EPSC Abstracts
Vol. 10, EPSC2015-524, 2015
European Planetary Science Congress 2015

Localized bending and heating at Enceladus' south pole

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1. Abstract

Since the discovery in 2005 of geysers at the south pole of Enceladus, this midsize moon of Saturn has become famous as the most active icy world in the solar system and as a potential harbor for microbial life. All data gathered during flybys by the Cassini probe point to the existence of a subsurface ocean maintained by tidal heating in the icy crust. This explanation, however, is in conflict with geophysical models which only account for a tenth of the heat output. Such models are based on an approach designed for larger satellites, for which elastic effects are weaker and lateral inhomogeneities are less prominent. By contrast, lateral variations of interior structure are probably the key to understand Enceladus' geological activity. We will test the hypothesis that tidal dissipation is greatly enhanced by local bending of a thinner crust in the south polar region. More generally, we plan to develop a new and faster method to compute tidal dissipation in small bodies with lateral heterogeneities, consisting in modeling the crust as a two-dimensional spherical shell with variable thickness or rigidity and with depth-dependent rheology.

2. Problem

Enceladus' heat budget is an enigma. At the present day, neither internal radioactivity nor chemical reactions provide enough energy but tidal forces (due to the non-circular orbit) can generate high rates of dissipation, as demonstrated by the volcanism on Jupiter's moon Io. In support of this explanation, Enceladus' plume is brighter at the apocenter of the orbit when tidal forces tend to open the tiger cracks [1], although the timing of individual jets appears to be random [2]. In principle, tidal heating can occur at all depths within the satellite but significant ocean dissipation requires a too large obliquity while the core does not dissipate enough even if it is very soft. Tidal heating due to shear friction along fault lines could provide enough heat but it does not cause plume brightening at apocenter and predicts wide warm zones which have not been observed [3].

The most likely source of tidal heating arises from deformations and friction within the whole crust [4]. However, this mechanism has its own problems. In present models, the power output is too small (by up to a factor 10) and the heat transport to the surface is too efficient, resulting in the freezing of the subsurface ocean and the end of the high-dissipation regime [5, 6]. Adding anti-freeze agents such as ammonia to the ocean only slows down the freezing. One possible solution is to postulate that Enceladus is now in a transient regime in which the dissipated energy is the leftover from an orbital state of higher eccentricity and higher dissipation. Episodic heat production would mean that we observe Enceladus at a very special time. The active phase indeed only lasts a few millions years, with a dormancy period of the order of 100 millions years. The difference in time scale between active and dormant phases results from the rapid decrease of the orbital eccentricity when the body dissipates a lot, whereas the eccentricity increases very slowly when dissipation is low. There is thus a low a priori probability that our observations coincide with Enceladus being at the end of its active phase, when the eccentricity has fallen to a low level but the icy shell is still warm. While episodic heating is favored by astronomical constraints imposing a maximum steady-state dissipation rate of 1.1 GW [7], a recent analysis of astrometry data allows a much higher dissipation rate [8], so that this argument is not conclusive. We will thus examine an alternative solution to the problem of 'too little heat/freezing ocean'.

3. Method

Classical computations of tidal dissipation are based on an approach designed for much larger satellites such as Europa, where gravity dominates elastic effects (the crust follows the deformation of the ocean) so that tidal deformations are not much affected by lateral crustal inhomogeneities. In that case, dissipation is mostly due to viscoelastic lateral extension/compression of the crust of harmonic degree two, with very little contribution from bending or twisting. However, Enceladus is small (252 km radius, a sixth of Europa's size) and its surface gravity is weak (0.1 m/s^2, less than a tenth of Europa's gravity) so that elasticity dominates gravity. Furthermore geologic activity is only present at the south pole, probably above a local underground sea under a thinner and weaker crust. We thus expect that tidal deformations have components of harmonic degrees other than two and that local viscoelastic effects with bending/twisting give a significant contribution to tidal heating. To date, there is only one model that self-consistently computes tidal dissipation in a three-dimensional viscoelastic body [6], but its complexity makes it difficult to examine all physically interesting cases.

We propose a new method - thin shell theory - for the computation of localized tidal dissipation in Enceladus, with the aim of finding the missing contribution to the crustal heat budget. Up to now, thin shell theory has only been used to predict elastic deformations, stresses and tectonics when the crust is uniform in thickness and rigidity. We have recently demonstrated, however, that the theory of thin shells with variable thickness that we developed for lithospheric flexure [9, 10] can be applied to large satellites such as Europa for the computation of tidal dissipation in a non-uniform crust [11]. There are no major technical hurdles to extend this work to a smaller body (Enceladus) where bending is important. Moreover, our recent work has shown that membrane theory (a special case of thin shell theory) can be modified in order to include the dependence on depth of the crustal rheology [12]. We will do the same in our thin shell approach, so that the rheology of Enceladus' crust will vary not only laterally but also radially, thus effectively in three dimensions, although the thin shell method remains intrinsically two-dimensional.

Acknowledgements

This work is financially supported by the Belgian Federal Science Policy Office through the Brain Pioneer contract BR/314/PI/LOTIDE.

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