Complex Planetary Systems II: Latest Methods for an Interdisciplinary Approach
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Can the stellar dynamical tide destabilize the resonant chains of planets formed in the disk?

Leon Ka Wang Kwok[1], Emeline Bolmont[1], Alexandre Revol[1], Stéphane Mathis[2], Aurélie Astoul[3], Corinne Charbonnel[1] and Sean Raymond[4]

[1]Observatoire de Genève, Université de Genève, 51 Chemin des Maillettes, 1290 Sauverny, Switzerland
email: leon.kawang.kwok@gmail.com

[2]Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, 91191, Gif-sur-Yvette, France

[3]Department of Applied Mathematics, School of Mathematics, University of Leeds, Leeds LS2 9JT, UK

[4]Laboratoire d'Astrophysique de Bordeaux, CNRS and Université de Bordeaux, Allée Geoffroy St. Hilaire, 33165 Pessac, France

Abstract. Evolution models of planetary systems find that resonant chains of planets often arise from the formation within protoplanetary disks. However, the occurrence of observed resonant chains, such as the notable TRAPPIST-1 system, is relatively low. This suggests that the majority of these chains become destabilized after the dissipation of the protoplanetary disk. Stellar tides, especially the wavelike dynamical tide, could be proposed as potential contributors to the destabilization of resonant chains. The dissipation of the dynamical tide, because of the frequency-dependant tidal excitation of stellar oscillation eigenmodes, potentially leads to a boost in migration for the close-in planets and disrupts the fragile stability of resonant chains. Thus, we investigate the influence of the stellar dynamical tide on multi-planet systems with taking their dissipation into account in the N-body code Posidonius. Notably, this research represents the first exploration of the impact of frequency-dependent dynamical tides on multi-planet systems.

Keywords. star-planet interactions, planetary dynamics, mean motion resonances (MMRs), resonant chains, tidal interactions, stellar tides, dynamical tides

1. Introduction

From the theories of planetary formation, the emergence of resonant chains of exoplanets is a common outcome, such as in the Trappist-1 system (Gillon *et al.* 2017). (Izidoro *et al.* 2017) showed that the cumulative distribution of the resonant chains resulting from formation mechanisms is higher than the statistical observations. While other mechanisms have been invoked (e.g. planet-planet instability, (Pichierri & Morbidelli 2020)), we focus here on the impact the tidal response of the host star to the presence of a close companion (Bolmont & Mathis 2016) could have on breaking the chains.

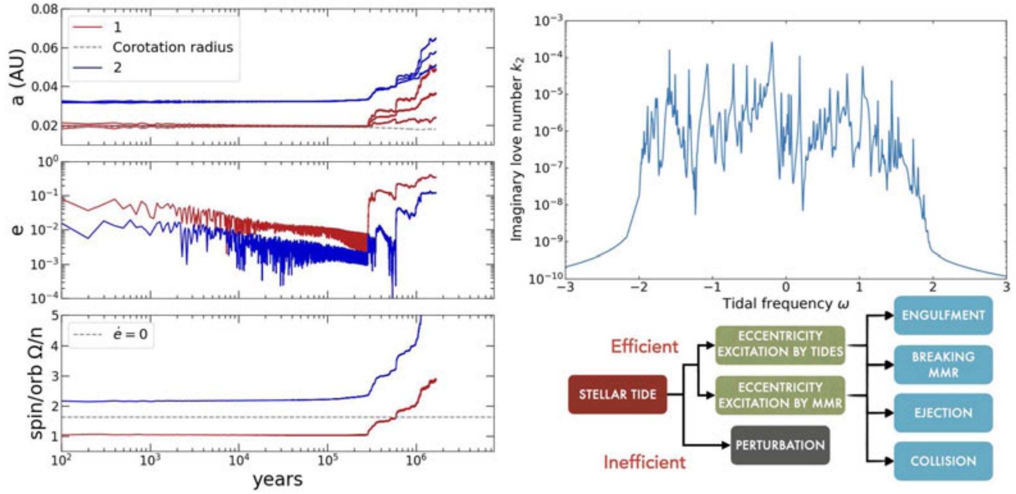

Figure 1. Left: Two hot Jupiters in 2:1 MMR experiencing an outward migration, with the inner planet initially located at $a = 0.02$ AU. Starting from the top panel: the evolution of semi-major axis a (including periastron and apastron), eccentricity e and spin-orbit ratio Ω/n. **Right**: The tidal response spectrum, illustrating the connection between tidal dissipation (quantified by the love number k_2) and tidal frequency, and a brief summary on the influence of the stellar dynamical tide on pairs of planets in first-order resonances.

In the convective envelope of low-mass stars hosting planets, the most efficient dissipation of tidal flows to allow the transfer of angular momentum from the star to planetary orbits is that of tidally-excited inertial modes (Ogilvie & Lin 2007; Bolmont & Mathis 2016). Their restoring force is the Coriolis acceleration. They are dissipated because of the turbulent friction applied by stellar convection. The resulting torque strongly depends on the tidal frequency depending on the strength of the coupling between the tidal force and stellar inertial modes.

As the classical equilibrium tide models (e.g. (Hut 1981)) often used in celestial mechanics are not designed to deal with complex frequency dependencies, we developed for this work a model which uses the Kaula formalism (Kaula 1964), which allows us to take into account any frequency-dependent tidal torque. We implemented it in the N-body code Posidonius (Blanco-Cuaresma & Bolmont 2017) in order to investigate this question.

2. Results

We performed simulations with different planetary masses (5 Earth masses $M_\oplus$ & 1 Jupiter mass M_J), and different initial stellar spin rates Ω, semi-major axis a and states of mean motion resonance (MMR). Figure 1 shows the result of a simulation with a pair of 1 M_J planets initially in 2:1 MMR, demonstrating the breaking of MMR from the dynamical tide. For the lower left panel, the grey dashed line indicates whether the stellar tide can excite the planetary eccentricities (above) or damp them (below).

Due to the resonant characteristics of the dynamical tide, the inner planet experiences several boosts of migration, as the frequency of the tidal interaction coincides with a resonant frequency of the star as we are close to a resonance of the tidal torque (different peaks of the tidal spectrum, see Fig. 1). Due to the migration boosts of the inner planet and the stellar tide, the outer one experiences boosts both in migration and eccentricity resulting mainly from the self-stabilization of the MMR (apart from the torque of the

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stellar tide). The MMR exhibits an intriguing property: by exciting the planet's eccentricities as the ratio of the orbital period decreases, the MMR configuration is reinforced. Note that the simulation is still ongoing but escape of MMR is expected due to the orbits crossing.

The general influence of dynamical tides on pairs of planets in first-order resonances is given in the lower right panel of Fig. 1. To conclude, if the dissipation of stellar dynamical tide is strong (massive or close-in planets), this interaction would be able to break the MMRs, potentially resulting in engulfment, ejections, and collisions; otherwise, its influence on the system is minimal. An upcoming article will present cases featuring more planets and ultra-short-period planets, with a more intricate analysis of the resonance states (Deck 2013).

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