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Coupling tidal effects and heat transfer in planetary bodies

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Abstract

Tidal dissipation plays a key role in the energy budget and in the thermal-orbital evolution of various bodies in our Solar system, including Io (e.g., [8]) and Enceladus (e.g., [11, 16]), but also in other planetary systems (e.g., [3, 1]). Some studies already modeled the thermal-orbital evolutions of Galilean moons [5], the early Moon [9] or super-Earths [13]. These pioneering studies all used parameterized, or semi-parameterized models for describing heat transfer. However, mantle convection is a strongly nonlinear process, particularly when feedbacks occur due to heterogeneous internal heating like tidal dissipation [1]. Besides, compressibility cannot be neglected for Earth-like planets, and all the more for super-Earths. Therefore, it is important to take into account all these effects to investigate the evolution of a planet-satellite system.

We have developed a numerical tool, CHEOPS-2D (**C**oupling **H**eat transfer and **E**volution of the **O**rbit of **P**lanets and of their **S**atellites in **2**-**D**imensional geometry), to self-consistently compute heat transfer, tidal dissipation and the resulting orbital evolution. Thermal regimes are computed by solving the coupled equations for the conservation of mass, momentum and energy in the infinite Prandtl number approximation, as it is usually done for planetary solid rocky or icy mantles. These equations are treated in the anelastic formalism [6] in order to take into account mantle compressiblity. The full system is solved through the spherical annulus bidimensional approach [4]. A SIMPLER-based [10] multigrid solver associated to a staggered mesh is used for Stokes' equation with a strongly temperature-dependent viscosity. The energy equation is treated by a second-order scheme for the conduction term and with a high resolution method (Superbee [12]) for advection, therefore minimizing numerical diffusion. Advance in time is performed by using a standard explicit method.

Tidal dissipation is computed for a viscoelastic body in the frequency domain. The correspondence principle [2] allows us to use complex rheologies to compute the forced spheroidal oscillations and dissipated energy. The numerical methodology is inspired by the radial functions formalism (following [14]) already used in [15, 11] for the computation of tidal dissipation in spherically-layered bodies. The resulting field is the average over longitudes, in order to include the 3D global response in the annulus geometry. Finally, the response is convolved with a temperature- and frequency-dependent dissipation factor. This results in a spatially heterogeneous dissipation field, which is included in the thermal equation as an internal heating term. A simple orbital evolution model, based on Kaula's formalism [7], is currently being implemented in the code.

After presenting the code CHEOPS-2D, we will show some of the effects induced by the compressibility of mantle materials, both for the viscous (i.e. heat transfer) and viscoelastic (i.e. tidal dissipation) rheologies on a generic planet or satellite. We will then discuss some simple but more realistic examples, focusing on 1:1 spin-orbit resonance cases.

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