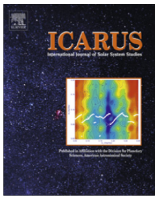
Icarus 227 (2014) 67–77

Contents lists available at ScienceDirect

Icarus

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



Stability of ice/rock mixtures with application to a partially differentiated Titan

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ARTICLE INFO

Article history:
Received 18 October 2012
Revised 15 July 2013
Accepted 10 September 2013
Available online 19 September 2013

Keywords:
Titan, interior
Saturn, satellites
Jupiter, satellites
Thermal histories

ABSTRACT

Titan's moment of inertia, calculated assuming hydrostatic equilibrium from gravity field data obtained during the Cassini–Huygens mission, implies an internal mass distribution that may be incompatible with complete differentiation. This suggests that Titan may have a mixed ice/rock core, possibly consistent with slow accretion in a gas-starved disk, which may initially spare Titan from widespread ice melting and subsequent differentiation. A partially differentiated Titan, however, must still efficiently remove radiogenic heat over geologic time. We argue that compositional heterogeneity in the major saturnian satellites indicates that Titan formed from planetesimals with disparate densities. The resulting compositional anomalies would quickly redistribute to form a vertical density gradient that would oppose thermal convection. We use elements of the theory of double-diffusive convection to create a parameterized model for the thermal evolution of ice/rock mixtures with a stabilizing compositional gradient. To account for large uncertainties in material properties and accretionary processes, we perform simulations for a wide range of initial conditions. Ultimately, for realistic density gradients, double-diffusive convection in the ice/rock interior can delay, but not prevent, ice melting and differentiation, even if a substantial fraction of potassium is leached from the rock component. Consequently, Titan is not partially differentiated.

1. Introduction

Titan is Saturn's largest satellite, the second largest in our Solar System. The surface of Titan features stable liquid methane/ethane lakes, a hydrocarbon precipitation cycle comparable to Earth's hydrology, and myriad additional geologic features such as dune fields and mountainous terrain (Jaumann et al., 2009). From an astrobiology perspective, Titan is interesting as a modern analogue for pre-biotic Earth (Raulin et al., 2009). Titan has a thick nitrogen atmosphere, which must be sustained by the continuous production of methane (Atreya et al., 2006). Methane may be stored subsurface or perhaps more deeply in stable clathrate-hydrates along with other volatiles and episodically outgassed when internal heating causes melting (Gautier and Hersant, 2005; Tobie et al., 2006). Understanding Titan's fascinating surface, atmosphere, and chemistry requires knowledge of the evolution of its interior.

Measurements of the gravity field of Titan can place indirect constraints on the current structure of its interior. Titan's gravity harmonics were determined to degree 3 through careful tracking of the Cassini spacecraft during four flybys (Iess et al., 2010). The calculated ratio J_2/C_{22} is consistent with the value of 10/3 that is itself consistent with a gravity field dominated by a nearly hydrostatic quadrupole, although non-zero values of other degree 2 and 3 coefficients indicate that non-hydrostatic features are present. If hydrostatic equilibrium is assumed, however, then Titan's moment of inertia (MoI) factor is found to be $C \sim 0.34$. Here, the MoI is $CM_sR_s^2$, where M_s and R_s respectively represent the mass and radius of Titan. Measurement of the tidal Love number k_2 from additional flybys reveals a relatively large response of the gravity field to the saturnian tidal field, indicating the presence of a global, subsurface ocean (Iess et al., 2012). The decoupling of Titan's shell from its interior with an ocean may also explain Titan's long-wavelength topography (Nimmo and Bills, 2010), spin pole orientation (Bills and Nimmo, 2011), and Schumann resonance (Simoes et al., 2012).

The 2-σ error on J_2/C_{22} is about 3%, centered on 10/3 and dominated by the error in J_2, according to Iess et al. (2010). We can write $J_2 = J_{2,h} + J_{2,nh}$ and likewise $C_{22} = C_{22,h} + C_{22,nh}$, where "h" means hydrostatic and "nh" means non-hydrostatic. So, $J_{2,h}/C_{22,h}$ is *exactly* 10/3. If the non-hydrostatic parts were completely uncorrelated (i.e., if they did not cancel in the ratio J_2/C_{22}), then the closeness of the observed value to 10/3 is highly significant and precludes a substantial error in MoI. If, on the other hand, the non-hydrostatic parts tend to be correlated (as they would, for example, in the tidal heating model of Nimmo and Bills (2010) or if Titan has undergone True Polar Wander to the preferred

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0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.09.010

orientation of the non-hydrostatic part of the MoI), then the small deviation away from 10/3 does not guarantee smallness of the non-hydrostatic part and the MoI is accordingly uncertain. The effects of the non-hydrostatic components on Titan's MoI are explored in detail in Gao and Stevenson (2013). Given the observed power in degree 3 gravity, Iess et al. (2010) propose that the MoI could be as low as 0.33 and we adopt this as a plausible lower bound. The true MoI is likely to be smaller than 0.34, the value inferred from J_2/C_{22}, because this is a lower rotational energy state. Since a fully differentiated Titan may allow 0.33 (but perhaps not 0.34), the differentiation state of Titan is accordingly not yet determined from observation.

Titan's MoI can be compared to previous results regarding other icy satellites. In particular, Titan's MoI coefficient is intermediate to the previously-measured $C \sim 0.31$ for Ganymede (Anderson et al., 1996a) and $C \sim 0.35$ for Callisto (Anderson et al., 2001), where hydrostatic equilibrium was assumed *a priori* for the Galilean satellites. While Ganymede is easily modeled as a differentiated satellite with an iron core under a rock shell and an outer ice layer (e.g., Sohl et al., 2002), models of a differentiated Callisto are not consistent with the reported MoI (e.g., Anderson et al., 2001). A proposed interior structure for Callisto features a rock/ice core with rock mass fraction near the close packing limit, with an overlying icy mantle that was depleted of rock by Stokes settling (Nagel et al., 2004). In this case, an ice/rock lithosphere in which density decreases with depth overlays the icy mantle.

Titan might represent an intermediate case between differentiated Ganymede and undifferentiated Callisto. However, the inferred (and widely cited) partially differentiated state for Callisto is based on a gravity inversion that *assumes* $J_2/C_{22} = 10/3$, and perhaps the inferred MoI is incorrect. As for Titan, the sense of the error is likely to cause an overestimate of the MoI because non-hydrostatic contributions to J_2 and C_{22} are likely positive. At present, we cannot exclude the possibility that *all* large icy satellites are fully differentiated. (In this paper, we use that term to imply the complete separation of ice from rock; the further differentiation of an iron core from the rock is a separate issue that we do not address.) It should be noted that non-hydrostatic effects are more likely to be important in slowly rotating bodies (Titan and Callisto) relative to Ganymede because the hydrostatic effects scale as rotational frequency squared for both tides and synchronous rotation (Gao and Stevenson, 2013). Certainly, Callisto and Ganymede are different in appearance and Callisto, like Titan, lacks a global magnetic field.

Relative differences in the experienced intensity of the Late Heavy Bombardment (LHB) may explain the Ganymede/Callisto dichotomy. In the so-called "Nice model", the gas giant planets swiftly realigned once Jupiter and Saturn crossed their mean motion resonance ~700 Myr after planetary formation, quickly causing the outward migration of Uranus and Neptune and the evolution of Jupiter and Saturn's orbital eccentricities (Tsiganis et al., 2005). The ensuing destabilization of the planetesimal disk and the asteroid belt caused the LHB of both the outer and inner Solar System (Gomes et al., 2005). Ganymede is closer to Jupiter than Callisto, so it likely suffered considerably more high-energy impacts during the LHB. For assumptions about the planetesimal disk consistent with the Nice model, the differences in received energy during the LHB are sufficient to cause Ganymede to differentiate, while Callisto's rock and ice components may remain unmixed (Barr and Canup, 2010). If Titan survived both accretion and the LHB without melting the ice in its deep interior, then it could have remained partially differentiated like Callisto, at least initially.

Gas giant satellites like Titan were accreted from the outskirts of the disk of material surrounding their parent planets. Nascent gas giant planets must accrete enough rock such that they can also accumulate large amounts of gas, principally hydrogen and helium, before the dissipation of the protoplanetary disk, which had a lifetime of a few Myr (e.g., Lissauer and Stevenson, 2007; Lunine et al., 2009). In the core-nucleated gas accretion model, for instance, the formation of Saturn began with the accretion of km-sized rocky planetesimals from the minimum mass sub nebula (MMSN) (e.g., Lissauer and Stevenson, 2007). However, if gas giant satellites accreted from the outskirts of a disk of planet-forming material as dense and gas-rich as the MMSN, then Jupiter's Galilean satellites (and, by analogy, Titan) would have formed quickly and hot and therefore differentiated. Additionally, recent work suggests that collisional mergers of Galilean-like satellites may have formed Titan (Asphaug and Reufer, 2013), which would have caused complete differentiation.

Internal structure models for Titan often assume widespread ice melting and thus differentiation. Many studies investigated the thermal evolution of Titan assuming a large silicate/iron core (e.g., Sohl et al., 2003; Tobie et al., 2005), before MoI data from Iess et al. (2010) cast doubt on such models. Papers invoked convection in a silicate core to melt clathrate hydrates and cause episodic outgassing of methane (e.g., Tobie et al., 2006). Another class of models assumes that Titan contains a large core of hydrated silicates, chiefly the serpentine mineral antigorite (Fortes et al., 2007; Grindrod et al., 2008; Castillo-Rogez and Lunine, 2010; Fortes, 2012; Tobie et al., 2012). Serpentinization of silicates in icy satellites is likely to be rapid in the presence of liquid water, e.g. during differentiation or subsequent hydrothermal convection (Ransford et al., 1981; Travis and Schubert, 2005), because the serpentinization reaction promotes crack formation and increasing material permeability (MacDonald and Fyfe, 1985). An interior dominated by hydrated silicates is consistent with constraints on Titan's chemical evolution (e.g., Fortes et al., 2007, 2012). But a partially differentiated Titan, in which Titan's deep interior is a mixture of ice and rock, is still consistent with the gravity data (Iess et al., 2010) and such models have not been fully vetted.

The accretion of undifferentiated icy satellites is often assumed to occur in a "gas-starved" disk, where material similar to that found in the gas giant's feeding zone is fed to the accretion process over millions of years. The resultant, long timescales for satellite accretion allow many of the Galilean satellites, particularly Callisto, to avoid complete differentiation (e.g., Canup and Ward, 2002). In another model, the major satellites of Jupiter and Saturn formed in a solid-enhanced minimum mass planetary nebula, avoiding differentiation as satellites opened gaps in the nebula (Mosqueira and Estrada, 2003a,b). With a particular compositional gradient in the initial circumplanetary disc, the compositions of the major saturnian satellites can be roughly reproduced (Mosqueira et al., 2010). In any model, accretion must also be delayed to escape intense, but short-lived, radiogenic heating from the decay of ^{26}Al and ^{60}Fe if an icy satellite is to avoid complete differentiation (e.g., McKinnon, 1997; Barr and Canup, 2008). Despite myriad threats to unmelted ice, slow accretion in a gas-starved disk permits the formation of a partially differentiated Titan (Barr et al., 2010).

The purpose of this study is to determine whether a partially differentiated Titan is stable over geologic time. After accretion, the internal ice/rock mixture must efficiently expel radiogenic heat, which would otherwise melt the ice and allow irreversible sinking and separation of the rock component. Because the major saturnian satellites are remarkably heterogenous, we argue that Titan likely accreted from planetesimals with disparate rock mass fractions. Even without that heterogeneity, there may be a tendency to form a stably stratified interior at the outset. Soon after accretion, a stabilizing density gradient would be established in which rock mass fraction increases with depth. Aspects of the theory of double-diffusive convection allow us to formulate a one-dimensional, parameterized thermal evolution model in which a