Icarus 307 (2018) 83–105

Contents lists available at ScienceDirect

Icarus

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

Variations in rotation rate and polar motion of a non-hydrostatic Titan

Alexis Coyette[a,b,*], Rose-Marie Baland[b], Tim Van Hoolst[b,c]

[a] Earth and Life Institute, UCL, Place Louis Pasteur 3, Louvain-la-Neuve B-1348, Belgium
[b] Royal Observatory of Belgium, Ringlaan 3, Brussels B-1180, Belgium
[c] Instituut voor Sterrenkunde, KU Leuven, Celestijnenlaan 200D, Leuven B-3001, Belgium

ARTICLE INFO

Article history:
Received 26 October 2017
Revised 29 January 2018
Accepted 2 February 2018
Available online 8 February 2018

Keywords:
Titan
Libration
Interior structure

ABSTRACT

Observation of the rotation of synchronously rotating satellites can help to probe their interior. Previous studies mostly assume that these large icy satellites are in hydrostatic equilibrium, although several measurements indicate that they deviate from such a state. Here we investigate the effect of non-hydrostatic equilibrium and of flow in the subsurface ocean on the rotation of Titan. We consider the variations in rotation rate and the polar motion due to (1) the gravitational force exerted by Saturn at orbital period and (2) exchanges of angular momentum between the seasonally varying atmosphere and the solid surface. The deviation of the mass distribution from hydrostaticity can significantly increase the diurnal libration and decrease the amplitude of the seasonal libration. The effect of the non-hydrostatic mass distribution is less important for polar motion, which is more sensitive to flow in the subsurface ocean. By including a large spectrum of atmospheric perturbations, the smaller than synchronous rotation rate measured by Cassini in the 2004–2009 period (Meriggiola et al., 2016) could be explained by the atmospheric forcing. If our interpretation is correct, we predict a larger than synchronous rotation rate in the 2009–2014 period.

1. Introduction

Changes in the spin of solar system bodies provide insight into their deep interior, and have, for example, recently been used to determine that the core of Mercury is at least partially liquid (Margot et al., 2007) and has a radius of about 2000 km (Margot et al., 2012; Hauck et al., 2013; Rivoldini and Van Hoolst, 2013). In a similar approach, the librations at orbital period of Enceladus, detected on the basis of Cassini optical data, show that Enceladus has a global ocean below an about 20 km thick crust (Thomas et al., 2016; Čadek et al., 2016; Van Hoolst et al., 2016), a conclusion that is also compatible with an examination of gravity and shape data (Beuthe et al., 2016). Rotation variations could also be used to probe the interior of large icy satellites, in particular of Titan for which the rotation, gravity and shape have been measured by the Cassini mission.

The observational determination of rotation variations is based on measurements of the shift in orientation in inertial space of Cassini radar images taken during different flybys. Cassini radar images taken between 2004 and 2009 have shown that the rotation period of Saturn's moon Titan differs slightly from its orbital period, although firm conclusions have been difficult to obtain (Lorenz, 2008; Stiles et al., 2008; 2010). The deviation from a synchronous rotation of the ice shell is $-0.024^{\circ} \pm 0.018^{\circ}$/year (one-$\sigma$ uncertainty, Meriggiola et al., 2016). Further analysis of the Cassini data, including data from the flybys performed since 2009, may improve the estimations of the rotational variations.

Titan is assumed to be in a mean state of rotation called a Cassini state (see e.g. Peale, 1969). It implies that Titan is in synchronous rotation and that the rate of precession of its rotation axis is close to that of the normal to its orbit. As a result, the spin axis, the normal to the orbit and the normal to the Laplace plane or inertial plane are nearly coplanar and the obliquity η (the angle between the rotation axis and the normal to the orbital plane) is nearly constant.

Variations in the rotation rate of Titan around this mean synchronous rotation can occur for several reasons (Tokano and Neubauer, 2005; Van Hoolst et al., 2013; Richard et al., 2014). First, Titan's rotation changes with a period equal to Titan's orbital period as a result of the gravitational torque exerted by Saturn. Current theoretical models (Van Hoolst et al., 2013; Richard et al., 2014) show that the amplitudes of the diurnal rotation variations are below the detection limit related to the position error of Cassini radar images of the order of one kilometer (Meriggiola et al., 2016). Second, dynamic variations in the atmosphere (and to a less extent in the hydrocarbon lakes) of

* Corresponding author at: Earth and Life Institute, UCL, Place Louis Pasteur 3, Louvain-la-Neuve B-1348, Belgium.
E-mail address: alexis.coyette@uclouvain.be (A. Coyette).

https://doi.org/10.1016/j.icarus.2018.02.003
0019-1035/

Titan induce changes in Titan's rotation with a main period equal to half the orbital period of Saturn. Depending on the model of the dynamics of the atmosphere and on the rotation model used (Goldreich and Mitchell, 2010; Richard et al., 2014), the maximum displacement of a given surface spot at the equator with respect to its equilibrium position without variations of the length-of-day (LOD) could be up to about 1 km. The maximal rotation rate variations associated with LOD variations predicted for a large set of interior models is about 0.013°/year (Van Hoolst et al., 2013), and is compatible with the observation in the $2-\sigma$ limit. Third, free librations with periods of the order of a year might be excited by the atmosphere of Titan, and fourth, deviations from a Keplerian orbit on different timescales introduce additional variability mostly at long periods (Richard et al., 2014; Yseboodt and Van Hoolst, 2014). Moreover, Titan might not exactly occupy the 1:1 spin-orbit resonance so that the rotation is non-synchronous (NSR) (Greenberg and Weidenschilling, 1984), even though the observed deviation from a synchronous rotation of the ice shell is compatible with a zero-NSR in the $2-\sigma$ limit.

In addition, the gravitational torque exerted by Saturn and the atmospheric and hydrologic torques also lead to fluctuations in the orientation of the spin axis. The position of the spin axis changes in two ways: with respect to inertial space (precession and nutations, e.g. Bills and Nimmo, 2008 and Baland et al., 2011) and with respect to the solid surface (polar motion). Polar motion of Titan due to its atmosphere and hydrocarbon lakes has recently been studied by Tokano et al. (2011) and Coyette et al. (2016). By assuming Titan (including its ocean) to be in hydrostatic equilibrium, the atmosphere forces the spin axis to follow an elliptical path with a typical amplitude of about 500 m in the y-direction and 200 m in the x direction and a main period equal to the orbital period of Saturn. These values apply to a shell thickness of about 200 km. For thinner shells, both the amplitude and the main period of the polar motion sensitively depend on whether a forcing period is close to the period of a free wobble mode of Titan. For shells thinner than 80 km, the amplitude of the polar motion could reach several tens of km or more.

In the existing models for the librations and polar motion of Titan with an internal ocean, it is assumed that Titan is in hydrostatic equilibrium. Within the observational errors, the ratio of the degree-two gravitational coefficients agrees with that expected for a hydrostatic Titan, suggesting that Titan is indeed close to a relaxed shape (Iess et al., 2012). However, this ratio is only a necessary but not a sufficient condition for a synchronous satellite to be in hydrostatic equilibrium. The observed shape of the surface, which is more flattened at the poles than expected for hydrostatic equilibrium (Zebker et al., 2009), as well as the non-zero degree-three gravity signal (Iess et al., 2012) clearly indicate some departure from hydrostatic equilibrium. Here, we will therefore relax the assumption of hydrostatic equilibrium in the rotation model by considering the flow in the subsurface ocean and the effect of the non-hydrostatic surface of Titan on the shape of the internal boundaries.

The plan of the paper is as follows. In Section 2, we use Airy-like models of isostasy to calculate the shape of the interfaces between different layers of Titan based on the observations of the degree-two gravity field (Iess et al., 2012) and topography (Zebker et al., 2009). Section 3 describes the extension of the libration theory developed in Van Hoolst et al. (2013) and the polar motion theory developed in Coyette et al. (2016) to non-hydrostatic satellites with the inclusion of a Poincaré flow in the subsurface ocean. As in Coyette et al. (2016), the precession of the rotation axis of the solid layers is assumed to be known and is therefore not solved jointly with the polar motion. In Section 4, numerical results are presented for the diurnal and seasonal forced librations and polar motion. We consider the sensitivity of the libration to various interior structure parameters such as the rigidity and viscosity of the ice shell in the discussion (Section 5). We also study in Section 5 the possible observations of librations, LOD and polar motion. Finally, concluding remarks are presented in Section 6.

2. Non-hydrostatic internal structure of Titan

2.1. Differentiation and density profile

The mean density ($\overline{\rho} = 1882 \pm 1$ kg m^3, from ssd.jpl.nasa.gov) and the moment of inertia (MOI) of Titan ($I/MR^2 = 0.3431 \pm 0.0004$, SOL1a of Iess et al., 2012) indicate that Titan is differentiated into an ice-ocean layer, a mantle (denoted by "m" in the following) and a core (c) (see also Grasset et al., 2000; Sohl et al., 2003; Tobie et al., 2005; Fortes et al., 2007). From the large tidal Love number $k_2 = 0.589 \pm 0.075$ (Iess et al., 2012) and the large value of the obliquity of Titan (Bills and Nimmo, 2008; Baland et al., 2011; 2014; Noyelles and Nimmo, 2014; Boué et al., 2017) it is assumed that the ice-ocean layer is divided into a shell (s) and a subsurface global ocean (o). The moment of inertia is derived by assuming that Titan is in hydrostatic equilibrium. Radau's equation then allows determining the moment of inertia from the degree-two coefficients of the gravitational field. Since the measured gravity and topography show that Titan deviates from hydrostatic equilibrium, we consider a range of MOI values. Gao and Stevenson (2013) showed that deviations from the hydrostatic equilibrium value of 10% or even more are possible. As in Baland et al. (2014), we consider that the true moment of inertia of Titan lies between 0.30 (Ganymede-like, e.g. Sohl et al., 2003) and 0.36 (Callisto-like, e.g. Fortes, 2012). The upper limit also corresponds to the value proposed by Hemingway et al. (2013) based on an analysis of the gravity to topography admittance. This wide range has the advantage of not excluding possible although less likely density profiles and at the same time allows better exploring consequences of a non-hydrostatic moment of inertia.

We assume that all layers are homogenous in composition. Pressure induced density variations within a layer are expected to be less than a few % for Titan's core and below 2% for Titan's ice shell. Since these variations are smaller than the uncertainty on the mean density of the layers and density variations have a small effect on the amplitudes of the forced librations (see, e.g. Dumberry et al., 2013 for the case of librations of Mercury), we assume each layer k to be of uniform density ρ_k. A spherically symmetric reference model of Titan is then determined by specifying in addition the outer radii (R_k) of the layers.

Since a reference interior structure model is uniquely specified by 8 parameters (the densities ρ_k and radii R_k of all four layers) and only two quantities (the surface radius R and the total mass M_T) are known, we consider physically plausible ranges of densities and interfaces radii as in Baland et al. (2014). The method used here to construct the interior models differs from Baland et al. (2014) as we will choose the densities and radii randomly inside the ranges instead of picking equally-spaced values. This has the advantage of giving a finer exploration of the parameters space.

We consider the density of the ice shell to be between 920 kg/m^3, the density of pure ice Ih at ambient pressure and temperature (e.g. Sotin et al., 1998) and 1065 kg/m^3, corresponding to contaminated ice and/or dense clathrates (e.g. Fortes et al., 2007). Depending on the composition (ammonia-water or salted water) and pressure, the ocean density may typically vary from 950 kg/m^3 to 1350 kg/m^3 (Croft et al., 1988; Vance and Brown, 2013). The mantle can be made of high-pressure water ices possibly contaminated with rocky materials with density between 1300 kg/m^3 (e.g. Grasset et al., 2000) and about 2000 kg/m^3. The core can be made of hydrated silicates or rocks mixed with ice and/or iron