Icarus 237 (2014) 16–28

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Structure and dynamics of Titan's outer icy shell constrained from Cassini data

Axel Lefevre [a,*], Gabriel Tobie [a], Gaël Choblet [a], Ondřej Čadek [b]

[a] Université de Nantes, CNRS, Laboratoire de Planétologie et Géodynamique, UMR-6112, 2 rue de la Houssinière, 44322 Nantes Cedex, France
[b] Charles University in Prague, Faculty of Mathematics and Physics, Department of Geophysics, V Holešovičkách 2, 180 00 Praha 8, Czech Republic

ARTICLE INFO

Article history:
Received 13 December 2013
Revised 5 April 2014
Accepted 10 April 2014
Available online 24 April 2014

Keywords:
Titan
Interiors
Satellites, shapes

ABSTRACT

The Cassini–Huygens mission has brought evidence for an internal ocean lying beneath an outer icy shell on Titan. The observed topography differs significantly from the reference hydrostatic shape, while the measured geoid anomalies (estimated up to degree three) remain weak. This suggests compensation either by deflections of the ocean/ice interface or by density variations in an upper crust. However, the observed degree-three gravity signal indicates either that the topography is not perfectly compensated, or that mass anomalies exist in the deep interior, or a combination of both. To investigate the compensation mechanisms, we developed an interior structure model satisfying simultaneously the surface gravity and long-wavelength topography. We quantified the excess deflection of ocean/ice I interface, the density anomalies in the upper crust, or the deflection of the ice/rock interface needed to explain the observed degree-three anomalies. Finally, we tested the long-term mechanical stability of the internal mass anomalies by computing the relaxation rate of each internal interface in response to interface mass load. We showed that the computed deflection of the ocean/ice I interface is stable only for a conductive highly viscous layer above a relatively cold ocean ($T < 250$ K). Solutions with a moderately convecting ice shell are possible only for models with crustal density variations. Due to fast relaxation, the high pressure ice layer cannot be the source of the degree three geoid anomalies. The existence of mass anomalies in the rocky core remains a possible explanation. Estimation of the degree-four gravity signal by future Cassini flybys will further constrain the compensation mechanism and the source of gravity anomalies.

1. Introduction

Since 2004, the Cassini–Huygens mission has performed a series of measurements that provide key constraints on the internal structure of Titan and its past evolution. Several lines of evidence (tides, rotation, electric field perturbations, long-wavelength topography; Iess et al. (2012), Baland et al. (2011, 2014), Béghin et al. (2012), Nimmo and Bills (2010), Hemingway et al. (2013)) indicate that Titan harbors a water ocean (possibly salt-rich) underneath an outer icy shell several tens to more than hundred kilometers thick. The spherical harmonics coefficients of the gravity field have been determined up to degree 3 from radio tracking of the Cassini spacecraft (Iess et al., 2010, 2012). The degree-two coefficients, C_{20} and C_{22}, can be used to infer the Moment-of-Inertia (MoI) factor (C/MR^2) of Titan's interior, which provides key information on its radial density structure. Assuming that the observed C_{22} coefficient is exclusively attributed to the fluid response of the satellite to tide, the fluid Love number of Titan, k_f, should be equal to 1.02, which gives $C/MR^2 = 0.343$ using the Radau–Darwin approximation (Iess et al., 2010). However, the existence of a significant degree-three signal in the gravity field (Iess et al., 2010, 2012) indicates some departure from the (hydrostatic) fluid response and suggests that the observed degree-two coefficients must be corrected from non-hydrostatic contributions (Gao and Stevenson, 2013; Hemingway et al., 2013; Baland et al., 2014). If about ±10% of the observed degree-two gravity signals are associated to non-hydrostatic effects, the corrected MoI factor may range between 0.32 and 0.355, corresponding to very different degrees of differentiation. As a comparison, the MoI factors estimated by the Galileo mission typically ranges between 0.31 for Ganymede and 0.355 for Callisto (Anderson et al., 1996; Sohl et al., 2002).

As illustrated in Fig. 1, owing to the small dynamical flattening of Titan, variations of the moment of inertia from 0.32 to 0.36 lead to moderate variations of the geoid anomalies. The degree-two geoid anomalies corresponding to such a variation of MoI factor remain comparable to the degree three signal. Once non-hydrostatic

* Corresponding author.
E-mail address: axel.lefevre@univ-nantes.fr (A. Lefevre).

http://dx.doi.org/10.1016/j.icarus.2014.04.006

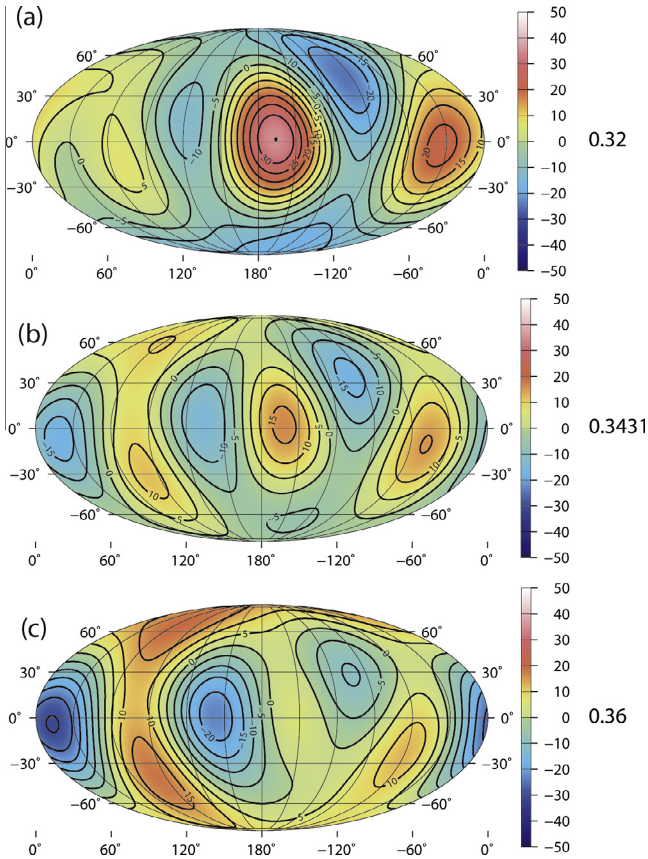

Fig. 1. Geoid heights (in m) from SOL1a of Iess et al. (2012), over reference ellipsoids defined from three different values of C/MR^2: 0.32, 0.343, 0.36.

uncertainties are taken into account for Titan, a wide range of internal structure becomes possible, including fully differentiated structure with a relatively dense rock core (Sohl et al., 2003; Tobie et al., 2006; Baland et al., 2014), with a low-density hydrated core (Fortes et al., 2007; Castillo-Rogez and Lunine, 2010), or partially differentiated structure comprising a mixed rock/ice layer (Sohl et al., 2010; Hemingway et al., 2013). In absence of additional constraints, it is very difficult to conclude which internal structure is more likely.

Another key constraint to infer Titan's subsurface structure is provided by the long-wavelength topography, which has been derived using Cassini Radar from direct altimetry and from SAR-topography (Fig. 2, Zebker et al. (2009); Stiles et al. (2009); Mitri et al. (2014)). The observed topography differs by several hundreds of meters from the reference hydrostatic shape, while the measured geoid anomalies (Fig. 1) remain very small in comparison.

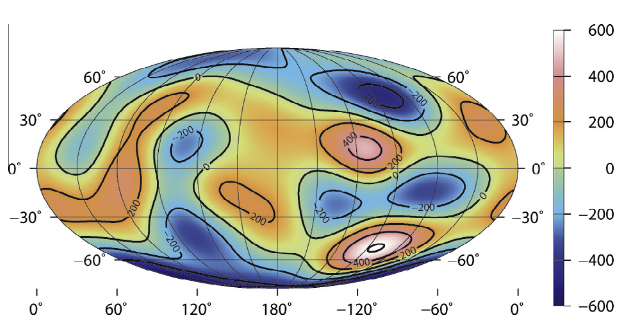

Fig. 2. Spherical harmonic expansion of Titan's topography (in meters), up to degree 6, from Mitri et al. (2014), defined with respect to the geoid provided by Iess et al. (2012).

These observations indicate that the gravity signal due to topography is compensated, most likely by mass anomalies in the outer icy shell, either by deflections of the ice/ocean interface (Nimmo and Bills, 2010) or by density variations of the upper crust (Choukroun and Sotin, 2012). However, the existence of a non-negligible degree-three signal indicates that the compensation is not perfect and that the layer is rigid enough to maintain the system out of equilibrium (Hemingway et al., 2013; Gao and Stevenson, 2013). The stresses associated with the geoid anomalies for a reference model with $C/MR^2 = 0.341$ (Fig. 1b) are $\leqslant$0.2 bar. These stresses do not exceed 0.4 bar even for a model with a significant departure from the hydrostatic reference state ($C/MR^2 = 0.32$, corresponding to geoid anomalies of ±40 m, Fig. 1a). Such a stress level is one order of magnitude below the mechanical strength of water ice (e.g., Litwin et al., 2012), and therefore the outer shell should be able to support it as long as viscous relaxation is limited. In a recent study, Hemingway et al. (2013) interpreted the observed degree-three geoid anomalies as resulting from efficient surface erosion and deposition on a substantially rigid ice shell. According to their interpretation, erosion processes would limits the topography variations produced by ice shell thickening/thinning associated with inhomogeneous ocean crystallization (e.g. Nimmo and Bills, 2010). Other scenarios are also possible, for instance as proposed by Choukroun and Sotin (2012), topography may be associated with density variations resulting from clathration processes in the upper crust. Following the scenario of Choukroun and Sotin (2012), accumulation of ethane at the poles and substitutions between methane and ethane in clathrate structures would progressively increase the crustal density leading to a progressive subsidence in the polar regions.

The aim of this work is to test the various hypotheses that have been proposed to explain the compensation processes and to determine the structure of the outer shell consistent with the observed topography and gravity signals for each compensation scenario. For that purpose, we have developed a generic interior structure model reproducing simultaneously gravity and topography data. Using this model, we derive the amplitude of thickness and/or density variations in the outer ice shell required to explain the observations. In order to assess whether any derived structure is stable on geological timescales, we also compute the viscous relaxation of any deflected interface, and we determine the viscosity structure compatible with the observed topography and gravity signals. In Section 2, we describe how the interior structure is modeled and how the gravity field and topography are used to determine the position and shape of the internal interfaces. The stability of the deflected interface presented in Section 2 is then computed and discussed in Section 3. We finally conclude and discuss the implications of our results for the structure and evolution of Titan's interior in Section 4.

2. Modeling the interior structure consistent with gravity and topography data

In the following, we develop interior models for Titan based on lateral perturbations of a radially-varying density structure and the associated gravitational potential outside and inside the moon is computed.

2.1. Average radial structure

We consider interior structures consisting of up to 5 main layers from center to surface: a rock core, a high-pressure (HP) ice V–VI layer, a liquid water ocean, an ice Ih layer and possibly a chemically different icy crust (Fig. 3). For a given MoI factor, we compute the rock/HP ice interface radius, $R_{C/HP}$, and the HP ice/ocean interface