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Do Titan's tides imply a dense subsurface ocean?

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1. Abstract

Time-dependent tidal effects in Titan's gravity field are strong evidence of a global subsurface ocean. Surprisingly, tides are 30% stronger than what plausible interior models predict. Two solutions are obvious: either the tidal amplitude is close to the 2σ lower bound of the measurements, or the ocean is extremely dense because it is nearly saturated in sulfate salts. I examine here a third possibility, consisting of an ocean mostly unsaturated in salts, except in a thin and dense layer close to the mantle. In this model, tidal amplitudes are within the 1σ bounds of the central measured value.

2. Problem

Cassini radio-science data yield a tidal gravity Love number of $k_2 = 0.589 \pm 0.15\,(2\sigma)$ [1]. Earlier interior models assuming a subsurface ocean predicted that k_2 would be about 0.45 [2] or even as low as 0.3-0.4 [3]. A first solution to this problem is to suppose that the actual value k_2 is at the lower end of the 2σ allowed range [4]. This assumption has the advantage of not imposing any radical change on the existing interior models, but could be invalidated by future measurements. If the value of k_2 is indeed as high as 0.6, the most plausible way to raise the predicted k_2 is to increase the ocean density. If the ocean is a brine rich in ammonium sulfate, its density can reach $1300\,\mathrm{kg/m^3}$ in which case the value of k_2 is 30% higher than if the ocean is made of pure water [5]. This effect is easily understood with the toy model of an infinitely rigid mantle surrounded by a surface ocean, for which

$$k_2 = \frac{3\xi}{5 - 3\xi}\,, \tag{1}$$

where $\xi = \rho_{ocean}/\rho_{bulk}$ is the ocean-to-bulk density ratio (a $50\,\mathrm{km}$ elastic crust reduces this k_2 value by about eight percents [6]). It is however not obvious how a large quantity of sulfur could leach from the core to the ocean through the icy mantle [1].

3. Another stratification model

Since the ocean density has such a large effect on k_2, it is worthwhile to go beyond the approximation of an ocean of uniform density. In particular, *Mitri et al.* observed that ocean density gradually increases with depth because of water compressibility [5]. The density difference between top and bottom is about $160\,\mathrm{kg/m^3}$ for a $350\,\mathrm{km}$-deep ocean. As a result, k_2 increases by about 3 to 4%.

In fluid bodies, density stratification typically leads to a decrease of k_2^f, the Radau approximation relating the fluid Love number k_2^f to the moment of inertia. The situation is more complicated if a fluid layer is sandwiched between elastic layers: the nearly rigid core-mantle system acts as a gravitational brake on the deforming ocean layer. If you redistribute mass from the top of the ocean to its bottom, the lower denser layer partially screens the gravitational braking effect of the mantle. As a limiting case, a lower denser layer having the same density as the core-mantle system would have the same effect as a fluid core-mantle, and thus significantly increase the deformation (Fig. 1).

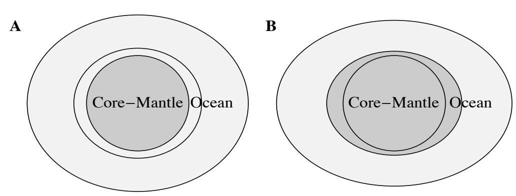

Figure 1: Screening effect due to ocean density stratification: (A) no stratification, (B) thin denser layer at the bottom of the cean. Darker shades represent higher densities [6].

This *screening effect* [6] suggests another stratification model: the ocean could be globally of low density, except for a thin bottom layer (say 1% of the ocean depth) saturated in sulfate salts. Fig. 2 shows that k_2 could increase by more than 10%, bringing it well inside the 1σ bounds of the measured value.

The possible presence of a thin dense layer at the

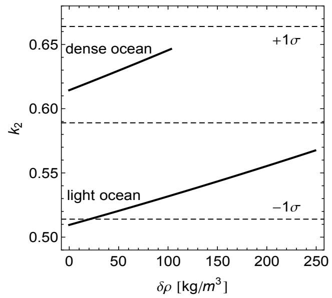

Figure 2: Effect of a thin dense layer at the bottom of the ocean on Titan's k_2. On the x-axis, $\delta\rho$ represents the density deviation of the bottom ocean layer with respect to the rest of the ocean. The 'light' and 'dense' ocean models are end-member models (50 km crust) taken from [5]. Dashed lines represent the measured values of k_2 and the 1σ error bounds.

bottom of the ocean immediately raises two questions: (1) how can it be formed, and (2) is it stable against convection or crystallization?

Acknowledgements

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