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The Shape of Enceladus' Core: Predictions for Degree-2 Nonhydrostatic Gravity, and Role in Survival of the Subsurface Ocean

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Abstract

The global shape of Enceladus is not consistent with a simultaneously hydrostatic and fully differentiated body, but hypotheses that Enceladus is either undifferentiated or preserves a globally unrelaxed figure from an earlier position closer to Saturn are implausible. Enceladus' geophysical activity (and surface) is best understood in the context of a differentiated (rock separated from ice) interior. Topographic profiles indicate that Enceladus' surface conforms to a triaxial shape, consistent with relaxation to a global geoid. Enceladus' rocky core need not be hydrostatic, however. A modestly "lumpy" core, either in terms of topography or density, and dynamically aligned, will act to enhance the global geoid. Explaining the global shape of Enceladus requires ~12 km of excess core polar ellipticity and ~5 km of excess core equatorial ellipticity, for a uniform density core. The stresses in Enceladus' core associated with this modest level of dynamically excess topography can be sustained indefinitely. Enceladus' icy shell should be isostatic with respect to the satellite's degree-2 gravity, but because the rocky core is not hydrostatic, Enceladus' degree-2 gravity coefficients J_2 and C_{22} should not conform to the hydrostatic ratio of 10/3. The moments-of-inertia implied also indicate that Enceladus could be near a low-order spin-orbit librational resonance, and thus tidal heating associated with this resonance type could have contributed to the moon's phenomenal heat flow. Finally, the core c-axis will be depressed by some 8 km with respect to a hydrostatic shape. This true topographic variation can help preserve polar ocean remnants against freezing (and grounding elsewhere) during epochs of low tidal heating.

1. Introduction

Enceladus is a geologically and geophysically remarkable midsized icy satellite, exhibiting active tectonics, cryovolcanic plumes, and a localized and prodigious heat flow [e.g., 6]. The ultimate power source on so small a moon is almost certainly tidal heating, wherein dissipation is greatly enhanced by the presence of a subsurface ocean that is at least hemispheric in extent [9]. Enceladus is almost universally regarded as a body that has differentiated into a rocky core and an icy mantle, the latter of which would overly the aforementioned ocean [e.g., 5,6]. Yet the shape of Enceladus is not consistent with these inferences. Limb profiles from Cassini images show that Enceladus is well represented by a triaxial ellipsoid whose principal axes are a = 256.6 ± 0.3 km, b = 251.4 ± 0.2 km, and c = 248.3 ± 0.2 km [7,8]. As first discussed in [4], the difference between the long and short axes, 8.3 ± 0.4, matches within error the predicted difference, 8.05 km, for a *homogeneous* Enceladus hydrostatically relaxed in synchronous spin at its present orbital position.

A differentiated Enceladus should have smaller principal axis differences if in hydrostatic equilibrium in its present orbital and spin configuration. For example, using the interior models illustrated in [1] — average core radius of 162 km and core density of 3450 kg m^{-3} — implies a normalized moment-of-inertia of 0.3; this in turn implies an $a - c$ = 5.5 km. Porco et al. [4] suggest and then reject the idea that Enceladus retains a more distorted but still hydrostatic figure from an earlier epoch when the moon was orbiting closer to Saturn. Regardless, even if Enceladus tidally evolved outward from Saturn over geologic time (which sensu stricto is correct to some degree), neither crater densities on its surface nor its active geophysics are consistent with the notion that the satellite supports a fossil shape. Moreover, such an earlier spin-orbit hydrostatic state *cannot* explain the full triaxial figure of Enceladus. To first order, $b - c$ for Enceladus should be onefourth the observed value of $a - c$, or 2.1 ± 0.1 km. The observed value of $b - c$ is 3.1 ± 0.3 km.

The simplest and most economical explanation for Enceladus' apparent lack of hydrostatic figure is that suggested by [7], that Enceladus' rocky core is irregularly shaped, and the gravity from this core has affected the Enceladus "geoid." I quantify the magnitude of this core irregularity below. With that, inferences can be drawn for Enceladus' internal structure and moments-of-inertia, and testable predictions made for its second-degree gravity field and possible librational tidal heating. Here I focus on a further inference: ocean survival.

2. Core topography on Enceladus

To raise an excess $a - c$ ellipticity of 2.8 ± 0.4 km at Enceladus' surface implies an excess *core* $a - c$, and to fully account for Enceladus' anomalous figure requires an additional degree-2 elongation of the core in the *b*-axis direction. Figure 1 shows the required excess core ellipticities as a function of core density, along with hydrostatic core ellipticities (after [2]). Total core topography would be the sum of the two.

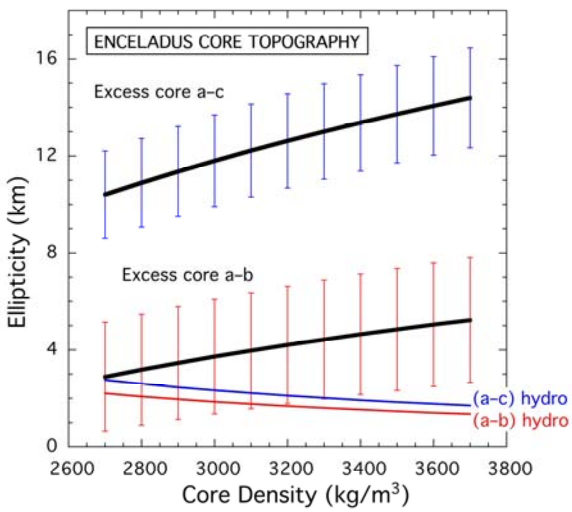

Figure 1: Enceladus excess core topography as a function of assumed core density. Reference hydrostatic models are based on uniform core and ice mantle densities (925 kg m^{-3} for the latter), the first-order Radau-Darwin formalism (e.g., [2]), and second-order corrections from [3].

3. Ocean Survival

It is now well appreciated that the prodigious heat loss from Enceladus cannot be sustained over geological time given orbit dynamical limits on Saturn's dissipation factor Q [6]. F. Nimmo (presentation at SETI Institute Workshop, 23-24 May 2011) has noted that tidal dissipation may be dynamically unable to supply even the minimum heat necessary to maintain a global ocean against freezing. Possible implications are that the ocean was frozen in the past (or goes through freeze-thaw cycles) or that the ocean is not global in extent (reducing the global tidal energy requirement). The greater radiogenic contribution in the past could stabilize a global cold ocean in the past. For the present, ocean freezing in conjunction with core topography as in Fig. 1 would yield contraction of ocean extent with time, with polar seas as the ultimate (possibly stable) end state.

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