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EUROPA'S LIBRATIONS AND ICE SHELL THICKNESS

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Abstract. The detection of an induced magnetic field in the vicinity of the Galilean satellite Europa by the Galileo mission suggests the existence of a subsurface ocean of liquid water. The thickness of the overlying ice shell provides important information on the thermal evolution of the satellite and determines the interaction between the ocean and the surface, which is fundamental for question of habitability. However, the thickness is not well known and estimates vary between several hundred of meters and tens of kilometers. Here, we investigate the use of libration observations to study the ice shell thickness and we isolate the signature of the relevant geophysical parameters. The amplitude of the libration in longitude of 3.55 days (the orbital period) depends on both the gravitational torque exerted by Jupiter on Europa and internal coupling. We investigate different scenario of internal structure of Europa and the libration of the outer ice shell is significantly different with an ocean. We include gravitational coupling between the ice shell and the solid interior, which contains most of Europas mass. We show that the presence of an ocean can increase the amplitude of libration by about 7% to 25% (147 $\pm$ 5 meters) than the purely rigid case (amplitude about 134 meters) depending mainly on the ice shell thickness. For small thickness, the amplitude of libration increases strongly due to a resonance with a normal mode. We present the impact of other parameters such as densities and internal flattenings on libration amplitude.

1 Introduction

Europa, the smallest of the Galilean satellites, has a young icy surface and probably contains an internal ocean. The existence of the liquid ocean is suggested by many observations such as geological mapping of its icy cracked surface (Pappalardo *et al.* 1998) or by detection of an induced magnetic field (Kivelson *et al.* 2000). Based on the radio-doppler tracking data of Galileo flybys, Anderson *et al.* (1998) proposed a four layers model of Europa composed of an icy shell, a liquid ocean, a solid silicate mantle and an iron core. Most of the studies of the librational motion of Europa have assumed that all layers are rigidly tied (Bills and Comstock 2003; Bills 2005; Henrard 2005). The presence of an ocean would result in differential rotation of the internal layers. As a consequence, an accurate observation of the satellite rotation will allow to obtain crucial information of its interior by confirming the existence of a liquid ocean and by determining some interior geophysical parameters such as the radius of the icy shell or density of the ocean. Recently Van Hoolst *et al.* (2007) (referred as paper 1, hereafter) proposed a new model of the spin-orbit motion of Europa where the shell and the interior rotate differentially. To study the impact of the interior structure, they built a series of models of internal structure of Europa. In paper 1, the interior models are built for ice thickness between 5 to 100 kilometers. In this paper, we extended our interior models to ice thickness between 0.1 and 5 kilometers and performed a study for an overall interval of 0.1-30 kilometers. We present and discuss the libration in longitude of 3.55 days (the orbital period) of Europa for these various models.

2 Spin-orbit Model

We use the spin-orbit model developed in paper 1. In this model, the orbit is assumed to be fixed and keplerian. We consider that the spin axis coincides with the normal to the orbit, the obliquity is then zero. The liquid ocean causes the icy shell and the interior to rotate differentially. The equations governing the rotational motion

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of Europa are the Euler-Liouville equations written separately for the shell and the interior (the core and the mantle are assumed to rotate rigidly). The longitudinal librations of Europa are driven by the gravitational attraction of the point-mass Jupiter as well as the internal gravitational coupling between the icy shell and solid interior associated with the internal flattening (see paper 1). The governing equations are then;

$$C_s\ddot{\theta}_s + \frac{3}{2}(B_s - A_s)n^2\left(\frac{a}{r}\right)^3 \sin 2(\theta_s - f) = K \sin 2(\theta_s - \theta_i), \tag{2.1}$$

$$C_i\ddot{\theta}_i + \frac{3}{2}(B_i - A_i)n^2\left(\frac{a}{r}\right)^3 \sin 2(\theta_i - f) = -K \sin 2(\theta_s - \theta_i), \tag{2.2}$$

where the subscripts s and i are for shell and interior, respectively (see paper 1). The angle θ_j (where j stands for s or i) is the angle of rotation for each layer. The principal moments of inertia of each layer are: A_j, B_j, C_j, with $A_j < B_j < C_j$. The flattening associated with the difference $B_j - A_j$ results from the effect of Joavian tides. It is calculated assuming hydrostatic equilibrium. The angle f is the true anomaly, n is the mean motion of the satellite, a its semi-major axis, and r the radius vector of the Jupiter to Europa. K is the constant of the gravitational coupling and depends on the flattening, radius and density of the different layers (paper 1):

$$K = \frac{4\pi G}{5}\frac{8\pi}{15}\left(\rho_s\beta_s + (\rho_o - \rho_s)\beta_o\right)\left[\left(\rho_\mathrm{m} - \rho_o\right)\beta_m r_m^5 + \left(\rho_\mathrm{c} - \rho_\mathrm{m}\right)\beta_c r_c^5\right], \tag{2.3}$$

where G is the gravitational constant, ρ_o the density of the ocean, ρ_s the density of the shell, ρ_m the density of the mantle, and ρ_c the mean density of the core. β_m is the equatorial geometrical flattening of the mantle. β_o and β_s are the equatorial flattenings of ocean (or more exactly the flattening of the boundary between the shell and the ocean) and the outer part of the shell, respectively. Finally, r_c and r_m are the radius of the core and of the mantle.

3 Geophysical Model

A series of models of internal structure of Europa have been developed in order to study the effect of the interior on librations. We consider Europa to be composed of four layers, namely a solid icy shell, a liquid ocean, solid mantle and a differentiated metallic core. Since the densities of the ocean and the ice shell are close, the gravity data alone is not sufficient to determine them separately and can only constraint the total height of the ice and water layers which can be as high as 160 km (Anderson *et al.* 1998). The present thickness of the icy shell of Europa remains unknown despite the various studies using different methods (see the review by Billings & Kattenhorn 2005). These methods are based on (i) thermal analysis (convection and termal equilibirum models) that give a range approximately between 10 and 30 kilometers, (ii) impact crater studies (result in smaller ice shell values, in the approximate range of 2.4-19 km), and (iii) mechanical methods (flexure, buoyancy) that provide a range roughly between 0.1-10 km. Note that an important feature of the latter method, which gives the thinnest icy shell, is that it generally estimates only the thickness of the brittle or the elastic portion of the total icy shell, and not the overall thickness. Williams and Greeley (1998) propose a buoyancy model where the ice thickness is of the order of 0.2-3 kilometer (and elastic part is estimated to be 100-500 meters). This model suggests that the ice could be regionally thin at the time the features formed. Consequenctly, the resulting overall range of the total ice shell thickness, suggested by these methods, is between 0.1 and 30 kilometers.

Europa being a rather small planet, models with layers of uniform density are a very good first-order approximation. The densities of the ocean (ρ_o) and ice shell (ρ_s) are 1000 kg.m^{-3} if they are composed of pure water but can be as high as 1200 kg.m^{-3} (Whar et al 2006) or as low as 800 kg.m^{-3} (Anderson et al 1998) depending on the type and amount materials mixed with pure ice, and on the porosity of the ice. The density of the metallic core (ρ_c) depends on the amount of light elements such as sulfur mixed with pure iron ($5150 < \rho_c < 8000$ kg.m^{-3}). The densities of the typical rocks of the mantle are expected to be within the range $3000 < \rho_m < 4450$ kg.m^{-3} (Anderson *et al.* 1998).

To determine a set of realistic geophysical parameters (densities and radius for each layers), we used three conservative equations concerning the mass, the radius and the moment of inertia for each models. The interior structure of a given satellite with N layers with constant density are constrained by the following three equations:

$$M = \frac{4}{3}\pi\sum_1^N \rho_i(r_i^3 - r_{i-1}^3) \tag{3.1}$$

$$R = \sum_{1}^{N} (r_i - r_{i-1}) \tag{3.2}$$

$$I = \frac{8}{15}\pi \sum_{1}^{N} \rho_i (r_i^5 - r_{i-1}^5) \tag{3.3}$$

To solve this system of equations, we fixed: the densities of ice and ocean to 800, 1000 and 1200 kg.m^{-3} (with the condition $\rho_o > \rho_s$); the radius of the mantle to two values 1400 and 1450 km; the radius of the core from 100 to 700 kilometer by intervall of 100 kilometer and thickness of the icy layer by steps of 100 meters between 0.5 and 1.5 kilometers, and then steps of 1 kilometer until 5 kilometer. The resulting densities of the core and the mantle are in the bounded intervall of $5150 < \rho_c < 8000$ kg.m^{-3} and $3000 < \rho_m < 4450$ kg.m^{-3}, respectively. We have 371 models satisfying the mass, radius and inertia constrains.

4 Libration

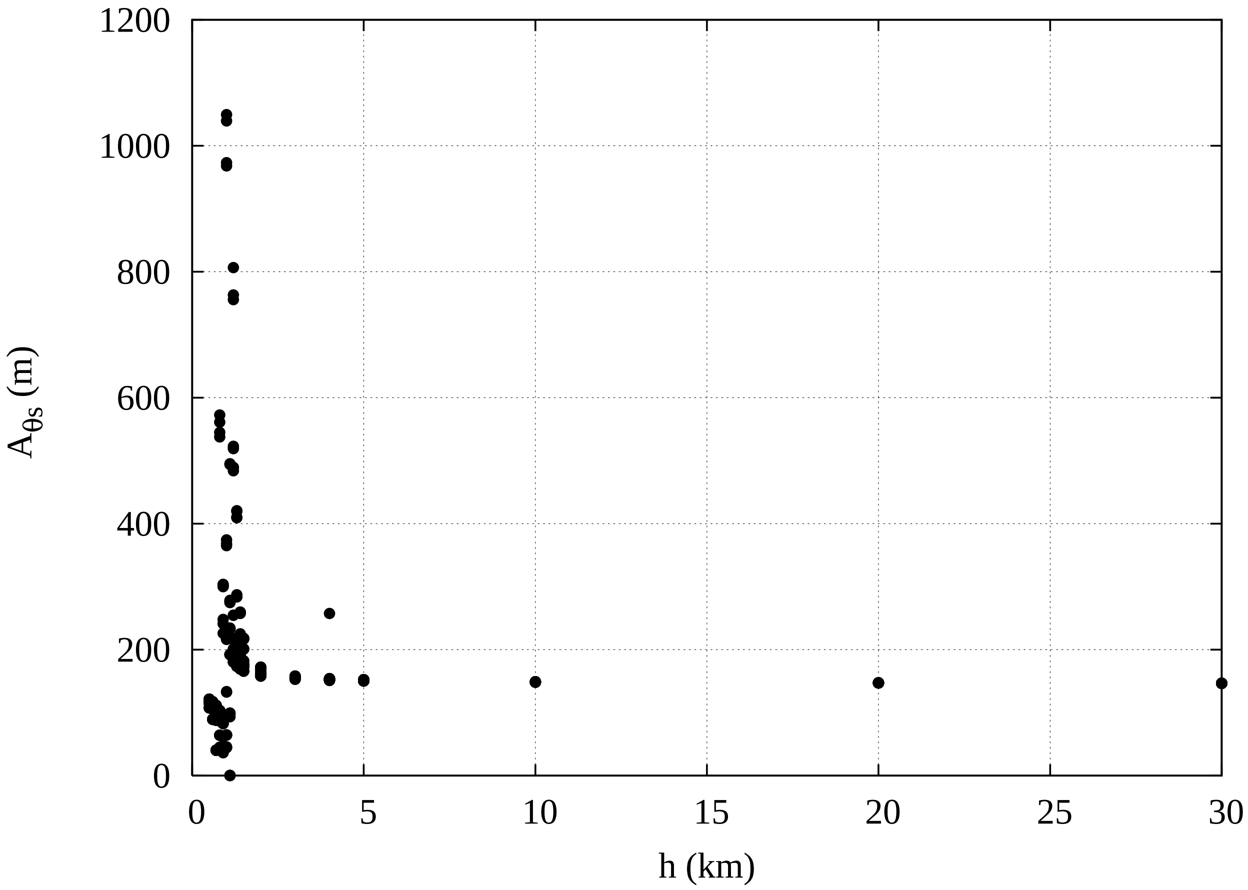

Fig. 1. Amplitude of the shell libration as a function of the thickness h of the icy shell.

We calculate the dynamical behavior of the rotational motion (Eqs. **??** and **??**) of a differentiated Europa for the large set of interior structure models defined in the previous Section. We concentrate our studies on the libration in longitude of 3.55 days, the orbital period of Europa. This libration is due to the non-zero eccentricity of satellite's orbit that generates a time-variable torque and Europa's long axis librates about the Jupiter-Europa direction, in its equatorial plane. We find that the amplitude of the libration depends mainly on the icy shell thickness. We distinguish two behaviors in Figure **??**. First, the libration amplitude shows a linear behavior characterized by an amplitude of 147 ± 5 meters for large ice shell thicknesses. This amplitude is 7 to 25% higher than for the rigid case (paper 1). So it is possible to obtain a strong constraint on the liquid ocean by observing accurately the libration amplitude of Europa. Second, the libration has an exponential behavior for icy shell smaller than 3 kilometers. The maximum amplitude of 1200 meters is obtained for an ice thickness of 0.8 kilometer. The alteration in the dynamics of the problem is due to a resonance with an internal normal mode (forthcoming paper). The main parameter that controls the resonance is $2K/C_s$, which represents the magnitude of the internal coupling (Eq. **??** the right-hand side term). Figure **??** shows how for thin ice models, the $2K/C_s$ parameter drives the proper period P_1 to be equal to the orbital period (3.55 days) and consequently generate a resonance. In addition, Figure **??** presents the relative difference $\alpha = (\sigma_1^2 - 2K/C_s)/\sigma_1^2)$ where σ_1 is the proper frequency equal to $\sigma_1 = 2\pi/P_1$. For models of thin ice shell, the relative difference is close to zero and the departure is due to the approximation used in K/C_s.

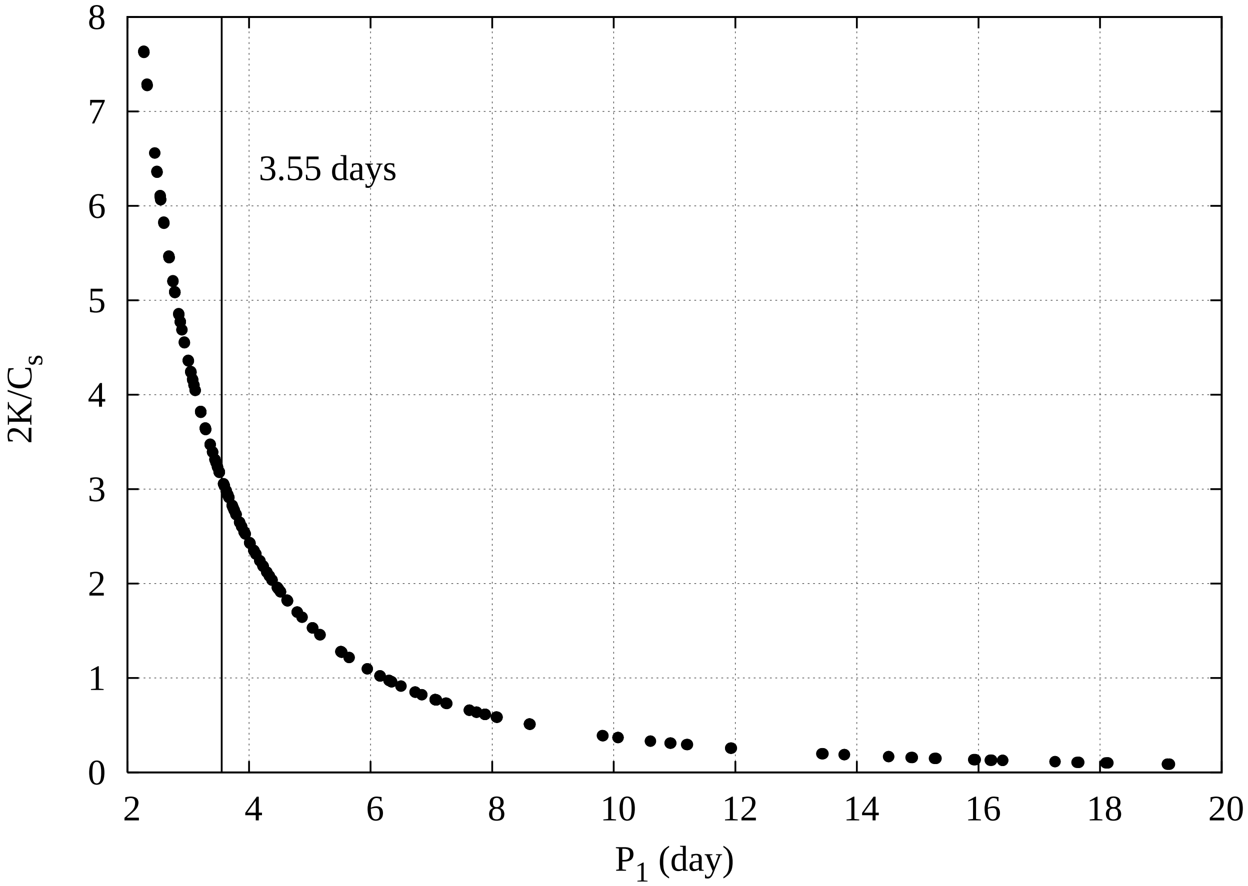

Fig. 2. Resonance criterium $2K/C_s$ as function of the period of the internal proper mode.

For thin shell, K/C_s can be approximated as:

$$\frac{K}{C_s} = \frac{4\pi G}{25} \frac{\rho_o}{\rho_s} \frac{\beta_o \beta_c \left[15/(8\pi)I - \rho_o R^5\right]}{hR^4} \tag{4.1}$$

where we have used the conservation of the total inertia defined in Eq **??** and equal to:

$$I = \frac{8\pi}{15}(\rho_c r_c^5 + \rho_m r_m^5 - \rho_m r_c^5 + \rho_o r_o^5 - \rho_o r_m^5 + \rho_s r_s^5 - \rho_s r_o^5) \tag{4.2}$$

Equation **??** shows how densities play a role in the value of the K/C_s. Especially, the ratio ρ_o/ρ_s is proportional to K/C_s and modifies the location of the resonance with respect to the ice thickness h_r. According the choosen values of the densities of ρ_o and ρ_s, we have six possible combination and 4 values for the ratio

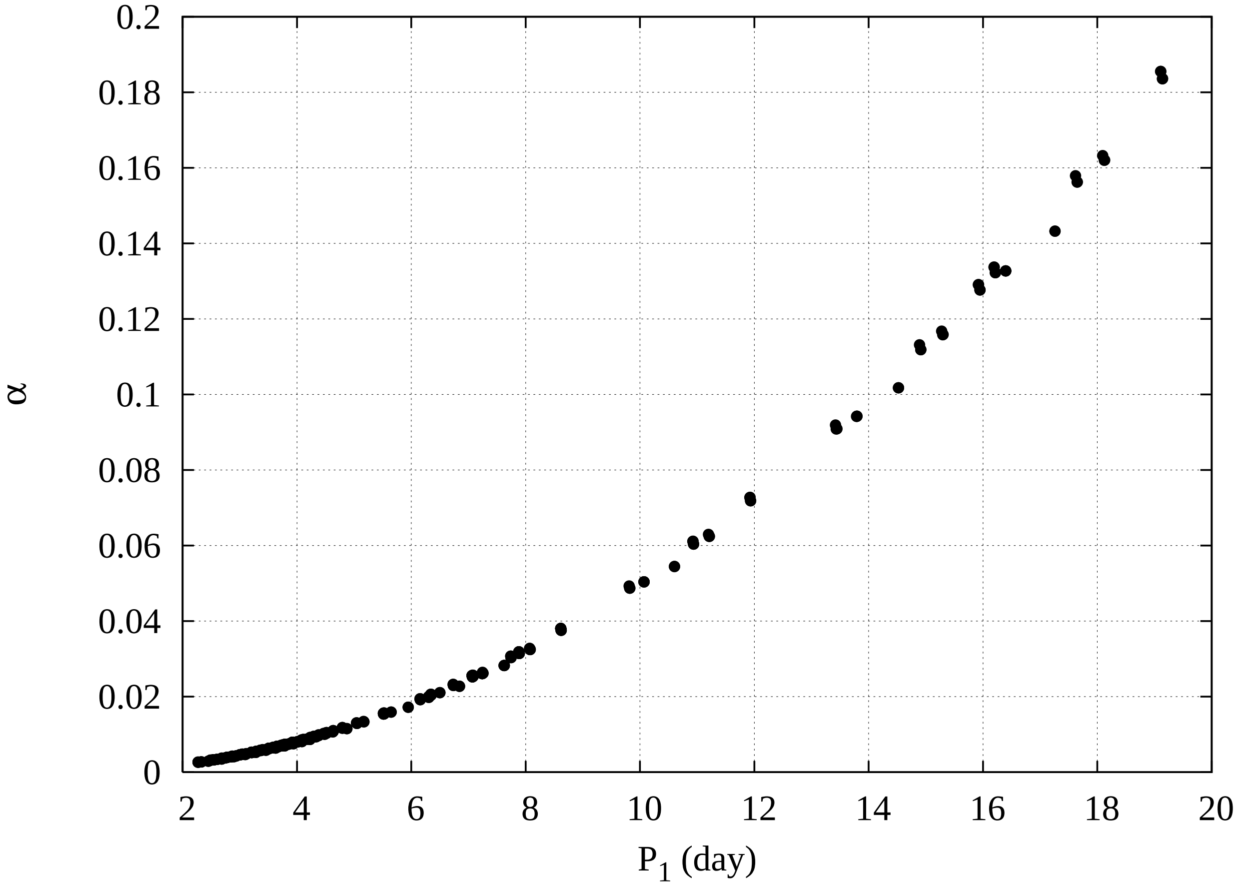

Fig. 3. Relative difference $\alpha = (\sigma_1^2 - 2K/C_s)/\sigma_1^2)$ as function of the period of the internal proper mode.

ρ_o/ρ_s: 1.5, 1.25, 1.2, and 1. For the first three cases, the resonant thickness h_r is located at: 1.1, 1.2, 1.0, respectively. The ratio $\rho_o/\rho_s = 1$ presents three values, 0.95, 0.85 and 0.75. This is due to the value of ocean's density containing in the numerator of K/C_s in Eq.(**??**). In addition, the flattenings β_o and β_c play a weak role. The impact of the flattenings is weak because their values are small (around 1.5 10^{-3}) and their variation for different interior models is also small (variation of 3 10^{-4} for β_o).

5 Conclusion

We built a series of interior models and we calculate the amplitude of the forced libration in longitude of 3.55 days (the orbital period) for various models. Physically, the amplitude of libration depends not only on the gravitational torque exerted by Jupiter but also on Europa's shape and internal structure. In our dynamical model, we include gravitational coupling between the icy shell and the solid interior, which contains most of Europa's mass. We show that the presence of an ocean can increase the amplitude of libration by about 7% to 25%, depending mainly on the thickness of the icy shell. This range of increase indicates the possibility to discriminate between models of internal structure by using accurate libration measurements. In addition, for small thickness, the amplitude of libration can even be larger due to a resonance with a normal mode. The second main parameter that governs the amplitude of libration is the ratio of the ocean to the shell density.

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