REPERCUSSIONS OF THERMAL ATMOSPHERIC TIDES ON THE ROTATION OF TERRESTRIAL PLANETS IN THE HABITABLE ZONE

P. Auclair-Desrotour[1], S. Mathis[2,3] and J. Laskar[4]

Abstract. Semidiurnal atmospheric thermal tides are important for terrestrial exoplanets in the habitable zone of their host stars. With solid tides, they torque these planets, thus contributing to determine their rotation states as well as their climate. Given the complex dynamics of thermal tides, analytical models are essential to understand its dependence on the structure and rotation of planetary atmospheres and the tidal frequency. In this context, the state of the art model proposed in the 60s by Lindzen and Chapman explains well the properties of thermal tides in the asymptotic regime of Earth-like rapid rotators but predicts a non-physical diverging tidal torque in the vicinity of the spin-orbit synchronization. In this work, we present a new model that addresses this issue by taking into account dissipative processes through a Newtonian cooling. First, we recover the tidal torque recently obtained with numerical simulations using General Circulation Models (GCM). Second, we show that the tidal response is very sensitive to the atmospheric structure, particularly to the stability with respect to convection. A strong stable stratification is able to annihilate the atmospheric tidal torque, leading to synchronization, while a convective atmosphere will be submitted to a strong torque, leading to a non-synchronized rotation state.

Keywords: hydrodynamics – waves – convection – planet-star interactions – planets and satellites: dynamical evolution and stability

1 Introduction

The dynamics of planetary systems over long times scales is tightly related to mutual interactions between their bodies, and particularly tides (e.g. Mathis & Remus 2013). Tides affect the rotation of planets, their distance to the star, and can generate a strong tidal heating, which is able to modify significantly the surface equilibrium of planets as observed for instance on the Jupiter's satellite Io (Lainey et al. 2009). Therefore, with the continuously growing number of discovered terrestrial planets orbiting in the habitable zone of their host stars, it is today crucial to understand physically the role played by tides for planetary dynamics. In this work, we focus on thermal atmospheric tides, namely tides generated by the stellar heating of a planetary atmosphere. These tides are of great importance for terrestrial planets close to spin-orbit synchronization because they are able to torque them *away* from this equilibrium state, in opposition to gravitationally excited tides. Typically, in the Solar system, they contribute to lock Venus at a non-synchronized rotation rate where the solid and atmospheric tidal torques exactly balance each other (Gold & Soter 1969; Dobrovolskis & Ingersoll 1980; Correia & Laskar 2001). In the absence of atmospheric tides, Venus would be today synchronized owing to the relatively small evolution timescales associated with gravitational tides. Hence, considering both the potential number of Venus-like terrestrial planets among the exoplanets discovered during the last decade and the impact that the rotation of a planet has on its atmospheric general circulation and climate, it is necessary to

[1] LAB, Université de Bordeaux, CNRS UMR 5804, Université de Bordeaux - Bt. B18N, Allée Geoffroy Saint-Hilaire CS50023, 33615 Pessac Cedex, France

[2] Laboratoire AIM Paris-Saclay, CEA/DRF - CNRS - Université Paris Diderot, IRFU/DAp Centre de Saclay, F-91191 Gif-sur-Yvette Cedex, France

[3] LESIA, Observatoire de Paris, PSL Research Université, CNRS, Sorbonne Université, UPMC Univ. Paris 6, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, F-92195 Meudon, France

[4] IMCCE, Observatoire de Paris, CNRS UMR 8028, PSL Research University, 77 Avenue Denfert-Rochereau, 75014 Paris, France

understand the dependence of the atmospheric tidal response on the physical properties of planetary atmosphere and the tidal frequency.

This question was addressed recently in a numerical way by Leconte et al. (2015), who used a General Circulation Model (GCM) to compute the atmospheric tidal torque. However, this approach is limited by the high computational cost of numerical simulations that do not yet allow to explore a broad domain of the parameters space. The classical theory of atmospheric tides (see e.g. Chapman & Lindzen 1970) offers an elegant analytic approach where the tidal response is treated as a linear perturbation and written as an explicit function of the atmospheric parameters. This approach, which ignores dissipative effects, explains well the Earth's atmospheric tides and more generically the case of rapid rotators. However, it has to be adapted to the case of slowly rotating planets where dissipative processes cannot be neglected any more. Thus, we adopt in this study the linear approach and generalize it to slowly rotating planets by introducing a Newtonian cooling. We compute the tidal response and the corresponding semidiurnal tidal torque first using a global modeling, second with a local Cartesian one. We show how the atmospheric structure affects the tidal torque through the stability of stratification of the fluid with respect to convection. We provide here the main lines of results, which are detailed in Auclair-Desrotour et al. (2017a), Auclair-Desrotour et al. (2017b) and Auclair-Desrotour et al. (2017c).

2   Physical setup

We consider a spherical terrestrial planet rotating at the spin angular velocity Ω and orbiting its host star at the orbital frequency $n_{\rm orb}$ (see Fig. 1, left panel). In the absence of perturbation, the fluid is supposed to be at the hydrostatic equilibrium and radially stratified (background distributions only depend on the vertical coordinate r). The stratification of the atmosphere with respect to convection is characterized by the Brunt-Väisälä frequency given by

$$N^2 = -g \left[\frac{d \ln \rho_0}{dr} - \frac{1}{\Gamma_1} \frac{d \ln p_0}{dr} \right], \qquad (2.1)$$

where g designates the gravity, Γ_1 the adiabatic exponent, and p_0 and ρ_0 pressure and density background distributions respectively. Taking into account radiative losses through a Newtonian cooling introduces an additional frequency σ_0, which is the inverse of the thermal timescale. Finally, owing to the compressibility of the fluid, the gravest horizontally propagating Lamb modes can be excited if the forcing frequency σ is greater than the characteristic acoustic cutoff frequency $\sigma_{\rm s}$. Hence, the hierarchy of the characteristic frequencies σ_0, 2Ω, N, $\sigma_{\rm s}$ and σ fully determines the nature of the tidal response and which kind of waves it is composed of (see Fig. 1, right panel): i.e. inertial, gravity and acoustic waves damped by radiative cooling.
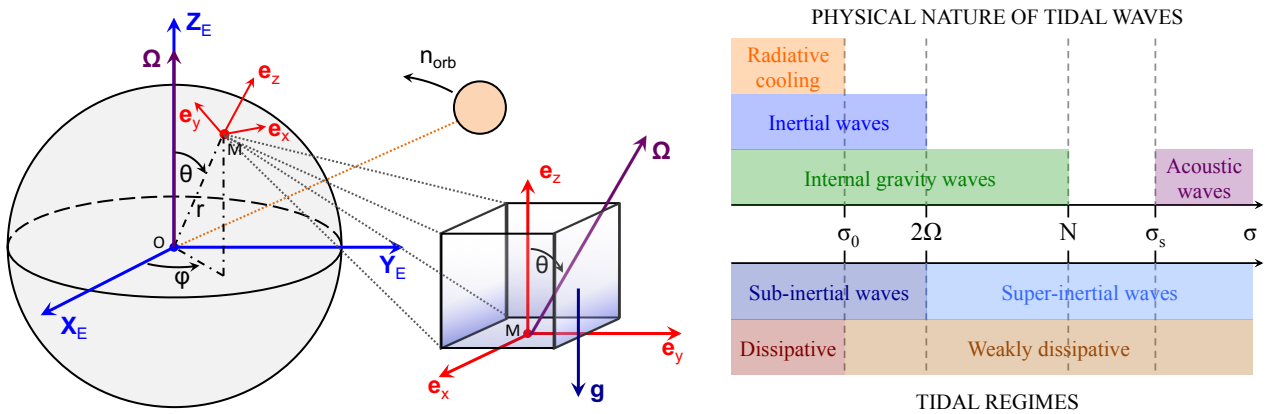

Fig. 1. Left: Spherical and Cartesian reference frames and systems of coordinates. The vectors $\boldsymbol{\Omega}$ and $\mathbf{g}$ designate the rotation and the gravity respectively. The notation $n_{\rm orb}$ refers to the orbital frequency of the star in the reference frame of the planet. **Right:** Frequency spectrum of tidal regimes and waves characterizing the atmospheric tidal response. The parameter σ designates the forcing frequency, 2Ω the inertia frequency, N the Brunt-Väisälä frequency, and $\sigma_{\rm s}$ the characteristic acoustic cutoff frequency.

Two types of models are used:

- Global model in spherical geometry. The background atmospheric structure only depends on the radial coordinate. We assume the *traditional approximation*, which filters out the components of the Coriolis acceleration related to the latitudinal projection of the rotation vector (we refer the reader to Auclair-Desrotour et al. 2017a, for a complete discussion).

- Local model constituted by a Cartesian local fluid section of the atmosphere (Fig. 1, left panel) (Auclair-Desrotour et al. 2017c). we assume the *f-plane* and *anelastic approximations* (where acoustic waves are filtered out). In this model, the complete Coriolis acceleration is taken into account.

3   Thermally generated atmospheric tidal torque

3.1   Global model

In Auclair-Desrotour et al. (2017a), we compute for two different atmospheric structures the tidal torque exerted on the atmosphere caused by the quadrupolar component of the thermally excited semidiurnal tide. The first structure corresponds to an isothermal atmosphere, where $N \gg \sigma$. It is strongly stably stratified with respect to convection. The second structure is an isentropic profile of temperature, which is such that $N = 0$ and thus enforces a neutral stratification. The tidal torques that we obtain in these two cases are plotted on Fig. 2 as functions of the normalized tidal frequency $\omega = (\Omega - n_{\mathrm{orb}})/n_{\mathrm{orb}}$ using for parameters a set of values derived from the Venus case. As can be seen, we recover in the neutral stratification case the tidal torque obtained by Leconte et al. (2015) with GCM simulations for Venus. The observed behaviour corresponds to that described by the Maxwell model: a global tidal bulge follows the perturber with a delay depending of the thermal inertia of the atmosphere. In the other case, the strong stable stratification of the atmosphere prevents a net tidal bulge to form, a local density decrease being immediately compensated by the motion of denser fluid particles driven upward by the Archimedean force. As a consequence, the tidal torque is very weak and cannot balance the solid torque as in the neutral case.
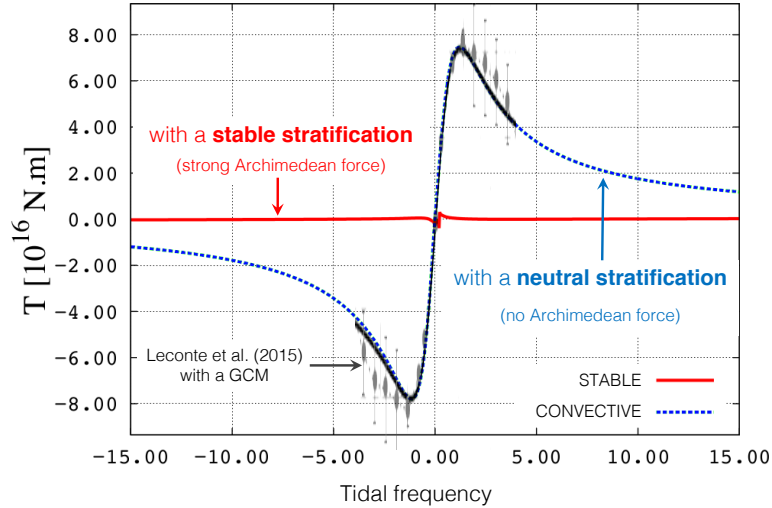

Fig. 2. Tidal torque given by the global model as a function of the tidal frequency $\omega = (\Omega - n_{\mathrm{orb}})$ for two different atmospheric structure: stably-stratified (red solid line) and neutrally-stratified (blue solid line) with respect to convection. For comparison, the shape of the tidal torque obtained by Leconte et al. (2015) using a GCM is plotted in addition to the two previous cases. Grey dots correspond to numerical simulations, the black solid line to a fit of these results with a Maxwell model.

3.2   Local model

The local model allows us to refine the diagnosis made with the global approach. Considering a planar wave propagating along the longitudinal direction, we obtain for the associated tidal torque the expression

$$\mathcal{T} = 2\sigma_0 \Im \left\{ \frac{i}{\sigma - i\sigma_0} \left[1 - \nu - \frac{\nu}{1 - K(\sigma, k_z)} \right] \right\}, \tag{3.1}$$

where $i^2 = -1$, $\Im$ is the imaginary part of a complex number, ν a function of the physical parameters of the system (forcing frequency, Brunt-Väisälä frequency, spin angular velocity, thermal frequency, colatitude, pressure height scale, horizontal wavenumber), and K a function of the forcing frequency σ and vertical wavenumber k_z of the associated tidal wave, which characterizes the contribution of internal gravity waves to the tidal torque. On the one hand, in the low-frequency range ($\sigma \to 0$), $\nu \to 0$ in the case of a neutrally-stratified atmosphere, leading to the Maxwell model identified previously. On the other hand, $\nu \to 1$ and $|K| \to +\infty$ in the stably-stratified case, which implies $\mathcal{T} \approx 0$. This suggests that the rotation rate of the planet will tend towards a *non-synchronized* state of equilibrium in the neutrally-stratified case and towards the spin-orbit synchronous rotation rate in the stably-stratified one. This is illustrated by Fig. 3 (right panel) where the normalized tidal frequency (ω) of a Venus-like terrestrial planet is plotted as a function of time for different atmospheric stratifications using Eq. (3.1) for the atmosphere and a constant tidal quality factor for the solid part of the planet. The corresponding atmospheric tidal torques are plotted as a function of ω (left panel).
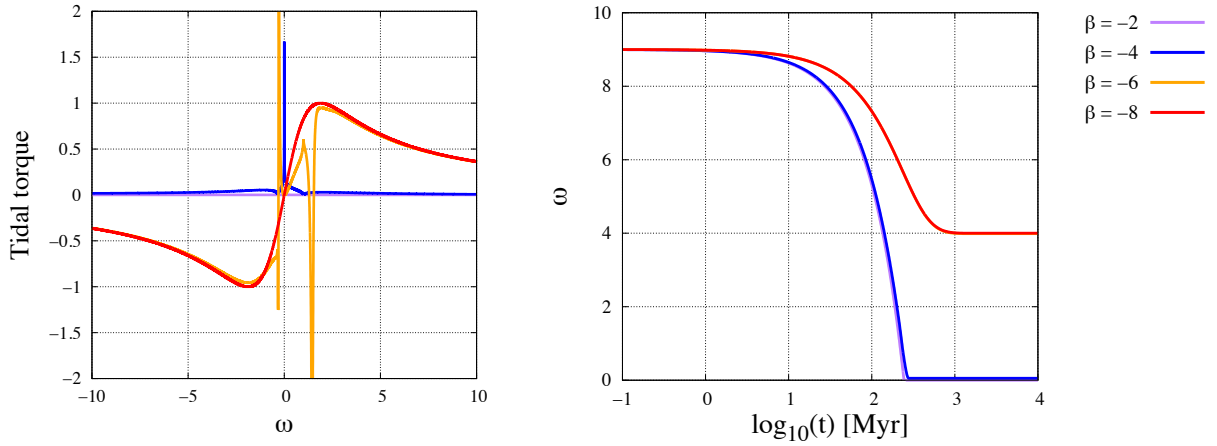

Fig. 3. Left: Tidal torque given by the local Cartesian model as a function of the frequency of the perturber $\omega = (\Omega - n_{\mathrm{orb}})/n_{\mathrm{norb}}$ for various values of the Brunt-Väisälä frequency from weak to strong stable stratification, i.e. $\beta = \log(N) = \{-8, -6, -4, -2\}$. The tidal torque is computed using Eq. (3.1). It is normalized by the maximum value of the torque of the convective case ($\beta = -8$). **Right:** Evolution of the rotation rate of a Venus-like planet for the same Brunt-Väisälä frequencies. The normalized frequency $\omega = (\Omega - n_{\mathrm{orb}})/n_{\mathrm{orb}}$ is plotted as a function of time (Myr) in logarithmic scale. The value $\omega = 0$ corresponds to spin-orbit synchronous rotation.

4   Conclusions

Motivated by the understanding of the role played by atmospheric tides in the evolution of the rotation rate of terrestrial planets, we computed the tidal torque generated by the thermally excited semidiurnal tide analytically by using an ab initio linear global model. We recovered the behaviour previously obtained with numerical simulations using GCMs, which corresponds to that described by the so-called Maxwell model. We showed evidence that the tidal response strongly depends on the structure and stability of the atmosphere through its stratification with respect to convection. In a second step, we explored this dependence by using a local Cartesian model, showing that it is determined by the hierarchy of characteristic frequencies of the system. We established the continuous transition between the stably and neutrally stratified cases, which lead to synchronized and non-synchronized rotation states of equilibrium respectively.

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