EPSC Abstracts
Vol. 7 EPSC2012-840-1 2012
European Planetary Science Congress 2012

Anelastic tidal dissipation in multi-layer planets

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Abstract

Earth-like planets have anelastic mantles, whereas giant planets may have anelastic cores. As for the fluid parts of a body, the tidal dissipation of such solid regions, gravitationally perturbed by a companion body, highly depends on its internal friction, and thus on its internal structure. Therefore, modelling this kind of interaction presents a high interest to provide constraints on planets interiors, whose properties are still quite uncertain. Here, we examine the equilibrium tide in the solid part of a planet, taking into account the presence of a fluid envelope. We derive the different Love numbers that describe its deformation and discuss the dependence of the quality factor Q on the chosen anelastic model and the size of the core. Taking plausible values for the anelastic parameters, and discussing the frequency-dependence of the solid dissipation, we show how this mechanism may compete with the dissipation in fluid layers, when applied to Jupiter- and Saturn-like planets. We also discuss the case of the icy giants Uranus and Neptune. Finally, we present the way to implement the results in the equations that describe the dynamical evolution of planetary systems.

1 Introduction

Once a planetary system is formed, its dynamical evolution is governed by gravitational interactions between its components, be it a star-planet or planet-satellite interaction. By converting kinetic energy into heat, the tides pertub their orbital and rotational properties, and the rate at which the system evolves depends on the physical properties of tidal dissipation. Therefore, to understand the past history and predict the fate of a binary system, one has to identify the dissipative processes that achieve this conversion of energy. Planetary systems display a large diversity of planets, with telluric planets having anelastic mantles and giant planets with possible anelastic cores. Since tidal mechanism is closely related with the internal structure, one has to investigate its effects on each kind of materials that may compose a planet. Studies have been carried out on tidal effects in fluid bodies such as stars and envelopes of giant planets (Ogilvie & Lin 2004-2007; Ogilvie 2009; Remus et al. 2012). However, the planetary solid regions, such as the mantles of Earth-like planets or the rocky cores of giant planets may also contribute to tidal dissipation. The purpose of this study is to determine the tidal dissipation in these solid parts of planets.

2 Description

We will consider as a model a two-bodies system where the main component has a viscoelastic core, made of ice or rock, surrounded by a fluid envelope, such as an ocean, streching out from core's surface up to planet's surface. Both core and envelope are considered homogeneous, with constant density. We follow the methodology of Dermott (1979).

In presence of dissipation, there is a lag between the line of centers and the tidal bulge. Then, the response ϕ' of the body to the tidal potential U defines the second order complex Love number $\tilde{k}_2$ whose real part corresponds to the purely elastic deformation, while its imaginary part accounts for dissipation (Biot 1954, see also Tobie 2003 and Henning et al. 2009).

This dissipation is quantified by the inverse *quality factor*:

$$Q^{-1} = -\frac{\mathcal{I}m\,\tilde{k}_2}{\left|\tilde{k}_2\right|}\;,\;\;\text{where}\;\;\tilde{k}_2 = \frac{\phi'}{U}\,. \qquad (1)$$

Note that this expression depends on the tidal frequency, the size of the core, the densities of both the core and the fluid shell, and on the rheological parameters of the solid core.

Acting as an overload on the solid core, the fluid shell, previously deformed by the tide, increases the tidal deformation of the core's surface. The second order Love number $\tilde{k}_2$ of the core takes then a different form than in the fully-solid case. We will notice in particular that the well-known limit of $3/2$ reached by a liquid uniform planet may be exceed when taking into account the overload of the fluid envelope.

3 Conclusion

In 2004, Ogilvie & Lin studied tidal dissipation in rotating giant planets with solid cores, resulting from the excitation of inertial waves in the convective region by the tidal potential. They obtained a decrease of the effective quality factor

$$Q_{\text{eff}} = \left(\frac{R_p}{R_c}\right)^5 \times \frac{|\tilde{k}_2(R_p)|}{|\tilde{k}_2(R_c)|} \times Q\,, \qquad (2)$$

which mesures the dissipation of the whole planet, associated to the fluid equilibrium tide of a fully convective planet (except for a small solid core): from $Q_{\text{eff}} = 10^6$ to $Q_{\text{eff}} = 10^5$.

The present two-layer model proposes an alternative process to reach such a dissipation , and even more depending on the viscosity η and the stiffness M. The results are presented for Jupiter-, Saturn-, Uranus-, and Neptune-like planets.

Since the composition of giant planets cores is weakly constrained (Guillot, 2005), we explore a large field of values of the visco-elastic parameters considering the Maxwell rheological model.

To explain the tidal dissipation observed in giant planets of our proper Solar System (eg. $Q_{\text{eff}}^{\text{Jupiter}} = (3.56 \pm 0.56) \times 10^4$ and $Q_{\text{eff}}^{\text{Saturn}} = (1.682 \pm 0.540) \times 10^3$ determined by Lainey et al. (2009,2012), all processes have to be taken into account.

Acknowledgements

This work was supported in part by the Programme National de Planétologie (CNRS/INSU), the EMERGENCE-UPMC project EME0911, and the CNRS *Physique théorique et ses interfaces* program.

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