Complex Planetary Systems II: Latest Methods for an Interdisciplinary Approach
Proceedings IAU Symposium No. 382, 2024
A. Lemaitre & A.-S. Libert, eds.
doi:10.1017/S1743921323004970

Tidal effects in resonant chains of close-in planets: TTV analysis of Kepler-80

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Abstract. Systems near mean-motion resonances (MMRs) are subject to large transit-timing variations (TTVs). The amplitude and period of the TTVs strongly depend on the distance to exact MMR and the planetary eccentricities which are shaped during the formation and long-term evolution of the system. For close-in planets, the tides raised by the star provide a source of dissipation, placing the planets further away from the MMR. In this work, we will discuss how the tidal interactions with the central star play an important role in shaping the period ratios and resonant angles in resonant chains. Moreover, we will show how they can impact the TTVs and therefore how the TTVs could serve as a means to put constraints on the tidal history of planetary systems. The study will focus on the four-planet resonant chain of Kepler-80.

Keywords. Planet-disk interactions – Long-term evolution – Transit timing variations

1. Introduction

Studying Systems with Tightly Packed Inner Planets (STIPs) is particularly important for understanding the evolution of planetary systems. During the migration phase in the protoplanetary disk, planet pairs get trapped in MMRs which excite their eccentricities, while the tides raised by the host star contribute to dissipation on long timescales. The effect of stellar tidal forces is more pronounced for planets closer to the star (e.g. Baruteau and Papaloizou 2013). Regarding STIPs harboring chains of resonances, Charalambous et al. (2023) showed that 3-planet MMRs among the planets can transport this effect outward and thus explain the observed departures from exact MMR for adjacent planet pairs.

Planets near MMRs exhibit prominent TTVs (i.e., deviations of the transit times with respect to the strictly periodic Keplerian case). The short orbital periods of the STIPS allow for multiple cycles of the variations to be observed. TTVs are a powerful technique for identifying previously undetected planets by measuring the non-periodicity of the times of transit (Agol et al. 2005; Holman and Murray 2005). Beyond merely revealing or confirming the presence of non-transiting planets, TTVs offer valuable insights into inferring and better constraining the masses and eccentricities of planets in multiple transiting systems. The amplitude and period of the TTV signal strongly depend on the proximity to exact MMR and the eccentricities of the planets. As previously said, these quantities are shaped during planet-disk interactions and further modified during the long-term evolution of the system.

In the present work, we will focus on the Kepler-80 system, a well-known resonant chain of four close-in planets. Our objective is twofold. Firstly, we will analyze the role of the tidal interactions between the planets and the central star in shaping the period ratios and the resonant angles in Kepler-80, extending the previous study of Charalambous et al. (2023) by considering different tidal parameters (i.e., different internal structure) among the planets. Secondly, we will present a preliminary result on how the TTVs vary with different tidal parameters, suggesting that the TTVs could serve as a means to put constraints on the tidal history of planetary systems.

2. Formation and tidal evolution of resonant chains

During the late stage of planetary formation, interactions between the planets and the gas disk in which they are embedded produce a transfer of angular momentum, changing the radial distance of the planets. During their migration, planets are expected to get trapped in MMRs. Resonant chains are particularly common for the STIPs, whose planets are found in (or close to) 2-planet and 3-planet MMRs (similar to the Laplace resonance).

Once the disk has dispersed, dissipative mechanisms such as tidal interactions with the central star become dominant. A classical formulation of the tidal damping timescale on the eccentricity is (Goldreich and Soter 1966; Papaloizou 2021)

$$\tau_{e_i}^{\text{tid}} = 7.63 \times 10^5 \left(\frac{a_i}{0.05\text{au}}\right)^{13/2} \left(\frac{M_\odot}{M_\star}\right)^{3/2} \left(\frac{m_\oplus}{m_i}\right)^{2/3} \left(\frac{\rho_i}{\rho_\oplus}\right)^{5/3} Q'\text{yr}, \tag{1}$$

with a_i the planetary semi-major axis (in au), $M_\star$ the mass of the star (in $M_\odot$), m_i the planetary mass (in $m_\oplus$), ρ_i the planetary mean density (in $\rho_\oplus$), and $Q' = 3Q/(2k_2)$, where Q represents the tidal quality factor and k_2 the Love number. The main effect of tides raised by the central star on resonant chains is to drive the planets out of resonance. The deviation from exact MMR, also known as *resonance offset*, for two planets near a $(p+q)/p$ MMR, is defined by

$$\Delta_{(p+q)/q} = P_2/P_1 - (p+q)/p, \tag{2}$$

where P_i is the orbital period of planet i.

TTVs are enhanced for planets near MMR (Agol et al. 2005). The characteristic timescale of the TTVs (i.e., the period of the sinusoidal TTV signal) for two planets near a $(p+1)/p$ MMR is the sinusoidal super-period (Lithwick et al. 2012; Teyssandier et al. 2022)

$$P_{\text{TTV}} = \frac{P_2}{p|\Delta_{(p+1)/p}|}. \tag{3}$$

Thus, the closer a pair of planets to a MMR (i.e., the smaller the Δ), the larger their TTVs. When more than two planets evolve in a resonant chain, the typical independent sinusoidal expressions as given in Lithwick et al. (2012) fail to describe the TTV signals. As shown by Libert and Renner (2013), the TTV signals are interlinked with the dynamical evolution of the planetary system: the shorter periods (e.g., the TTVs characteristic timescales) are associated with 2-planet MMRs, while longer periods arise from 3-planet MMRs (see also the frequency analysis of Teyssandier et al. 2022, for the TRAPPIST-1 resonant chain).

3. Study of Kepler-80

Kepler-80 is a 6-planet STIP with all adjacent pairs near a 2-planet MMR (see Table 1) and orbiting a M0/K5 star with $M_\star = 0.73\,\text{M}_\odot$ and star age $t_\star \sim 2$ Gyr (MacDonald et al.

https://doi.org/10.1017/S1743921323004970 Published online by Cambridge University Press

Table 1. Parameters of Kepler-80 from MacDonald et al. (2021). The columns successively show the planetary masses and densities, the orbital periods, the 2-planet MMRs between adjacent planets, and their respective resonance offsets.

		m_i [m$_\oplus$]	ρ_i [$\rho_\oplus$]	P_i [day]	$(p+q)/p$	$\Delta_{(p+q)/p}$
Kepler-80	f	–	–	0.98678	3/1	0.1133
	d	5.95	14.6	3.07222	3/2	0.0118
	e	2.97	6.9	4.64489	3/2	0.0186
	b	3.5	1.45	7.05246	4/3	0.0168
	c	3.49	1.22	9.52355	3/2	0.0385
	g	0.065	–	14.6455		

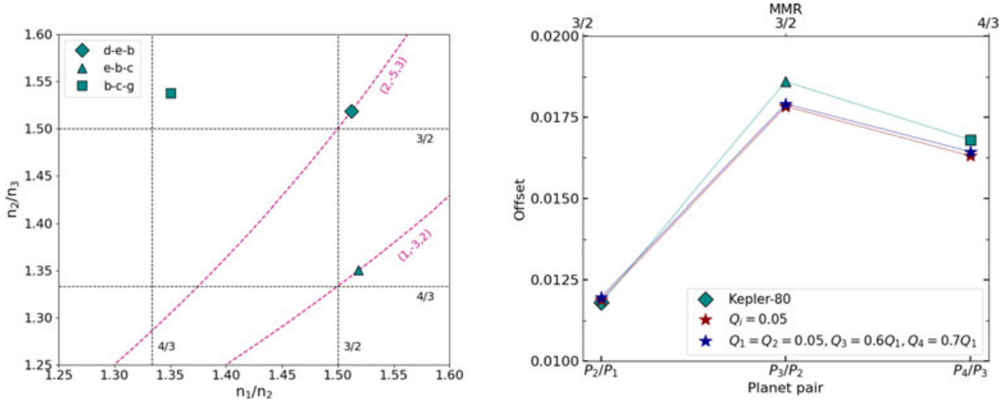

Figure 1. Left: Departures from exact 2-planet MMRs for the Kepler-80 resonant chain in the $(n_1/n_2, n_2/n_3)$ plane. Vertical and horizontal lines indicate 2-planet MMRs, while the dashed purple curves indicate 3-planet MMRs. Right: Resonance offsets for the successive planet pairs within the Kepler-80 d-e-b-c resonant chain. The observed values are represented by cyan symbols.

2016). By looking at the TTVs, MacDonald et al. (2016, 2021) concluded that the four planets Kepler-80 d, e, b, and c dynamically interact in a resonant chain, while the innermost planet Kepler-80 f is decoupled from the rest of the planets and the libration of resonant angles involving the outermost planet Kepler-80 g is not guaranteed. As a result, we only focus here on the 4-planet resonant chain between the middle planets of Kepler-80. Regarding the triplets in Kepler-80, planets d-e-b are in a $(2, -5, 3)$ 3-planet MMR†, while the second triplet e-b-c is in a $(1, -3, 2)$ 3-planet MMR, both being thus in a zeroth-order ($q_{3\mathrm{pl}} = 0$) resonance (see the purple curves in the left panel of Figure 1).

3.1. *Offset analysis*

In Charalambous et al. (2023), we showed that the resonance offsets for the four middle planets of Kepler-80, whose planet pairs are successively close to the 3/2, 3/2, and 4/3 MMRs, do not increase monotonically with the distance to the star, but follow a specific trend. The offset of the second pair increases with respect to the offset of the first pair, while the offset of the last pair decreases with respect to the one of the second pair (see the cyan symbols in the right panel of Figure 1). We computed the period of the

† A 3-planet MMR is characterized by the relation $k_1n_1 + k_2n_2 + k_3n_3 = 0$ for some set of $(k_1, k_2, k_3) \neq (0, 0, 0)$ with $k_i \in \mathbb{N}$ and n_i the mean motion of planet i. The order of the 3-planet MMR is given by $q_{3\mathrm{pl}} = |k_1 + k_2 + k_3|$ (see e.g., Charalambous et al. 2018, for details on the resonant structure).

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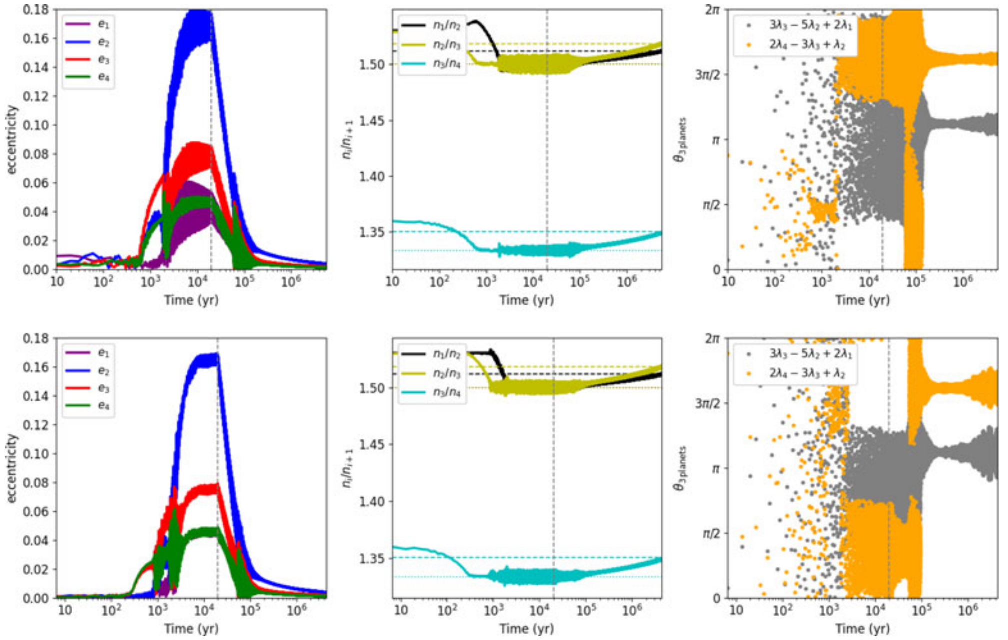

Figure 2. Evolutions of the eccentricities, mean-motion ratios and 3-planet resonant angles of Kepler-80, when Q' is fixed to 0.05 for all the planets (top panels) and to $Q'_1 = Q'_2 = 0.05$, $Q'_3 = 0.6 \times Q'_1$ and $Q'_4 = 0.7 \times Q'_1$ (bottom panels).

third (resp. fourth) planet assuming that the two preceding ones are in an exact 3-planet MMR with the third (resp. fourth) one. We found that the 3-planet MMRs are guiding the dynamics of Kepler-80 since the trend in the observed resonance offsets perfectly fits the analytic estimation.

To analyze whether the formation history of the system is consistent with the observed resonance offsets, we performed simulations of the late-stage formation (planetary migration) and long-term evolution under tidal effects of a Kepler-80-like system. For the tidally-damped N-body simulations we used the REBOUNDx N-body code (Tamayo et al. 2020) with the WHFast symplectic integrator (Rein and Tamayo 2015). Both disk-induced planetary migration and tidal interactions with the host star were included. The planets were assumed to be coplanar with eccentricities initially fixed to 10^{-4} and random orbital angles in $[0, 2\pi]$. Regarding the disk-induced migration which is applied on the outer planet only, we assumed a constant damping timescale of $\tau_a = 10^7$ days and a circularization timescale of $\tau_e = 10^5$ days. Tidal damping effects were included for all the planets, initially by setting Q' to 0.05 for all planets and then adjusting it individually for each planet in a subsequent step.

The time evolution of the 4-planet resonant chain of Kepler-80, with equal Q' for all the planets (top panels of Figure 2), is detailed in Charalambous et al. (2023). During the migration phase induced by the protoplanetary disk, when the planet pairs become trapped in MMRs, their eccentricities gradually increase and eventually stabilize at specific values (left panel). Simultaneously, both the 2- and 3-planet resonant angles undergo libration (right panel). After the disk dispersal, tidal interactions with the central star cause the eccentricities to decrease, reaching values consistent with observational estimates. Meanwhile, the planet pairs cease their oscillations around exact MMR and tend towards the observed departure from MMR (middle panel). The orbital circularization driven by the tides with the host star precisely reproduces the observed values of the

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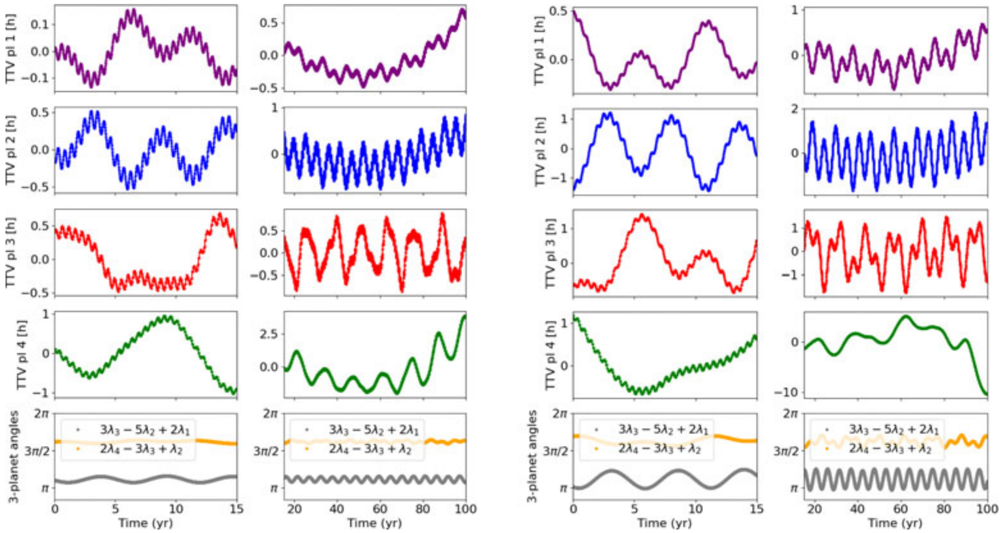

Figure 3. TTVs of the two simulations shown in Figure 2, on 15 yr and 100 yr. In the two left panels, the Q' tidal quality factor is fixed to 0.05, while it is varied individually for each planet in the two right panels.

resonance offsets, as shown in the right panel of Figure 1 by the dark-red stars which represent the simulation outcome when $Q'_i = 0.05$ for all the planets.

A second evolution of the Kepler-80 system is shown in the bottom panels of Figure 2 for different tidal parameter values among the planets, namely $Q'_1 = Q'_2 = 0.05$, $Q'_3 = 0.6 \times Q'_1$ and $Q'_4 = 0.7 \times Q'_1$. As explained in Ferraz-Mello (2013), the Q' value can be understood as a measure of planetary viscosity or elasticity, representing the internal friction inside the body and how fast the planet returns to its equilibrium figure. The fact that different planets have the same Q' is an indication that they dissipate different amounts of energy because their orbital frequencies are different, likely because their internal structure are different as well. The resonance offsets of this second evolution are very similar to the previous ones, as depicted by the blue stars in the right panel of Figure 1. However, during the migration phase, the 3-planet resonant angle $\theta_{234} = \lambda_2 - 3\lambda_3 + 2\lambda_4$ (with λ_i the mean-longitude of planet i) exhibits libration around different centers in the two simulations and after the dispersal of the disk, as tidal forces come into play, the libration center of θ_{234} in the second evolution shifts to finally adopt the same libration center values as in the previous simulation. This second simulation suggests that the migration history with regard to the libration centers of the resonant angles could be erased in the long-term evolution of planetary systems under tidal effects. This observation will be investigated in more detail in future work.

3.2. *TTV analysis*

In line with prior studies that inferred potential formation scenario of resonant extrasolar systems by analyzing the TTVs of the planets (e.g., Teyssandier and Libert (2020) for K2-24 and Teyssandier et al. (2022) for TRAPPIST-1), we computed the TTVs of the two previously described evolutions, at the end of the simulations displayed in Figure 2. While the final system configurations are very similar in terms of resonance offsets and dynamical evolution of the resonant angles (as shown in Figures 1 and 2), the TTV signals of the two evolutions present some significant differences, in both the amplitudes and frequencies (see Figure 3). The latter quantities strongly depend on the proximity to exact MMR and the eccentricity of the planets. As previously said, they are shaped during the formation of the system, in particular the disk-induced migration phase and the tidal dissipation process. According to our preliminary investigation, a change in the tidal parameters among the planets slightly modifies the TTVs and this leads us to think that TTV analysis could be useful to put constraints on the tidal history of planetary systems.

4. Conclusions

We observed distinct patterns in the resonance offsets of detected systems with resonant chains, as for the Kepler-80 system presented here. These resonance offset trends are governed by 3-planet MMRs, align with analytical estimates, and are replicable through tidal damping effects induced by the host star, regardless of the chosen value for the tidal quality factor Q' among the planets. Interestingly, during the tidal phase, a change of libration center was observed for Kepler-80.

We also conducted a preliminary study of the TTVs of Kepler-80 for different tidal parameters. The change in periods and amplitudes of the TTVs observed when considering different tidal parameter values among the planets suggests that resonant chains could prove valuable for uncovering the formation history of planetary systems and eventually help to constrain the Q' values (i.e., the internal structure) of individual planets.

Acknowledgements. C.C. was supported by FONDECYT grant n° 3230283. Computational resources have been provided by the Consortium des Équipements de Calcul Intensif (CÉCI), supported by the FNRS-FRFC, the Walloon Region, and the University of Namur (Conventions No. 2.5020.11, GEQ U.G006.15, 1610468 and RW/GEQ2016).

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https://doi.org/10.1017/S1743921323004970 Published online by Cambridge University Press

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