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The diurnal libration and interior structure of Enceladus

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ABSTRACT

We determine constraints on the ice shell and ocean of Enceladus from the observed libration at orbital period by assessing the effects of uncertainties in the size, density, rigidity, and viscosity of the internal layers and of the non-hydrostatic structure on the libration. The observed libration amplitude implies that the average thickness of the ice shell is between 14 km and 26 km and that the ocean is 21 km to 67 km thick.

1. Introduction

The gravitational force exerted by Saturn on Enceladus raises tides that are thought to be responsible for the observed geyser activity at the south pole of Enceladus (Porco, 2006; Spencer et al., 2006). Although the precise cause and mechanism of cryovolcanism is not well understood, the variation of the plume intensity and its correlation with the orbital position of Enceladus is strongly indicative of a tidal mechanism driving the geysers (Hedman et al., 2013; Hurford et al., 2007; Porco et al., 2014). The detection of sodium-salt-rich ice grains emitted from the plume suggests that the plume is connected to a subsurface salty water reservoir in contact with silicate rocks (Hsu et al., 2015; Postberg et al., 2009; 2011). The subsurface ocean might exist only beneath the region of activity near to the south polar region (Tobie et al., 2008), although recent gravity and topography data cannot distinguish between a local and a global subsurface ocean (Iess et al., 2014; McKinnon, 2015).

The gravitational interaction with Saturn also periodically changes the rotation of Enceladus, which might be co-responsible for the observed variations in plume activity (Nimmo et al., 2014a). The diurnal librations of Enceladus, representing the variations at orbital period in the rotation angle with respect to the steady change for a constant rotation rate, have recently been accurately determined by a detailed analysis of images of Enceladus taken by the Cassini imaging system (Thomas et al., 2016). Although the libration amplitude of 0.120 ± 0.014 degree (2σ) is too small for diurnal libration to play an important role in the variation in tidal stress needed to explain the plume variability (Nimmo et al., 2014b), it provides unique direct insight into the interior structure through the sensitivity of libration to the existence and certain characteristics of a liquid global internal layer. Thomas et al. (2016) showed that the libration amplitude proves the existence of a global ocean beneath an icy surface.

Here we perform an extended study of the diurnal librations of Enceladus in order to determine the best constraints on ice shell and ocean, in particular on the mean thickness of the ice shell. We study the effect of the rigidity and visco-elastic behavior of the ice shell on the librations and assess the uncertainty they introduce in the interpretation of the libration amplitude in terms of the depth to the ocean. We first use an approach in which Enceladus is considered to be in hydrostatic equilibrium. Next, we use the observed topography and gravitational field of Enceladus to develop non-hydrostatic models of the interior structure. Two different end-member assumptions are considered for the shape of the interfaces between the core, the ocean and the ice shell. By means of those models, we then investigate the librations for non-hydrostatic models of Enceladus that are consistent with gravity and topography data (Iess et al., 2014; Nimmo et al., 2011). We show that although many uncertainties remain about Enceladus' interior structure, the mean thickness of the ice shell can be well constrained by the libration amplitude.

2. Libration without global subsurface ocean

The gravitational torque of Saturn exerted on Enceladus forces the rotation of Enceladus to vary slightly during the orbital motion.

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Since Enceladus is likely in a 1:1 spin-orbit resonance, the torque will have periods commensurate with the orbital period, which is equal to the rotation period of Enceladus, and will force librations with the same periods. In addition, Enceladus has librations with longer periods related to the variations in the torque associated with periodic perturbations of the orbit of Enceladus due to Dione. The two main long-period librations have periods of about 4 and 11 years (Rambaux et al., 2010). Since the observations of Thomas et al. (2016) have a period equal to the orbital period, we neglect those long-period librations here.

The polar gravitational torque leading to variations in the rotation rate can be expressed in terms of the external gravitational field coefficients of Enceladus (e.g. Dehant and Mathews, 2015), which have been determined up to degree 3 by Iess et al. (2014). Six gravitational coefficients have been estimated, all five of degree two (J_2, C_{21}, S_{21}, C_{22}, S_{22}) and the zonal component of degree three (J_3), but only the torque on C_{22} needs to be taken into account.The polar torque does not depend on the zonal gravitational coefficients because of the geometric symmetry of the zonal harmonics with respect to the polar axis. The contributions of the tesseral coefficients to the polar torque can be neglected since they are approximately proportional to the very small obliquity of Enceladus. The obliquity is not known, but theoretical calculations predict values below 10^{-5} radians (Baland et al., 2014). The S_{22} sectorial coefficient is about 70 times smaller than the C_{22} coefficient (Iess et al., 2014), and its contribution to the gravitational torque is therefore also neglected.

The torque forces libration at the orbital period and at the subharmonic periods of it. The latter will also be neglected as the torque at the nth subharmonic is smaller than that at orbital period by a factor e^n (e.g. Van Hoolst et al., 2008), where $e = 0.0047$ is the orbital eccentricity (Thomas et al., 2016). We introduce the libration angle $\gamma = \phi - M$, where ϕ is the rotation angle of Enceladus and M the mean anomaly. When the libration at orbital period of 1.37 days is written as $\gamma = g\sin(M + \pi)$, the libration amplitude g_{solid} for an entirely solid and elastic Enceladus can be expressed as

$$g_{\text{solid}} = 6\frac{\tilde{B} - \tilde{A}}{\tilde{C}}\frac{en^2}{n^2 - \omega_f^2} \approx 6e\frac{\tilde{B} - \tilde{A}}{\tilde{C}}, \tag{1}$$

where ω_f is the frequency of the free libration

$$\omega_f = n\sqrt{\frac{3(B - A)}{\tilde{C}}\frac{k_f - k_2}{k_f}} \tag{2}$$

and $\tilde{B} = B(k_f - 5k_2/6)/k_f$, $\tilde{A} = A(k_f - 5k_2/6)/k_f$ and $\tilde{C} = C + 4k_2n^2R^5/(9G)$ (Van Hoolst et al., 2013). Here $A < B$ are the equatorial principal moments of inertia, C the polar principal moment of inertia, $R = 252.1$ km the radius and G the universal gravitational constant. The mean motion of Enceladus' orbit is denoted by n, k_2 is the classical potential Love number, and k_f the fluid Love number. The libration amplitude of the forced libration at orbital period depends on a free frequency, similarly to a harmonic oscillator, but we assume that the free libration mode is damped as the damping timescale is extremely short compared to the age of the Solar System (see, e.g. Tiscareno et al., 2009).

For the numerical evaluation, we use the degree-two, order-two gravitational coefficient $C_{22} = (B - A)/(4M_ER^2) = (1549.8 \pm 15.6) \times 10^{-6}$, with mass $M_E = 1.0794 \times 10^{20}$ kg, and the estimate of the mean moment of inertia $I = (A + B + C)/3 = (0.335 \pm 0.005)MR^2$ (2 sigma) derived from Radau's equation and the degree-two gravity field of Enceladus (Iess et al., 2014). For an entirely solid Enceladus, k_2 is small and approximately 1.5×10^{-4} depending somewhat on the density and rigidity profile (Baland et al., 2016), and $k_f = (B - A)/(qM_ER^2) \approx 0.989$ with $q = (n^2R^3)/(GM_E)$ the ratio of the centrifugal acceleration to the gravitational acceleration. The free libration period is then 5.81 days (5.77 days for a homogeneous model, Thomas et al., 2016), far enough from the forcing period of 1.37 days for the approximation in Eq. (1) to be valid. Elasticity, which has been included here, lengthens the free period by less than 0.01% since the tides of a solid Enceladus are very small with a radial tidal displacement of the order of a centimeter. A local subsurface ocean will be able to increase the tides, at least locally, but cannot substantially change the free libration period since the shell librates together with the deeper solid interior.

The libration amplitude for a solid and elastic Enceladus is about 132 m at the equator, four times smaller than the observed value of (528 ± 62) m (Thomas et al., 2016). Thomas et al. (2016) argued that the incompatibility of the observation with the libration amplitude of a solid and rigid Enceladus is evidence of a subsurface ocean. Elasticity does not change that conclusion since elasticity decreases the libration amplitude (by less than a meter). Any larger elasticity (smaller rigidity) than assumed here, for example for a porous core as suggested by Hsu et al. (2015), would imply an even smaller libration amplitude and a stronger inconsistency with the observations. Visco-elastic behavior of the ice would also drain energy from libration to deformation and dissipation and will further reduce the libration amplitude.

We conclude that a partially decoupling layer must exist, which allows for differential rotation between different layers of the satellite. Since measurements of the plume composition demonstrate that the water has been in contact with rocks (Postberg et al., 2011), libration strongly suggests that Enceladus is composed of a solid icy outer shell on top of a liquid ocean mainly composed of water that is in contact with a solid core containing silicates in its top layers. A detailed study of the libration of Enceladus with an ocean is presented in the next section.

3. libration with a global subsurface ocean

3.1. Libration model

In order to assess the effect of various interior structure parameters, such as the thickness of the ice shell, on the libration amplitude, and to constrain some of these parameters based on the observed libration, we construct a large set of interior structure models of Enceladus with a global subsurface ocean for which we calculate the libration. All models satisfy the total mass M_E and radius R and have a mean moment of inertia $I/(M_ER^2)$ between 0.325 and 0.345, covering the moment of inertia estimate of Iess et al. (2014) within the two sigma precision ([0.33, 0.34]) and the range [0.328, 0.333] obtained by McKinnon (2015). The ranges of values considered for the radii and densities of the core, ocean and ice shell are given in Table 1. We choose the density of the ice shell to be in the interval [900, 1000] kg/m^3. This range is somewhat larger than the range of [900, 950] kg/m^3, often considered for pure ice including some degree of porosity in studies of the ice shells of icy satellites (e.g. Nimmo et al., 2014a), to include also the effect of the presence of contaminants. For the ocean, we consider a density range of [950,1100] kg/m^3 to include a wide range of salinity values and temperatures. We refer to Sharqawy et al. (2010) for seawater densities on Earth and the online density table at web.mit.edu/seawater/ where water density values are given between 943.1 kg/m^3 and 1096.2 kg/m^3 for temperatures between 0 and 120 °C, atmospheric pressure, and salinities between 0 and 120 g/kg.

The reference models of the interior structure of Enceladus are spherically symmetric. To be able to study the libration, we calculate the degree-two shape of the three interfaces (surface, interface between the ocean and the ice shell, and interface between the core and the ocean). As explained above, libration only depends on the degree-two shape and we therefore consider that the