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Slichter modes of large icy satellites

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ABSTRACT

Because of the presence of an ocean below the ice shell of icy satellites such as Europa, Callisto, Ganymede and Titan the solid interior of these satellites can be displaced with respect to the ice shell, similarly to the translational oscillation of the inner core of the Earth called the Slichter modes of the Earth.

We construct a set of interior structure models of Europa, Callisto, Ganymede and Titan satisfying the observed mass, radius and moment of inertia and study the properties of the Slichter mode for these models. The periods obtained range from a few hours to a few tens of hours depending mainly on the ocean thickness. Ganymede has two Slichter modes since it is thought to have a liquid outer core besides a global subsurface ocean. The second Slichter mode describes essentially the oscillation of the solid inner core inside the liquid outer core and its period is determined principally by the thickness of the outer core. We study the possible observation of these modes with a lander on the surface or a spacecraft in orbit about Europa, Callisto, Ganymede or Titan. We show that an impactor with a radius of at least a few kilometers to a few tens of kilometers could excite the Slichter modes to a level observable by a lander. Such impacts occur on average once in >30 My for Europa, once in >70 My for Callisto, once in >40 My for Ganymede and once in >0.4 Gy for Titan. Observation of the Slichter mode would allow constraining the thickness of the ocean.

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1. Introduction

The detection by the Galileo spacecraft of an induced magnetic field in the vicinity of Europa, Callisto and Ganymede provides strong evidence of the presence of a salinic ocean below the ice shell in these satellites (Khurana et al., 1998; Kivelson et al., 1998, 2000). Also Titan is thought to have a global subsurface ocean. The tidal Love number of Titan, recently obtained by Iess et al. (2012), is much larger than for an entirely solid Titan, and is evidence of the presence of a global subsurface ocean for this satellite. The presence of an ocean also leads to a better consistency between the moment of inertia and the obliquity of Titan (Baland et al., 2011). Moreover, the measurements of low frequency waves and atmospheric conductivity in the atmosphere of Titan by the Huygens probe seem to indicate the presence of a subsurface conducting layer below the surface (Béguin et al., 2010).

Because of the existence of a liquid layer in Europa, Ganymede, Callisto and Titan the solid interior of these icy satellites can move with respect to the ice shell. In particular, it can perform translational oscillations with respect to the ice shell similarly to the translational oscillations of the inner core of the Earth with respect to its mantle. For the Earth, these translational oscillations are called Slichter modes as these modes were theoretically introduced for the Earth by Slichter (1961). They have, however, not yet been observed unambiguously (e.g. Smylie, 1992; Jensen et al., 1995; Hinderer et al., 1995; Courtier et al., 2000; Kroner et al., 2004; Sun et al., 2006; Rosat et al., 2007; Xu et al., 2010). Due to the rotation of the planet and to its ellipsoidal shape, the Slichter mode period is decomposed into a triplet of periods. The three Slichter modes of the Earth describe translations of the inner core in three perpendicular directions with eigenperiods of between 4 h and 6 h (e.g. Rogister, 2003). The center of mass of the inner core oscillates around the planet's center of mass, which is unaffected by the Slichter modes because of a small compensating translation of the mantle.

The first analytical study to determine the period of the Slichter modes of the Earth was performed by Busse (1974). Busse considered an Earth divided into a static rigid mantle, a homogeneous fluid outer core and a rigid inner core, and assumed that no mantle motion is associated with the Slichter modes. Grinfeld and Wisdom (2005) developed a method for a model of the Earth or Mercury consisting of three homogeneous layers that takes into account the motion of the mantle. In that method, the Slichter mode period is obtained by using the equation of conservation of momentum of the planet and Newton's second law for the inner core. More

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recently, Escapa and Fukushima (2011) obtained the same expression for the Slichter mode period as Grinfeld and Wisdom, 2005 by using a Lagrangian method. They calculated the Slichter mode period of some medium-sized icy bodies as Europa, Titania and Pluto.

Here, we study Slichter modes of large icy satellites such as Europa, Titan, Callisto or Ganymede by using a generalization (Coyette et al., 2012) of the method developed by Grinfeld and Wisdom (2005) for planetary interiors consisting of more than three layers. The motivation for this study is that the subsurface oceans of icy satellites are expected to be thin and close to the surface, even if their distance to the surface or their thickness are not well constrained, so that the solid interior is very large in comparison with the thickness of the shell and the ocean. From the conservation of momentum of the satellite, it then follows that a small motion of the large solid interior leads to a larger motion of the shell. As a result, sufficiently large excitation of the Slichter modes to allow detection of the associated shell motion might require a less energetic excitation source such as an impact. The Slichter modes of icy satellites are therefore expected to be more likely detectable than the Slichter modes of Mercury by future missions involving a lander on these icy satellites.

The plan of the paper is as follow. We first develop interior models of Europa, Ganymede, Callisto and Titan satisfying the observed mass, radius and moment of inertia (Section 2). We then calculate and study the properties of the Slichter mode for these models in Section 3. Ganymede is treated differently than the other satellites because it is thought to have two global liquid layers, the outer iron core and the subsurface ocean. We can therefore have two translational motions: the translational oscillation of the inner core with respect to the mantle and the translational oscillation of the interior with respect to the ice shell. Finally, the possible excitation and detection of the Slichter modes by a lander or a spacecraft in orbit about these satellites is investigated in Section 4.

2. Interior models

2.1. Method

We consider icy satellites as spherical bodies consisting of a finite number of homogeneous and spherical layers. The spherical approximation implies that there is no preferential direction for the Slichter modes and that the theoretical three different Slichter modes in the three orthogonal directions are degenerate.

The interior models of icy satellites satisfying the observed mass, radius and moment of inertia are constructed using a random process. We proceed as follows. After selection of the number of layers N of the interior structure of the body, the radius R_k and density ρ_k of each layer are chosen randomly in a certain range of possible values based on the composition of the layer considered (see Table 1). We consider the density of a solid or liquid core to be within the range 5150–8000 kg/m^3, corresponding to the range of densities between an iron sulfur mixture at the eutectic composition and pure iron (Anderson et al., 1998). The density of the ice–rock interior of Callisto is considered to be within the range 2100–2500 kg/m^3 in order to take into account a wide range of ice concentration in the interior (Anderson et al., 2001). The density of a rock mantle is considered in the range 3000–3800 kg/m^3 which covers the range of densities from the density of hydrated silicate (Anderson et al., 1998) to the density of a silicate-metal mixture (Anderson et al., 1996). We take densities of the subsurface ocean within the range 800–1200 kg/m^3 in order to take into account possible impurities as ammonia or sulfur inside the ocean (Iess et al., 2012). For Titan, we consider ocean densities up to 1400 kg/m^3 in order to account for the large k_2 Love number recently determined by Iess et al. (2012). The density of the core of Titan is taken within the range 2400–3700 kg/m^3, corresponding to the range of densities between carbonaceous chondrites and ordinary chrondrites (Castillo-Rogez and Lunine, 2010), and the density of its mantle within the range 1000–2900 kg/m^3 (from a pure ice–mantle to a mantle enriched in hydrate silicates as antigorite (Castillo-Rogez and Lunine, 2010; Fortes, 2012)). The density of the ice shell is also within the range 800–1200 kg/m^3 in order to take into account possible impurities inside the ice or porosity of the ice. We also impose the layer densities to decrease with increasing layer radii, so that the ice shell density will always be smaller than the ocean density. The radius of the last layer is fixed to the mean radius R of the body considered (see Table 2). The mean density

$$\bar{\rho} = \rho_N + \sum_{k=1}^{N-1} (\rho_k - \rho_{k+1}) \left(\frac{R_k}{R}\right)^3 \tag{1}$$

and mean moment of inertia

$$\frac{I}{MR^2} = \frac{2}{5}\left[\frac{\rho_N}{\bar{\rho}} + \sum_{k=1}^{N-1} \frac{\rho_k - \rho_{k+1}}{\bar{\rho}} \left(\frac{R_k}{R}\right)^5\right] \tag{2}$$

of all the models are then calculated and the models retained are those for which the mean density and mean moment of inertia fall within the error range of the observed values (see Table 2).

Using this methodology, we constructed 100.000 interior structure models of Europa, Titan, Callisto and Ganymede. We have chosen this number in order to have a sufficiently large number of interior structure models for obtaining a dense representation in parameter space and to avoid excessively long computation time. Taking into account more interior structure models will only change layers radii obtained by less than 1 km.

2.2. Europa

Galileo gravity measurements of the mean moment of inertia and mean density of Europa revealed a differentiated structure consisting of a metallic core, a rock mantle and a water ice outer shell (Anderson et al., 1998). A mixed interior made of dense silicate and metal is also consistent with the measurements but is unlikely as the temperature rise due to radiogenic heating of silicates is high enough to force differentiation of Europa (Anderson et al., 1998). Furthermore, the detection of an induced magnetic field (Khurana et al., 1998; Kivelson et al., 2000; Schilling et al., 2007) shows that a conducting layer is present near the surface of Europa, which implies that part of the ice layer is molten and that Europa has a salty subsurface ocean. The presence of a subsurface ocean is also suggested by models of formation of ridges, chaos terrains and other surface features on Europa (Schubert et al., 2009).

Table 1
Density ranges used for the interior models.

Layer	From (kg/m^3)	To (kg/m^3)
Core (solid or fluid)	5150	8000
Callisto ice/rock interior	2100	2500
Titan ice/rock interior	2400	3700
Rock mantle	3000	3800
Ice mantle	1000	1400
Titan ice/rock mantle	1000	2900
Ocean	800	1200 (1400[a])
Ice shell	800	1200

[a] For Titan Iess et al. (2012).

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