbital period. Grey lines indicate tracks of constant angular momentum for circularized systems with periods of 10,  $10^2$ ,  $10^3$ , and  $10^4$  d. The red shaded area marks the range of periods,  $15 \leq P_{\text{circ}} \leq 45$  d. *Right:*  $e$  versus the circularization function  $\epsilon_r$ . Following VP95, the horizontal axis is inverted. Filled symbols mark systems with known mass ratio, while blue solid ‘H’-symbols indicate the  $\epsilon_r$ -range, calculated for the mass ratio range,  $1 \leq q \leq 1/5$ , and blue dotted lines represent a mass ratio between unity and  $q \simeq 1:1000$ . The vertical grey line depicts the value of  $\epsilon_{\text{crit}}$ .

hard to detect from the  $\sim 1400$  d of *Kepler* photometry. The *Kepler* sample however contains systems with a wide range of eccentricities ( $0 \leq e \lesssim 0.8$ ) at  $P_{\text{orbit}} \leq 45$  d. Combining both samples allows us to explore tides in short and long period systems. It is interesting to note that both samples are lacking systems with  $0.5 \lesssim e \lesssim 0.7$ . While the *Kepler* and cluster samples are different in their distribution in period (Fig. 3, left-hand panel), viewing both samples in the  $e$ - $\epsilon_r$  plane leads to a very homogeneous pattern (right-hand panel) with circularized systems (excepting KIC 2720096 and KIC 8095275) if  $\epsilon > \epsilon_{\text{crit}} \simeq 0.478$  (and eccentric ones if  $\epsilon < \epsilon_{\text{crit}}$ ). This shows that the VP95 formalism for the turbulent friction applied on the equilibrium tide in convective regions alone is sufficient to explain the observed time-scales of circularization of binary stars hosting giant-components and the corresponding eccentricity distribution. It is thus not necessary to invoke the action of the dynamical tide, which is predicted to be weak as demonstrated in Section 2.2 in the case of tidal inertial waves in RGB stars (see Fig. 2). A similar result is found for the planets (Fig. 3). Yet, the circularization time-scales are longer by several orders of magnitude (Fig. 3, right-hand panel).

With KIC 2720096 ( $e = 0.49$ ,  $P_{\text{orb}} = 26.7$  d) and KIC 8095275 ( $e = 0.32$ ,  $P_{\text{orb}} = 23.0$  d) we find two eccentric heartbeat systems with  $\epsilon_r \gg \epsilon_{\text{crit}}$  if a mass ratio  $1/5 \leq q \leq 1$  is assumed. A lower value of  $q$  would place these systems closer or even below to  $\epsilon_{\text{crit}}$ . Comparing the power spectra of a synthetic and the observed light curve (following B18), indeed revealed no signature of the potential tidal inertial waves in the low-frequency regime. The VP95 formalism does not forbid such objects with  $\epsilon_r \gg \epsilon_{\text{crit}}$ , but because time scales for circularization are short for such systems, we argue that they could be in a short lived phase of rapid circularization during the evolution of some binary systems. We refer to them as ‘forbidden binaries’, in analogy to Kroupa (1995).

To investigate theoretically which tide dominates on the RGB, we define the quantity  $\delta = \log(\mathcal{D}_{\text{eq}}/(\mathcal{D})_{\omega})$  as the logarithm of the ratio between the dissipation of the equilibrium and the dynamical tide (Appendix A and B). Most stars with measured rotation periods originate from the G16 sample, in which the effective temperature and hence radius could be overestimated (see text above). To compensate for this complication in the estimate of the dissipation ratio, we computed the evolution of  $\delta$  for each star with known  $P_{\text{rot}}$  along the RGB phase of our non-rotating stellar tracks (see Fig. 2). Us-

ing the 10th percentile  $\delta_{10}$  (i.e. the value below which 10 percent of the distribution may be found) of each  $\delta$  evolution, we found that stars in the *Kepler* sample with known  $P_{\text{rot}}$ , and regardless of the stellar mass, have 90 percent of chance to have at least a  $\delta = 2.3$ . This means that the equilibrium tide clearly dominates over the dynamical tide on the RGB and consequently also in the more advanced red giant phases. Note that taking into account the effect of the stellar rotation on the effective turbulent friction (Mathis et al. 2016) significantly reduces  $\mathcal{D}_{\text{eq}}$  (see Strugarek et al. 2017) while still producing  $\delta_{10} > 0$ . Table C2 shows  $\delta_{10}$  and the corresponding convective timescale  $\tau_{\text{conv}, 10}$  (computed in the middle of the convective envelope) for the subsample of *Kepler* stars. In addition, most of the systems in our sample have a tidal period ( $P_{\text{tide}} \equiv 2\pi/\omega$ ), with  $\omega$  the principal tidal frequency defined in Appendix A, longer than the possible range of convective turnover timescale computed from our stellar tracks. In these systems ( $P_{\text{tide}} \geq 12$ – $14$  d,  $1.0 \lesssim M/M_{\odot} \lesssim 2.2$ ), the reduction factor for the eddy viscosity can thus be neglected.

#### 4 SYNERGIES WITH SPACE PHOTOMETRY

The unparalleled quality of the photometric measurements collected by the *Kepler* mission allows for a discussion of the tidal interaction in the *Kepler* sample beyond the mere comparison with VP95. The detection of solar-like oscillations enables a thorough characterization of the oscillating binary component (e.g. F13, G14, G16, B14, B18), as well as the detection of surface activity, modulated by rotation (as depicted in Fig. 1). Furthermore, asteroseismology of giant stars allows one to avoid systematic uncertainties, introduced by reddening corrections and the sample is not limited by the turn-off as it is the case for observations of cluster stars. By comparing surface rotation rates, derived from *Kepler* photometry (e.g. García et al. 2014; Ceillier et al. 2017) with the orbital periods, G14 associated short-period systems with mode depletion. When the surface rotation and orbital motion become synchronized in close binaries, the red giant component could be spun up and the magnetic field generated by the dynamo (Privitera et al. 2016) can be responsible for the mode damping. Fig. 3 shows that these four non-oscillating primaries are located in short period and quasi-circularized systems ( $15 \leq P_{\text{orbit}} \leq 45$  d and  $e \leq 0.02$ ).

As for the orbital eccentricity,  $\epsilon_{\text{crit}}$  serves as a proxy rather than a sharp cutoff between oscillating and non-oscillating systems, whereby the eccentricity plays an important role. Stars with no or suppressed oscillation amplitudes are all systems with  $e \simeq 0$  at  $\epsilon_r \gg \epsilon_{\text{crit}}$ , as shown in the right-hand panel of Fig. 3. This suggests that for quasi-circularized systems that  $\epsilon_{\text{crit}}$  acts also as a limit between oscillating stars and stars with additional damping or complete suppression of oscillations. The only primary of a quasi-circularized system with detected oscillations is KIC 5308778 ( $e \simeq 0.006$ ), which shows very small oscillation amplitudes, compared to compatible red giant oscillators. With a difference of  $\sim 1.6$  d between  $P_{\text{orb}}$  and  $P_{\text{rot}}$ , KIC 5308778 (see Fig. 1 Table C1) is indeed not yet fully spun up at the surface, which is the first layer to be synchronized with the orbital motion (e.g. Zahn 2013, and references therein), indicating that the deeper layers may be not synchronized as well. The forbidden binaries KIC 2720096 ( $\epsilon_r \simeq 0.83$ ) and KIC 8095275 ( $\epsilon_r \simeq 1.86$ ) are both oscillating. KIC 2720096 is showing depressed dipole modes with respect to the radial modes and exhibits the highest chromospheric activity found in the sample of B14. The oscillation amplitude of KIC 8095275 is normal. The tidal interaction affects the surface magnetism through the rotation-driven stellar dynamo. Since the surface magnetism is the responsible of the low amplitudes of the modes (e.g. G14, García et al. 2014), the connections with tidal interactions is thus an indirect one.

From their diagnostic diagrams (fig.5 in VP95), VP95 note that for primaries with radii between the maximum stellar radius at the tip of the RGB and the minimum radius in the red-clump (RC) phase, an ambiguity between evolutionary states exists. The high dependence of  $\epsilon_r$  on the stellar radius (equation 3) suggests that H-shell burning stars, which are ascending the RGB should have been circularized when they reach the RC phase of quiescent He-core burning. Therefore, VP95 proposed the orbital eccentricity as a diagnostic to distinguish between the RGB and RC evolutionary stages, suggesting that circularized systems host RC stars. Based on the detection of mixed-dipole modes from high precision space photometry (Beck et al. 2011), asteroseismic techniques have been developed to discriminate between RGB and RC giants (e.g. Bedding et al. 2011; Kallinger et al. 2014). Applying such techniques, B14 found that all heartbeat systems in their sample are located on the RGB, while G14 found a mix of evolutionary states among their binaries. In a detailed reanalysis, Kallinger et al. (2018) found that all except one *oscillating* star from G14 (KIC 9246715,  $e \sim 0.36$ , see also R16) belong to the less advanced RGB phase. This includes the only circularized oscillating system KIC 5308778.

With  $14 R_{\odot}$ , KIC 4569590 could either be a RC star or a RGB star. On the other hand, the primary's radius from light curve models (G16) of the three other systems ( $\sim 8 R_{\odot}$ ) are only compatible with the stars belonging to the low-luminosity part of the RGB. To test if a more eccentric version of the system would have hosted a red giant star at the tip of the RGB, we calculated tracks of constant angular momentum in the  $P_{\text{orbit}}-e$  plane (Mazeh 2008) for a system with a circular orbit periods,  $P_{\text{circ}}$ ,

$$P_{\text{circ}} = P (1 - e^2)^{3/2}. \quad (6)$$

The possible area for eccentric versions of the now-circularized *Kepler* stars in this diagram is shown as red surface in the left-hand panel of Fig. 3. We note that the track for  $P_{\text{circ}} = 15$  d describes the outer envelope for the distribution of binaries. Therefore, a progenitor system with  $e \simeq 0.7$  would have had a period of about 100 d. Given the close separation at periastron, such system will eventually undergo a common envelope phase on the low-luminosity

RGB (B14). Therefore, the orbital eccentricity cannot serve as a diagnostic of the evolutionary state for stars.

## 5 CONCLUSIONS

We tested the theory of tidal interaction on binary systems that host a red giant component and are well characterized through *Kepler* photometry. We found that the action of the turbulent friction acting on the equilibrium tide in the deep convective envelope of RGB stars allows us to understand the eccentricity–period distribution. Dissipation of tidal inertial waves is thus not required to explain the observed eccentricities in the analysed sample of stars. From our calculations, based on models of Remus et al. (2012) and Gallet et al. (2017), we show that this component of the dynamical tide is expected to be weak when compared to the equilibrium tide. This is confirmed by the lack of observational signatures (B18). Therefore, the dynamical tide has a negligible contribution to the tidal dissipation budget in evolved stars with large convective envelopes.

This study benefits from complementary observational constraints, provided by the *Kepler* satellite. Therefore, we could extend the discussion of  $\epsilon_r$  beyond eccentricity and use the presence of stellar oscillation. Knowing the surface rotation, allows us to test for synchronization of the primary with orbital motion. From this approach, we suggest that the previously reported mode depletion is connected indirectly, via a rotation-driven dynamo, to strong tidal interactions on short circularization time scales ( $\epsilon_r > \epsilon_{\text{crit}}$ ). Consequently, the control physical parameter is the volume of the convective envelope of the giant component. Using asteroseismic constraints, we showed that eccentricity cannot serve as a diagnostic for the evolutionary state of the primary.

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## REFERENCES

- Barker A. J., Ogilvie G. I., 2010, *MNRAS*, 404, 1849
- Beck P. G. et al., 2011, *Science*, 332, 205
- Beck P. G. et al., 2014, *A&A*, 564, A36
- Beck P. G. et al., 2018, *A&A*, 612, A22
- Bedding T. R. et al., 2011, *Nature*, 471, 608
- Borucki W. J. et al., 2010, *Science*, 327, 977
- Brun A. S., García R. A., Houdek G., Nandy D., Pinsonneault M., 2015, *Space Sci. Rev.*, 196, 303
- Ceillier T. et al., 2017, *A&A*, 605, A111
- Di Mauro M. P. et al., 2016, *ApJ*, 817, 65
- Frandsen S. et al., 2013, *A&A*, 556, A138
- Gallet F., Bolmont E., Mathis S., Charbonnel C., Amard L., 2017, *A&A*, 604, A112
- García R. A. et al., 2014, *A&A*, 572, A34
- Gaulme P. et al., 2016, *ApJ*, 832, 121
- Gaulme P., Jackiewicz J., Appourchaux T., Mosser B., 2014, *ApJ*, 785, 5
- Hut P., 1980, *A&A*, 92, 167
- Kallinger T. et al., 2014, *A&A*, 570, A41

- Kallinger T. et al., 2018, preprint ([arXiv:1805.06249](https://arxiv.org/abs/1805.06249))
- Kirk B. et al., 2016, *Astron. J.*, 151, 68
- Kroupa P., 1995, *MNRAS*, 277, 1507
- Kumar P., Ao C. O., Quataert E. J., 1995, *ApJ*, 449, 294
- Mathis S., Auclair-Desrotour P., Guenel F., Gallet F., Le Poncin-Lafitte C., 2016, *A&A*, 592, A33
- Mathis S., 2015, *A&A*, 580, L3
- Mathur S. et al., 2017, *ApJS*, 229, 30
- Mazeh T., 2008, in *EAS Pub. Series.*, 29, 1
- Ogilvie G. I., 2013, *MNRAS*, 429, 613
- Ogilvie G. I., 2014, *ARA&A*, 52, 171
- Ogilvie G. I., Lin D. N. C., 2007, *ApJ*, 661, 1180
- Privitera G. et al., 2016, *A&A*, 593, L15
- Rawls M. L. et al., 2016, *ApJ*, 818, 108
- Remus F., Mathis S., Zahn J.-P., 2012, *A&A*, 544, A132
- Strugarek A., Bolmont E., Mathis S., Brun A. S., Réville V., Gallet F., Charbonnel C., 2017, *ApJ*, 847, L16
- Terquem C., Papaloizou J. C. B., Nelson R. P., Lin D. N. C., 1998, *ApJ*, 502, 788
- Thompson S. E. et al., 2012, *ApJ*, 753, 86
- Torres G., Andersen J., Giménez A., 2010, *A&Ar*, 18, 67
- Verbunt F., Phinney E. S., 1995, *A&A*, 296, 709
- Zahn J. P., 1966, *Annales d'Astrophysique*, 29, 489
- Zahn J.-P., 1975, *A&A*, 41, 329
- Zahn J.-P., 1977, *A&A*, 57, 383
- Zahn J.-P., 2013, in Beiglböck W., Ehlers J., Hepp K., Weidenmüller H., eds, *Lecture Notes in Physics*, Vol. 861, *Stellar Tides.*, Springer-Verlag, Berlin, p. 301
- Zahn J.-P., Bouchet L., 1989, *A&A*, 223, 112

## SUPPORTING INFORMATION

Supplementary data are available at [MNRASL](https://www.mnrasl.org/) online.

**Appendix A.** Efficiency of the equilibrium tide dissipation.

**Appendix B.** Frequency-averaged dissipation of the dynamical tide

**Appendix C.** Literature values for *Kepler*-systems.

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