Short period librations in a three-layer Titan

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Goal

The knowledge of the rotational motion is an important piece of information about the interior process of bodies and to understand the tidal response. Recently, trough the observations acquired by the space mission Cassini, the rotational motion of Titan has been determined (Stiles et al. 2008, 2010, Lorenz et al. 2008). The variations around the uniform rotational motion are the librations and they present a wide spectrum of frequencies due to the orbital variations of the satellite. Here we investigate the librational signature of Titan in longitude and latitude by taking into account the gravitational coupling of Saturn with a non-keplerian orbit and internal couplings.

Two different timescales dominate the spectrum, long periods related to the motion of the nodes of the orbit and short periods related to the orbital period of the satellite. These long period librations have amplitudes almost independent of the distribution of mass and bring no information on the geophysical interior. On contrary, the short period librations are sensitive to the interior as for example the presence of the putative ocean increases strongly the amplitude of short period librations. Nevertheless, it is necessary to take into account all librations (long and short) in order to interpret the spacecraft observations.

Orbital motion

The orbital motion of Titan is obtained from the JPL Horizons ephemeris for 400 years (Giorgini etal 1996). The forcing frequencies acting on Titan can be determined by a frequency analysis of the true longitude υ (Laskar, 1988, 2005). The largest forcing term is found at orbital frequency, with an amplitude of two times the eccentricity of Titan. Two frequencies are identified related to the orbital motion of Saturn around the Sun, at 14.72 years and 29.43 years respectively (semi-annual and annual period of Saturn). Very long period terms are expected (Vienne et al. 1995), but are missing in our analysis because of the relatively short period of data available.

Internal model

Titan's internal structure has been partially constrained by different analysis: gravity field (Iess et al. 2010) and topography (Zebker et al.2009) give information on the interior and shell structure, and conductivity measurements argued for an ocean at 30 to 60km below the surface (Béghin et al. 2010).
Several internal structure models of Titan are investigated, with or without ocean. We used the models developed by Fortes (Fortes, 2012), which are consistent with different chemical and thermal evolutions of Titan. Two of them are ocean models, with extremal densities (about 1000 kg.m^{-3} and 1200 kg.m^{-3}), and the four others are non-ocean models with different chemical composition, densities and layer sizes (Fig. 1). Actually, Bills & Nimmo (2008) and Baland et al. (2011) showed that full solid models are not compatible with the measured obliquity for Titan in a Cassini's state. However, investigation of solid models compatible with the different scenarios of evolution of Titan's interior is still interesting since the possibility to be offset of Cassini's state can not be ruled out.

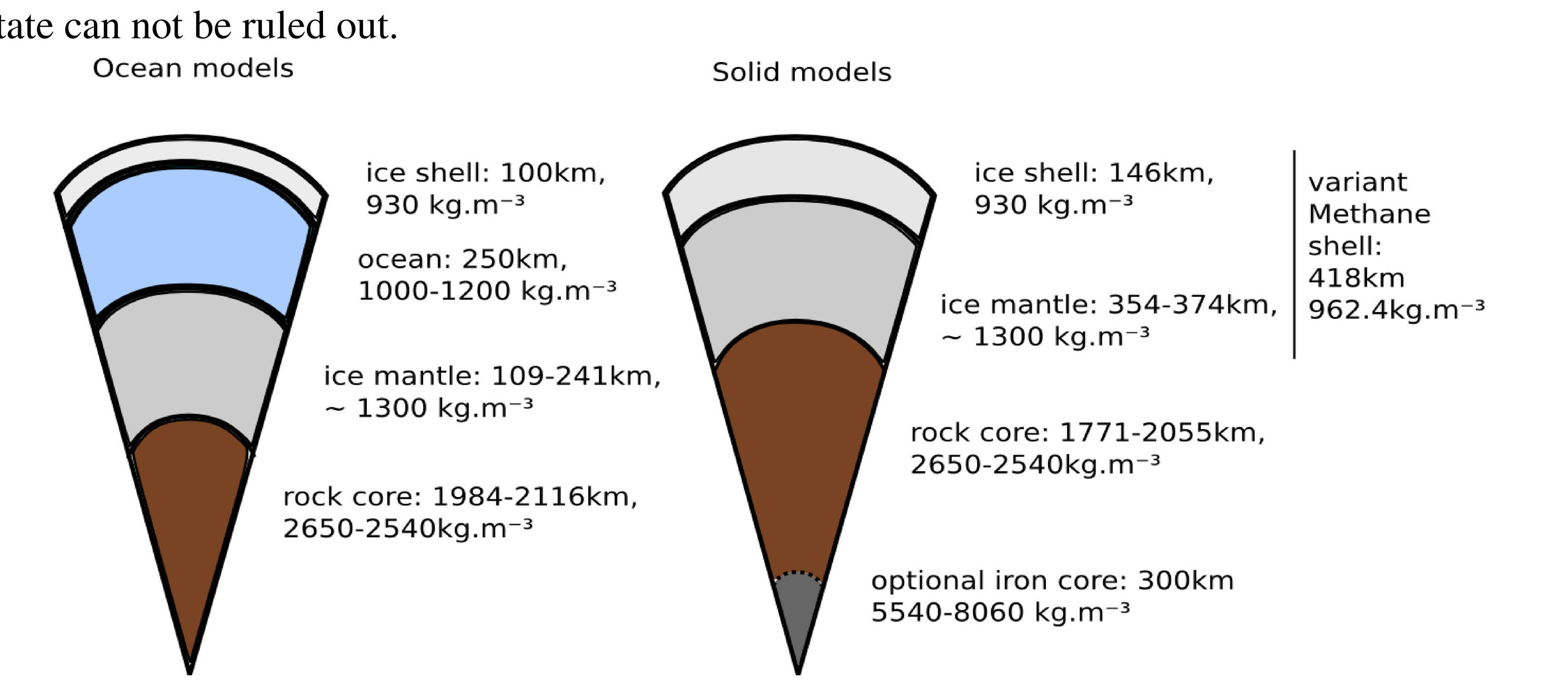

Fig 1. Different internal structure models of Titan from Fortes (2012). Two models are oceanic, with different densities (1000 kg.m^{-3} and 1200kg.m^{-3}) corresponding to extremal possibilities. The four other models are solid, with different ice mantle size (or methane shell), rock core density or eventually the presence of an iron core. These models are compatible with the different formation and evolution scenarios of Titan.

Librational motion

The angular momentum equation for Titan has been computed by Van Hoolst et al. (2009), depending on the libration angle γ of each layer and the angle between the principal axis and the direction of Titan to Saturn Ψ.

$$\sum_j C_j \ddot{\gamma}_j = \frac{3}{2}\frac{Gm}{r^3}\sum_j (B_j - A_j)\sin 2\Psi_j \quad ; \quad C_i\ddot{\gamma}_i = \Gamma_{grav} + \Gamma_{int} + \Gamma_{pressure}$$

We can express the different torques (gravitation, internal, pressure) acting on the triaxial body and on each layer are expressed following the approch of Van Hoolst et al. (2009). The torques depend on the density variations, moments of inertia (Aj<Bj<Cj for each layer j) and misalignment between the shell and the inner core.
The moments of inertia for three-layer models of Titan are computed assuming the hydrostatic equilibrieum with the Clairaut's equation extented to a synchronous rotating body deformed by rotation and tides (Van Hoolst et al. 2008).
The non-keplerian forcing has been introduced for the Galilean satellites by Rambaux et al. (2011), and we follow the same approach.

Freq.(rad/days)	Period (days)	A(0) (")	Identification
0.3940	15.945421	-25.6238	$L-\varpi$
0.7880	7.972710	-0.1150	$2L-2\varpi$
0.3941	15.942355	-0.1696	–
0.001169	5374.8375	42.5859	$2\lambda_{Sun}$
0.0005840	10758.8785	39.3566	λ_{Sun}
0.3928	15.9919	-0.6423e-1	–
0.001753	3584.2472	6.0357	$3\lambda_{Sun}$
1.1821	5.3151	-0.1276e-2	$3L-3\varpi$

Table 1. Librations of Titan due to orbital forcing for the light ocean model. The solutions are written in terms of $(A(0)+A(1)t+...)\sin(\omega_j t+\alpha_j)$. Terms with periods of 3263 years (magnitude=307.17") and 703 years (magnitude=129.49") are predicted by Vienne et Duriez (1995), but are out of the period cover by Horizons ephemeris. We suspect that these frequencies are responsible for the time variable terms. L is the mean longitude of Titan, ϖ the longitude of its pericenter and L_{Sun} the mean longitude of the Sun. (10" = 0.124 km)

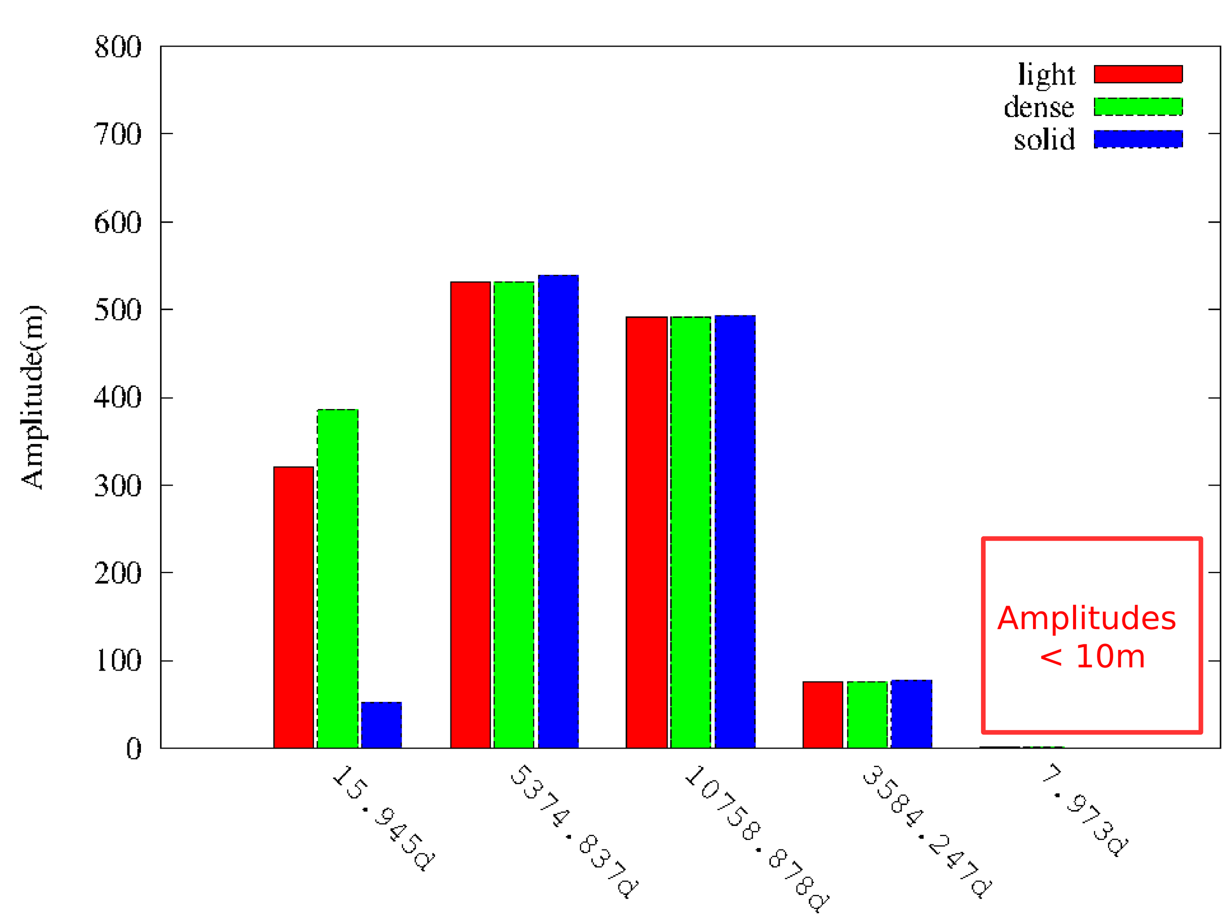

Fig. 4. Amplitudes of librations in longitude for different excitation periods (days) for light ocean, dense ocean and solid models. All the solid models have almost the same response to excitation whatever their internal composition, they are represented by the blue bar. The amplitudes are expressed in terms of equatorial deviations in meters. At long periods, both solid and ocean models are acting similarly. At short periods, ocean models respond with a largest libration than the solid models. Information on the internal structure can be extracted from this period.

For each model and frequency, we compute the librations amplitudes in longitude (Fig. 2, Table 1 for a light ocean model). At low forcing frequencies, the gravitational torque is dominant compared to the inertia of the satellite (a general behavior shown in Rambaux et al. 2010). Consequently, the amplitudes are almost identical for all kind of model at long period (about 570 meters at equator for period of 14.72 years). There is no measurable difference between structure models for longitudinal librations at long periods.
For high frequencies, especially the orbital one (period of 15.945 days), the amplitude of the librations for oceans models are about six to eight times larger than for the solid models (about 375 m for the dense ocean model and 50 m for the solid models). This difference is due to that at high frequencies, the inertia dominates the gravitational torque. Since the ocean models depend on the moment of inertia of the ice shell, which is lower than the entire moment C, the amplitude of the librations will increase. The amplitude of the ice shell is constrained by the fact that it is coupled to the inner core with a gravitational torque.
The proper periods of each model (Fig. 3.) are far from the exciting periods given in Table 1. Proper periods are of about 250 and 1000 days for ocean models, and 850 days for solid models.
Taking into account the atmospheric torque from Tokano et al. (2005), the libration amplitude of light ocean model at Saturn's semi-annual period is increased by 45% (about 770m). This value of amplitude variation is two order of magnitude smaller than the observed value of 0.36°/year given by Lorenz et al. (2008).

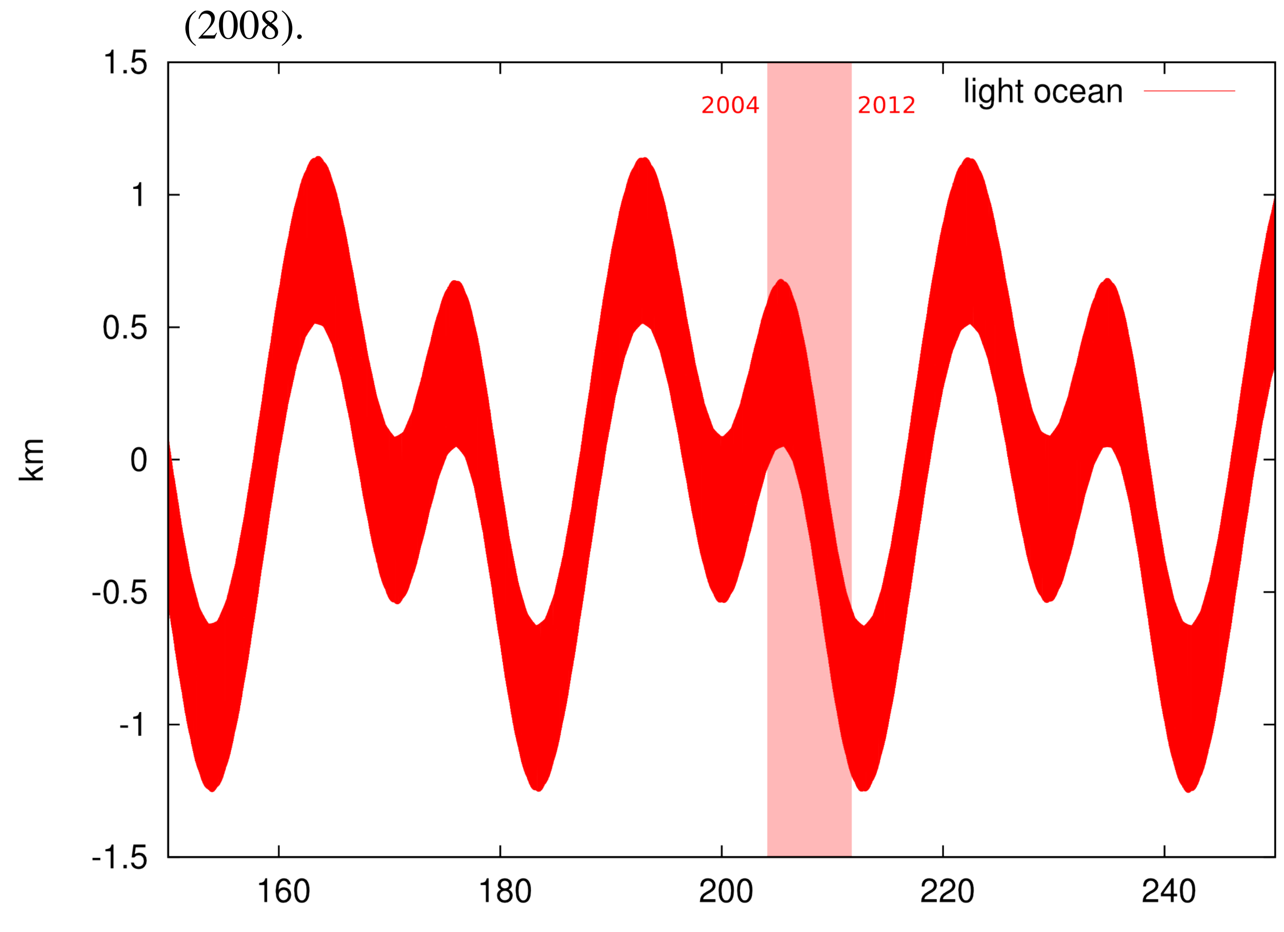

Fig 2. Amplitudes of longitudinal librations over 100 years for light ocean model expressed in equatorial deviation (km). The years are starting at January 1800. Saturn's annual and semi-annual terms are dominating the global response, but the 15.945 days excitation period is visible by the thickness of the curve. Amplitudes A(0) from Table 1 are summed here with the associated phases.

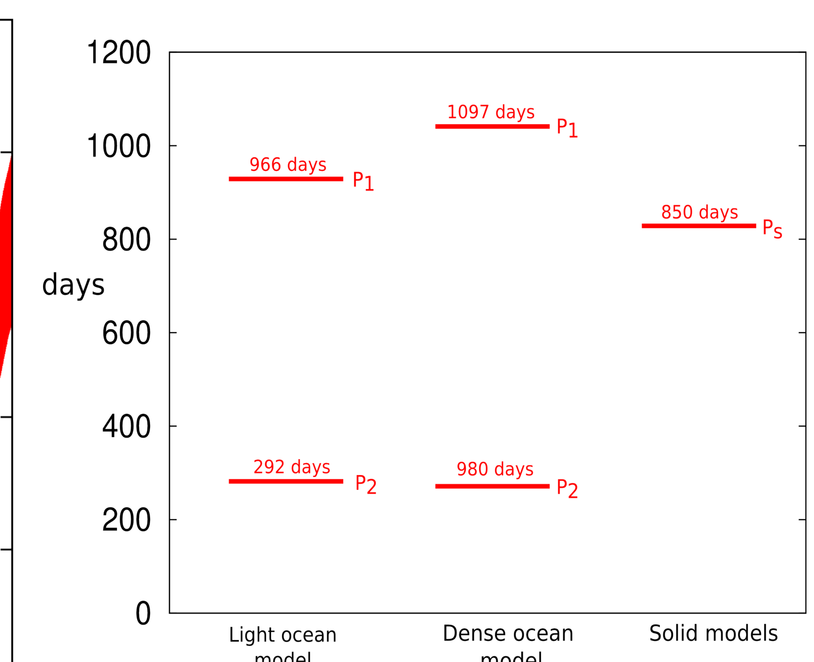

Fig. 3. Proper periods of the differents models in days. The two ocean models are distinctive with their double proper periods (P1, P2) induced by the ice shell and the inner core. Solid models have a proper period of about 850 days (Ps). All these periods are far from the excitation periods given in Table 1.

Conclusion

Detection of a 300-400 meters equatorial librational motion at orbital frequency could give some information on the internal structure, particularly the presence of a subsurface ocean. As mentionned by Stiles et al. (2008), the angular resolution of Cassini is at best 300m. This resolution seems to be sufficient to confirm the existence of an ocean. However, observation data and Titan spin model give a best error value of about 850 meters for landmark locations.
Investigation of the influence of deformations on the librations of Titan is actually in progress.

References

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