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Spin equilibria of eccentric ocean planets

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Abstract

Eccentricity tides generate a torque that can drive an ocean planet towards asynchronous rotation states of equilibrium when enhanced by resonances associated with the oceanic tidal modes. We investigate the impact of eccentricity tides on the rotation of rocky planets hosting a thin uniform ocean and orbiting cool dwarf stars such as TRAPPIST-1, with orbital periods $\sim 1 - 10$ days. Combining the linear theory of oceanic tides in the shallow water approximation with the Andrade model for the solid part of the planet, we develop a global model including the coupling effects of ocean loading, self-attraction, and deformation of the solid regions. We derive from this model analytic solutions for the tidal torque exerted on the planet. These solutions allow us to fully characterize the frequency-resonant tidal response of the planet, and particularly the features of resonances associated with the oceanic tidal modes (eigenfrequencies, resulting maxima of the tidal torque and Love numbers) as functions of the planet parameters (mass, radius, Andrade parameters, ocean depth and Rayleigh drag frequency). Resonances resulting from the oceanic tide decrease the critical eccentricity beyond which asynchronous rotation states distinct from the usual spin-orbit resonances may exist. This critical eccentricity is found to be lowered by one order of magnitude, switching from ~ 0.3 to ~ 0.05 in typical cases and to ~ 0.01 in extremal ones.

1. Introduction

The discovery of Earth-sized rocky planets located in the habitable zone of their host star naturally leads to wonder about the nature of their climates and surfaces conditions. This is illustrated by the emblematic TRAPPIST-1 ultracool M-dward star, which harbours not less than seven rocky planets [e.g. 3], some of them being potentially habitable owing to the existence of significant water reservoirs [e.g. 1, 5, 9, 10]. As the climate of such bodies strongly depends on their rotation rate, it is crucial to preliminary characterize their spin equilibria and to determine whether they are – or not – tidally locked in spin-orbit synchronous rotation.

Over long timescales, the spin evolution of the planet is driven by the tidal torque resulting from the gravitational forcing of the host star[1]. This torque depends on the planet internal structure and dissipative mechanisms. In the case of ocean planets, it strongly varies with the forcing tidal frequency because of the resonances associated with the propagation of surface gravito-inertial modes. Combined with the accelerating action of some eccentricity tidal components, such resonances can lock the planet in non-synchronized spin equilibria as shown by early studies in the case of solid bodies with spin-orbit resonances [4, 7, 2].

In this work, we use the linear theory of oceanic tides [e.g. 8] to compute the tidal torque exerted on a planet hosting a global ocean of uniform depth by taking the coupling due to ocean loading, self-attraction, and deformation of solid regions into account self-consistently. We use the derived analytic results to investigate the dependence of the final spin states of the planet on the eccentricity and the ocean depth, which leads us to establish scaling laws characterizing the regions of the parameter space where asynchronous rotation may occur at small eccentricities. Results are detailed in a forthcoming article submitted to Astronomy & Astrophysics.

2. Overview of main results

In the coplanar case (no obliquity), the tidal torque exerted on the planet is expressed as

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[1] In addition to the tidal gravitational potential, the atmosphere is thermally forced by the stellar flux [e.g. 6].

$$\mathcal{T}_{\rm p} = \frac{3}{2} G M_\star^2 \frac{R_{\rm p}^5}{a^6} \sum_{s=-\infty}^{+\infty} \left[X_s^{-3,2}\left(e\right)\right]^2 \Im\left\{k_{\rm p;2}^{2,\sigma}\right\}, \tag{1}$$

where G designates the gravitational constant, $M_\star$ the mass of the host star, $R_{\rm p}$ the planet radius, a the semi-major axis, s an integer, $X_s^{-3,2}$ the so-called Hansen coefficients, and $k_{\rm p;2}^{2,\sigma}$ the degree-2 tidal Love numbers, which are obtained by solving the Laplace's tidal equation.

The spin equilibria are defined by $\mathcal{T}_{\rm p} = 0$ and calculated using Eq. (1) as functions of the eccentricity and the ocean depth in logarithmic scale. An example of the obtained results is shown by Fig. 1 in the case of an Earth-sized planet with a 6 days orbital period. The horizontal peaks that are observed here correspond to the resonances of oceanic tidal modes forced by eccentricity terms. At the associated ocean depths, these eccentricity terms are enhanced by resonances and decrease the minimal eccentricity for which asynchronous states may exist.

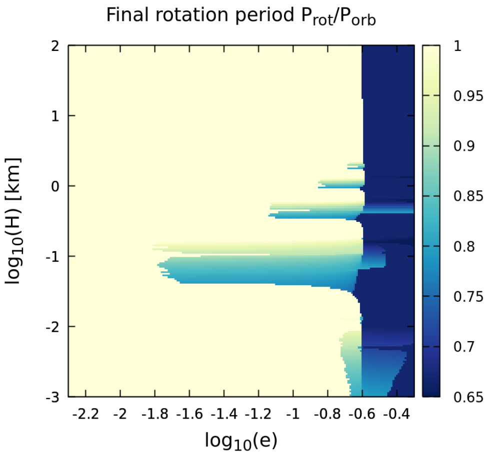

Figure 1: Final rotation period of the planet normalized by its orbital period as a function of the eccentricity and the ocean depth in logarithmic scales. Yellow areas indicate the regions where the planet ends in spin-orbit synchronous rotation, shaded areas the regions where it is driven towards an asynchronous spin state.

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