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Reorientation of the rotation axis of triaxial viscoelastic icy moons: Europa and Titan

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Abstract

We provide an analysis of the rotational response of triaxial viscoelastic icy moons, focusing on the free rotational behavior of Europa and Titan. In a similar way as for terrestrial planets, the rotational behavior of icy moons is dominated by a secular shift of the pole and the periodic Chandler wobble. However, unlike terrestrial planets, the Chandler wobble of icy moons is associated with the viscoelastic response of the layers located below the ocean. The fast relaxation of low-viscous ice layers induces additional wobble frequencies. However, these wobbles are generally weak compared to the strength of the main Chandler wobble.

1. Introduction

Mass displacements in the interior and the atmosphere of planetary bodies induce changes in the moments and products of inertia of a body, which in turn lead to the reorientation of the rotation axis with respect to the surface of the body [3, 4, 6, 7]. Although the reorientation of the rotation axis is often regarded as a long-term secular shift or true polar wander [4, 6, 8], the motion of the pole also includes periodic wobbles on a smaller time scale [7]. One of these wobbles is the so-called Chandler wobble, which is essentially the Eulerian free precession of the planetary body.

Reorientation of the polar axis of icy moons could be a source of large surface stresses, depending on the rheological properties of the icy surface and the time scale of the reorientation. On Europa, $\sim 80^\circ$ of true polar wander have been suggested to explain the formation of sets of small-circle depressions on the surface [8], whereas [5] suggests that the current location of the geologically active south polar region of Enceladus can be explained by true polar wander as a consequence of a low-density diapir. On the other hand, the effect of wobbles on the formation of surface features has not been yet studied as the amplitude of free wobbles might have decayed in the absence of geophysical forcing [7]. Since it is uncertain whether free wobbles are currently maintained by some geophysical process, we aim here to model both the Chandler wobble and the secular shift of the pole of viscoelastic icy moons with a subsurface ocean.

2. Modeling

Due to rotational and tidal deformation, the figure of large icy satellites in our Solar System is best described by a triaxial ellipsoid with equatorial moments of inertia A and B ($B > A$), and polar moment of inertia C. The introduction of triaxiality and the adjustment of the tidal bulge into the analytical model for the rotation of ellipsoidal planets [7] leads to the following expressions for the x- and y-components of the linearized Liouville equation for the entire satellite:

$$\frac{A}{(C-B)\Omega}\dot{m}_x + \left(1 - \frac{k_2(t)}{k_f}\right) m_y = \phi_y, \quad (1)$$

$$\frac{B}{(C-A)\Omega}\dot{m}_y - \left(1 - \frac{k_2(t)}{k_f}\right) m_x = -\phi_x, \quad (2)$$

where $k_2(t)$ is the degree-2 time-variable tidal Love number related to the geopotential perturbation, and k_f is the degree-2 secular or fluid Love number. Furthermore, the variables $m_x\Omega$ and $m_y\Omega$ describe the small deviations in the x- and y-components of the angular velocity vector ω, where the x-axis coincides with the tidal axis and the y-axis is orthogonal to both the tidal and the spin axis z in a right-handed coordinate system. The functions ϕ_x and ϕ_y are defined as the excitation functions and include the contribution of loading, relative motions and external torques on the rotational dynamics of the body.

The effect of viscoelasticity enters the problem through the Love number $k_2(t)$, which has been computed for several interior models of Europa and Titan using the method described in [2]. The interior of Europa will be assumed to consist of five homogeneous incompressible layers: a metallic core, a silicate mantle, a liquid ocean, a low-viscous ice layer (asthenosphere) and a high-viscous outer layer of ice (lithosphere). The mantle and both ice layers are modeled as Maxwell viscoelastic layers, whereas the core and the ocean are modeled as inviscid fluid layers. In the case of Titan we add a high pressure (HP) ice layer between the mantle and the ocean, and we consider that Titan's rocky interior is not differentiated into a metallic core and a silicate mantle, as suggested by [1].

3. Reorientation of the pole

We assume that the excitation functions ϕ_x and ϕ_y in equations 1 and 2 do not depend on the deviations m_x and m_y or that their dependence on the deviations is negligibly small. This assumption, although with some limitations, allows us to determine the rotational eigenmodes of a given planetary interior from equations 1 and 2 following an approach similar to [7]. The obtained rotational modes a_j are complex numbers, in which the real part refers to the inverse rotational relaxation times and the imaginary part refers to the frequency of free wobbles.

After determination of the rotational eigenmodes of Jovian moon Europa we observe that only the modes M_3 (relaxation of mantle/ocean boundary) and T_2 (due to viscosity contrast in the ice shell) have a non-negligible imaginary part, thereby implying the theoretical existence of two wobble frequencies. The Chandler wobble, which is associated with the mantle mode M_3, has a period of about 12.7 years depending on the properties of the rocky interior and is by far the strongest rotational mode. On the other hand, the wobble of the ice shell has a period of about 200 years for thick ice shells to more than 2000 years for very thin ice shells. In all cases, the strength of this last wobble is negligibly small when compared to the strengths of the main Chandler wobble or even the secular term.

In Titan's case, an additional third wobble frequency appears when the relaxation of the HP-ice/ocean boundary (M_3 mode) is faster than the relaxation of the core/HP-ice boundary (C_0 mode). If the opposite holds, the wobble of the HP-ice layer is "absorbed" by the main Chandler wobble and hence only two wobble frequencies are found. In both cases, the rotational response is dominated by the Chandler wobble frequency and the secular shift as they are significantly stronger than the other (slower) wobbles. Furthermore, it is important to notice is that Titan's Chandler wobble is very slow (period ~ 1000 years), especially when three wobble frequencies are present in the response (period ~ 1300 years).

Finally, we see that the long-term rotational behavior of Europa differs from the one of Titan. Mainly due to its fast rotation and large tidal deformation, Europa's pole is more prone to secular wander on the long-term while wobbling on short time scales. On the other hand, the long-term reorientation of Titan's pole is more prone to be affected by its Chandler wobble. These results are in agreement with the theoretical discussion presented in [9] for terrestrial planets.

Acknowledgements

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