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The influence of internal global liquid layers on the obligquity of the Galilean Satellites

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1. Introduction

The Galilean satellites (Io, Europa, Ganymede and Callisto) are synchronous satellites assumed to be locked in the Cassini state, an equilibrium state for the orientation of the rotation axis, first described for the Moon. The obliquity, the angle between the rotation axis and the normal to the orbit, of the Galilean satellites has not been measured yet but they are known to be small.

The orientation of the rotation axis of each of these satellite depends on the orbital precession, which is known from the ephemerides [4], and on the internal structure, which is currently mainly constrained by the second degree gravity field coefficients [5]. However, the gravity coefficients alone do not indicate whether the satellites harbour internal global liquid layers and they do not provide accurate constraints on the thickness of the layers (for instance, the ice shell thickness of Europa is poorly constrained). Therefore future measurements of the obliquity could provide additional constrains on the internal structure of the Galilean satellites.

The simplest model for the Cassini state is for an entirely solid satellite with a constant precession rate. A straightforward extension is to consider a non-uniform orbital precession, as in [3]. Recently, we have taken into account the effect of an internal global liquid layer for Titan [2]. Here we apply these two extensions to the Galilean satellites, in order to study the effect of a global liquid layer and to assess expected improvements on the internal structure from future obliquity measurements.

2. Multi-frequency solid case

Following [3], we solve the angular momentum equation for each satellite. The precession of the rotation axis is forced by the gravitational torque between the central planet, considered as a point mass, and the satellite, which is flattened and has its long symmetry axis oriented toward the planet. Because the orbit precesses around a mean position (known as the Laplace plane), this torque never vanishes. The forced precession also depends on a free mode, with a frequency ω_f that can be obtained by averaging the torque, or equivalently by setting to zero the inclination of the orbital plane with respect to the Laplace plane.

The frequency ω_f is inversely proportional to the polar moment of inertia C and linearly proportional to the difference $(C - A)$ with A, the smallest principal moment of inertia of the satellite. Therefore the free mode period T_f can be estimated (Tab.1) from the second degree gravity field coefficients given in [5].

Each forcing frequency $\dot{\Omega}_j$ and associated inclination i_j of the orbital precession leads to an obliquity amplitude ε_j given by

$$\varepsilon_j = -\frac{i_j \dot{\Omega}_j}{\omega_f + \dot{\Omega}_j}. \tag{1}$$

Because of the different forcing frequencies, the obliquity ε changes with time (the minimal and maximal values for the four Galilean satellites are given in Tab.1). For Europa, the main precession rate dominates the solution and the obliquity remains close to its mean value. For the other three satellites, the solution is dominated by a combination of the main precession rate Ω_1, with period T_1, and another precession frequency, Ω_{res} with period, T_{res} (see [4]), which is close enough to the free mode frequency to produce a significant resonant amplification. Therefore, the obliquity oscillates between two very different values.

3. Liquid layer case

As in [2], we take into account the gravitational and pressure torques arising between the different layers, to compute the solution for the obliquity amplitudes of the surface layer, $\varepsilon_{j,s}$, at each forcing frequency $\dot{\Omega}_j$.

For the four satellites, we consider the same internal structure models as in [1], where Io has a fully liquid core, Europa has a liquid water ocean between an ice-shell and a rocky mantle and Ganymede and Callisto have a liquid water ocean beneath two ice layers. The obliquity of the surface layer $\varepsilon_{1,s}$ depends on its thickness h_s (see e.g. Fig. 1 for Europa) but also on other internal structure parameters, such as the radius of the solid interior. For Europa, there is no significant resonant amplification and the shell obliquity remains close to $\varepsilon_{1,s}$. For Ganymede, Callisto, and Io, resonant amplifications with one or two free modes can occur. For Ganymede and Callisto the obliquity can reach high values (up to a few degrees) for specific values of the ice shell thickness.

4. Summary and Conclusions

For Europa, obliquity measurements could strengthen the evidence for the presence of an internal ocean, because the obliquiy values are different in the solid ($\simeq 0.055°$) and the ocean (between $0.033°$ and $0.044°$) cases. On the other hand, the obliquity only weakly depends on the shell thickness so that it will be difficult to constrain the ice shell thickness from the obliquity.

For Ganymede, Callisto and Io, the obliquity values of the solid case and of the liquid layer case can be the same. Therefore obliquity measurements would not necessarily indicate the presence of a liquid ocean, unless the obliquity is of the order of a few degrees for Ganymede or Callisto.

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Table 1: Main precession period (T_1, in years); free mode period (T_f), resonant precession period (T_{res}), and minimal and maximal obliquity (ε_{min} and ε_{max} in 10^{-3} deg) for the solid case; free modes period (T_+ and T_-), obliquity amplitude of the shell corresponding to the main precession period ($\varepsilon_{1,s}$), and possibility of resonance for the liquid layer case.

	Io	Europa	Ganymede	Callisto
		Orbital precession		
T_1	-7.43	-30.2	-137.7	-562.9
		Solid case		
T_f	0.41	3.2	20.0	203.1
T_{res}	-0.68	–	-30.2	-137.7
ε_{min}	1.3	51.6	0	46.3
ε_{max}	2.9	58.5	67.2	244.2
		Liquid layer case		
T_+	$0.38 - 0.41$	$3.1 - 3.7$	$1.0 - 30.9$	$181.7 - 233.7$
T_-	–	$0.01 - 0.34$	$0.3 - 6.3$	$4.0 - 58.4$
$\varepsilon_{1,s}$	$2.0 - 2.1$	$33.0 - 44.4$	$1.2 - 20.5$	$53.4 - 132.5$
Res?	Yes	No	Yes	Yes

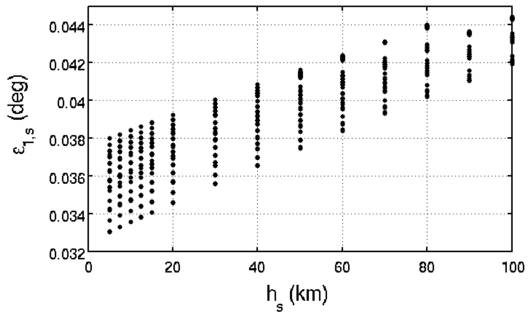

Figure 1: Obliquity amplitude of the shell, $\varepsilon_{1,s}$ (in deg), corresponding to the main forcing frequency, $\dot{\Omega}_1$, as a function of the shell thickness h_s (in km), for a representative range of possible internal structure models of Europa constrained by the second degree gravity field.