Understanding tidal dissipation in gaseous giant planets: the respective contributions of their core and envelope

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Abstract

Tidal dissipation in planetary and stellar interiors is one of the key mechanisms driving the evolution of planetary systems, especially for planets orbiting close to their host star. It strongly depends on the internal structure and rheology/friction mechanisms in the involved bodies. Here, we focus on the tidal response of Jupiter and Saturn-like gaseous giant planets using a simplified bi-layer model consisting of a rocky/icy core surrounded by a deep fluid convective envelope. For these planets, we compare the frequency-averaged amplitudes of the viscoelastic dissipation in the central solid region and of the damping of inertial waves by turbulent friction in fluid layers, as a function of the core size and mass. We find that the two dissipation mechanisms could generally have the same strength. This demonstrates that tidal dissipation in giant planets must be examined from their centre to their surface taking into account mechanisms occurring both in solid and fluid parts of the giant gaseous planets. These conclusions will be discussed in the context of exoplanetary systems and of recent observational constraints obtained in the Solar system for Jupiter and Saturn thanks to high precision astrometry.

1 Introduction

The numerous exoplanets discovered during the latest twenty years after the discovery of 51 Peg b (Mayor & Queloz 1995) has uncovered the existence of many close-in giant planets – often referred to as “hot Jupiters” – orbiting around their host star. Since our Solar system shelters no such planet, these discoveries have challenged our understanding of how planetary systems form and evolve. Observations of extrasolar planets by the radial-velocity and transits methods have developed rapidly over the past decade and stimulated interest in looking for signatures of tidal interactions in star-planet systems: for instance, Pont (2009) looked for an excess rotation in star-hosting planets (due to substantial inward migration), Leconte et al. (2010) tested tidal heating as the energy source for bloated hot Jupiters, while Husnoo et al. (2012) used observed eccentricities to conclude that tidal interactions play a prominent role in the orbital evolution and survival of hot Jupiters (see also Lai 2012; Valsecchi & Rasio 2014).

Indeed, theoretical models predict that the orbital and rotational evolution of a close-in planet around its host star is strongly dependent on the tidal dissipation inside each body (Hut 1980; Bolmont et al. 2012; Zhang & Penev 2014). However, the response of fluid and solid planetary layers to tidal excitation is not well-understood yet, as well as the associated dissipative processes which are very different in each type of region (e.g. Mathis & Remus 2013; Auclair-Desrotour et al. 2014). For these reasons, there is a strong need for reliable calculations of the energy dissipation rate due to tidal displacements in each kind of planetary layer.

Recent progress on observational constraints was obtained using high-precision astrometry measurements in the solar system (Lamey et al. 2009, 2012) especially for Jupiter and Saturn, and space-based high-resolution photometry for exoplanetary systems (Albrecht et al. 2012; Fabrycky et al. 2014). These results showed that there may be a strong tidal dissipation in gaseous giant planets, and its smooth dependence on the tidal frequency in the case of Saturn indicates that the inelastic dissipation in their central dense core may be strong (e.g. Remus et al.)
However, on one hand, the mass, the size, and the rheology of these cores are still unknown. On the other hand, inertial waves, whose restoring force is the Coriolis acceleration, may be excited by tides in the surrounding fluid convective envelope. Moreover, it seems that turbulent friction acting on these waves can be strong too (e.g. Ogilvie & Lin 2004; Ogilvie 2013). As a consequence, it is necessary to develop new models that take into account the appropriate dissipative mechanisms, so that we can predict how much energy each type of layer can dissipate. This should be achieved not only for gaseous giant planets but for all multi-layer planets, that may consist of differentiated solid and fluid layers.

In this work, we used a simplified two-layer model that accounts for the internal structure of gaseous giant planets. We used the frequency-dependent Love number to evaluate the reservoirs of dissipation in both regions, in a way introduced by Ogilvie (2013). It allows us to give the first direct comparison of the respective strengths of different dissipative mechanisms occurring in a given planet. In sec. 2 we describe the main characteristics of our simplified planetary model. Next, we recall the method we used to compute the reservoirs of dissipation that is a result of viscoelastic dissipation in the core (Remus et al. 2012, 2014) and of turbulent dissipation in the fluid envelope (Ogilvie 2013). In sec. 3 we explore their respective strength for possible values for the parameters of our two-layer model. Finally, we discuss our results and the potential applications of this method.

2 Modelling tidal dissipation in gaseous giant planets

2.1 The two-layer model

This model features a generic giant planet $A$ of mass $M_p$ and mean radius $R_p$ assumed to be in solid-body rotation with a moderate angular velocity $\Omega$ in the sense that $\epsilon^2 \equiv \Omega^2 / \sqrt{GM_p / R_p^3} \ll 1$ (see fig. 1). In this regime, the Coriolis acceleration, which scales as $\Omega^2$, is taken into account while the centrifugal acceleration, which scales as $\Omega^2$ is neglected. The planet $A$ has a rocky (or icy) solid core of radius $R_c$, density $\rho_c$ and rigidity $G$ that is surrounded by a convective fluid envelope of density $\rho_o$. Both regions are assumed to be homogeneous for the sake of simplicity. Finally, a point-mass tidal companion $B$ of mass $M_B$ is orbiting around $A$ with a mean motion $n$.

![Figure 1: The two-layer model.](image)

2.2 Mechanisms of dissipation

The time-dependent tidal potential exerted by the companion leads to two different dissipation mechanisms. In the following, we detail how they operate and the hypotheses we used to evaluate their respective strength.

- First, we consider the viscoelastic dissipation in the solid core, for which we assume that the rheology follows the linear rheological model of Maxwell with a rigidity $G$ and a viscosity $\eta$; we also assume that the surrounding envelope is inviscid and only applies hydrostatic pressure and gravitational attraction on the core.
Figure 2: **Left**: Gravitational forces ($\vec{f}_1$), internal constraints ($\vec{f}_2$) and hydrostatic pressure ($\vec{f}_3$) acting on the solid core, which is deformed by the tidal force exerted by the companion. **Right**: Attractor formed by a path of characteristics of inertial waves.

- Then, the turbulent viscosity in the fluid convective envelope dissipates the kinetic energy of tidal inertial waves propagating in that region. The restoring force of inertial waves is the Coriolis acceleration and their frequency is smaller than the Coriolis frequency: $\omega \in [-2\Omega, 2\Omega]$. Moreover, their kinetic energy may concentrate and form shear layers around attractor cycles, which leads to enhanced damping by turbulent viscosity. In order to compute it, the core is assumed to be perfectly rigid.

### 2.3 Evaluation of the tidal dissipation reservoirs

We compute for each of these mechanisms the "reservoir of dissipation", a weighted frequency-average of the imaginary part of the Love number $k_2^2(\omega) = \Phi'_2 / U_2^2$ (which is the ratio between the $Y_2^2$-components of the Eulerian perturbation $\Phi'$ of the self-potential of body A, and of the tidal potential $U$) defined as:

$$\int_{-\infty}^{+\infty} \text{Im} \left[ k_2^2(\omega) \right] \frac{d\omega}{\omega} = \int_{-\infty}^{+\infty} \frac{\left| k_2^2(\omega) \right|}{Q_2^2(\omega)} \frac{d\omega}{\omega} ,$$  \hspace{1cm} (1)

where $Q_2^2(\omega)$ is the corresponding tidal quality factor.

- We find for the viscoelastic dissipation mechanism (see Remus et al. 2012, 2014; Guenel et al. 2014):

$$\int_{-\infty}^{+\infty} \text{Im} \left[ k_2^2(\omega) \right] \frac{d\omega}{\omega} = \frac{\pi G (3 + 2 \alpha)^2 \beta \gamma}{\delta (6 \delta + 4 \alpha \beta \gamma G)},$$  \hspace{1cm} (2)

where $\alpha, \beta$ and $\delta$ are positive functions of the aspect and density ratios $(R_\ast / R_p, \rho_o / \rho_i)$, whereas $\gamma$ only depends on $R_\ast$ and $\rho_i$. This result is remarkably independent of the viscosity $\eta$ while $\text{Im} \left[ k_2^2(\omega) \right]$ is not.

- Meanwhile, Ogilvie (2013) provides us for inertial waves:

$$\int_{-\infty}^{+\infty} \text{Im} \left[ k_2^2(\omega) \right] \frac{d\omega}{\omega} = \frac{100\pi}{63} \varepsilon^2 \left( \frac{R_\ast / R_p}{1 - (R_\ast / R_p)} \right)^5 \left[ 1 + \frac{1 - \rho_o / \rho_i}{\rho_o / \rho_i} \left( \frac{R_\ast / R_p}{1 - (R_\ast / R_p)} \right) \right] \left[ 1 + \frac{5}{2} \frac{1 - \rho_o / \rho_i}{\rho_o / \rho_i} \left( \frac{R_\ast / R_p}{1 - (R_\ast / R_p)} \right) \right]^{-2} .$$  \hspace{1cm} (3)

### 3 Comparison of the two dissipation mechanisms

- Our goal is to compare quantitatively the respective strength of the two dissipative mechanisms in order to determine if one of them can be neglected in gaseous giant planets similar to Jupiter and Saturn. Their respective mass and radius are $M_p = \{317.83, 95.16\} M_\oplus$ and $R_p = \{10.97, 9.14\} R_\oplus$ ($M_\oplus = 5.97 \times 10^{24}$ kg and $R_\oplus =$...
6.37 \times 10^7 \text{ km being the Earth’s mass and radius}. Their rotation rate is \( \Omega_{J(5)} = \{1.76 \times 10^{-4}, 1.63 \times 10^{-4}\} \text{ rad} \cdot \text{s}^{-1} \). Internal structure models for these bodies are still not well constrained (Guillot 1999; Hubbard et al. 2009). This is why we choose to explore wide ranges of core radii (left) and core masses (right) in fig. 3.

- We choose to use as a reference \( G_{\text{J(5)}}^0 = [4.46 \times 10^{10}, 1.49 \times 10^{11}] \) Pa that allows the viscoelastic dissipation model to match the dissipation measured by Lainey et al. (2009, 2012) in Jupiter at the tidal frequency of Io and in Saturn at the frequency of Enceladus (with \( \eta_{J(5)} = [1.45 \times 10^{14}, 5.57 \times 10^{14}] \) Pa \cdot s).

- Figure 3 shows that for both dissipation models and both planets, the tidal dissipation reservoirs generally increase with the core radius (left) while they slightly decrease with increasing core mass — or decreasing \( R_c / R_p \) (right). These plots show that in Jupiter- and Saturn-like gaseous giant planets, the two distinct mechanisms exposed earlier can both contribute to tidal dissipation, and that therefore none of them can be neglected in general (see Guenel et al. 2014).

4 Conclusions

In the case of Jupiter and Saturn-like planets, we show that the viscoelastic dissipation in the core could dominate the turbulent friction acting on tidal inertial waves in the envelope. However, the fluid dissipation would not be negligible. This demonstrates that it is necessary to build complete models of tidal dissipation in planetary interiors from their deep interior to their surface without any arbitrary a-priori.
References

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