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What can we learn on the interior of icy moons from libration observations?

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Abstract

We show that libration (spin rate variation) does not sensitively depend on the presence and location of a possible subsurface ocean inside icy moons. However, constraints on the material properties (shear modulus, viscosity, density) of the ice shell can be obtained from libration observations. Our libration model relies on a systematic approach where tide and libration are concurrently considered.

1. Introduction

Insights into the state of Mercury's core has been obtained by tracking the orientation of its surface against the background of distant stars [5]. Since a number of icy moons are thought to harbour a liquid subsurface ocean and/or a liquid core in their interior (e.g. [4]), similar ideas have been proposed to study their interior structure. For these moons, the major departure from a state of steady rotation is the libration due to the time-variable gravitational pull exerted by their parent body on their elongated shape. This torque alternately speeds up and slows down their spin as they move along their eccentric orbit. We evaluate the usefulness of libration as a geophysical observable by assessing its sensitivity to various interior parameters. Our method is inspired by Wahr's model for the nutations of a biaxial Earth [7].

2. Method

For illustrative purposes, we focus the discussion on the libration of Europa at orbital period. Given a model of Europa's interior, we first construct a reference configuration, then compute the tide and libration, which are infinitesimal departures from the reference configuration induced by the time-variable gravitational pull of Jupiter.

2.1. Interior model

We use a spherically symmetric interior model composed of a solid metallic core, a solid silicate mantle, a liquid water ocean (not for all models), and a solid ice shell. We have checked that the effect of compressibility and of a liquid core is small. Since we wish to evaluate the signature of ice shell thickness while satisfying the constraints imposed by Europa's observed mass and equatorial moment of inertia [1], we assume here for simplicity that water and ice have equal density. This means we can move the ocean-shell boundary without changing the total mass.

2.2. Reference configuration

The reference configuration is the tidally locked state of steady synchronous rotation on a circular orbit around Jupiter. We assume that stress relaxation has shaped Europa into a slightly triaxial body in hydrostatic equilibrium. Consequently, density, pressure and gravity potential are constant on level surfaces shaped according to hydrostatic figure theory (for instance, first-order flattenings are given by Clairaut's equation).

2.3. Tide and libration

The material displacement, as well as the incremental density, gravity, and stress resulting from the perturbation are subject to the laws of continuum mechanics, the laws of Newtonian gravitation, and the constitutive equations corresponding to the interior model. These are tensor equations in an infinite-dimensional (Hilbert) space. We use TenGSHui [6] to produce the truncated set of radial ordinary differential equations with boundary conditions suitable for numerical treatment (for instance, first-order truncation of the coupling pattern leaves 60 independent equations in solid layers and 36 independent equations in liquid layers). We then obtain libration as the radially linear part of the degree-1 order-0 toroidal displacement.

3. Results

The libration amplitude critically depends on shell shear modulus and is almost insensitive to shell thickness (Fig. 1). This point was already raised by [3]. With higher shell rigidities, we find a behaviour similar to [2]. Although information on the ocean cannot be obtained from libration observations, the ice shear modulus can be constrained (e.g. Fig. 2). Viscosity can also significantly reduce the libration amplitude (Fig. 3) and introduce a lag in the librational response.

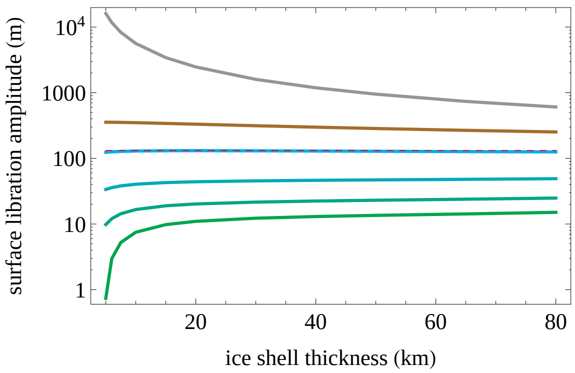

Figure 1: Libration amplitude versus shell thickness for different ice shear moduli μ_{ice}, from 0.1 GPa to 3.487 GPa to 10 GPa. Rigid shell also shown. Corresponding oceanless values in red.

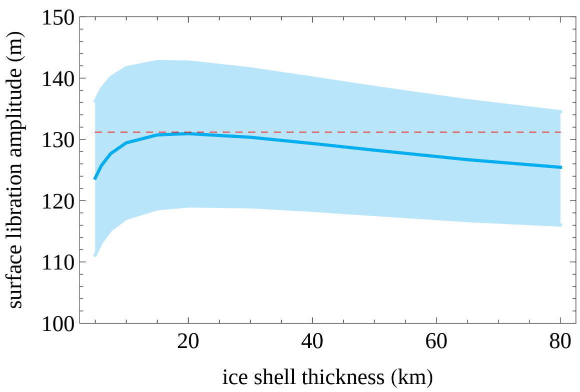

Figure 2: Same as Fig. 1 with 10% uncertainty on μ_{ice}.

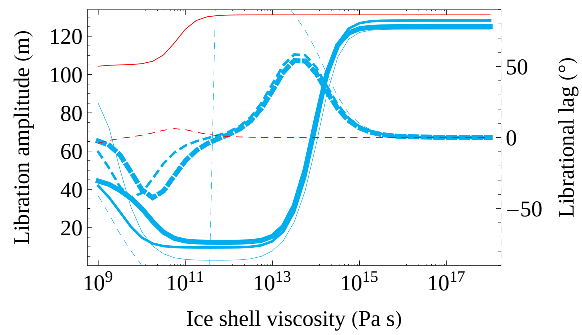

Figure 3: Libration amplitude (plain) and lag (dashed) versus shell viscosity for thin (5 km), medium (50 km), and **thick (95 km)** shell. Corresponding oceanless values in red.

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