Journey to the Center of Titan

Evidence of a subsurface ocean

Gwenaël Boué

May 10, 2019

IAP Seminar

Titan and Saturn

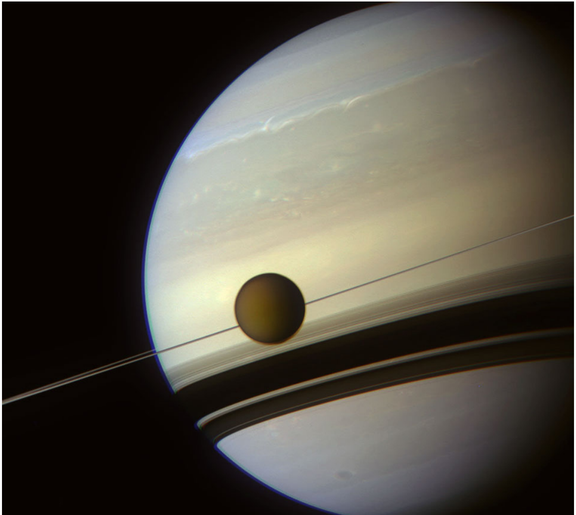

Image Credit: NASA/JPL-Caltech/Space Science Institute/J. Major

Titan interior

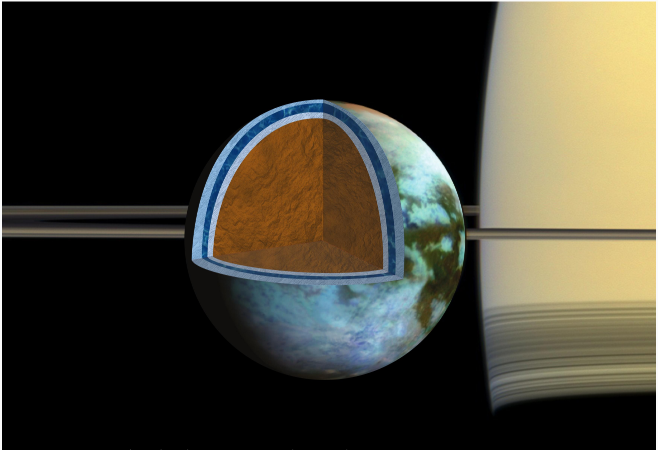

Image Credit: NASA/JPL/SSI/Univ. of Arizona/G. Mitri/University of Nantes

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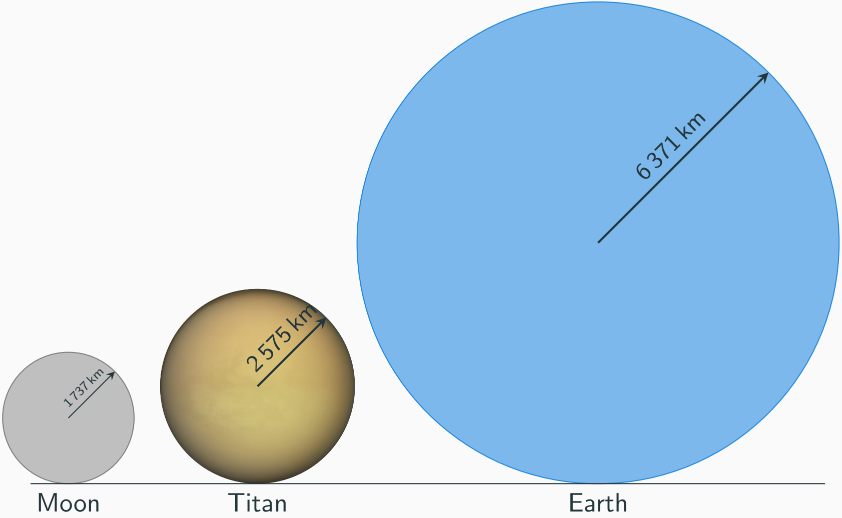
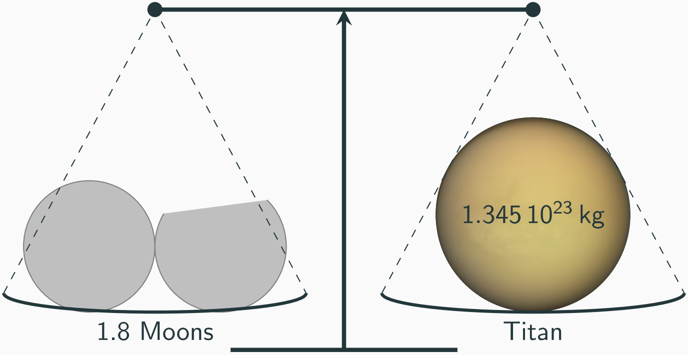
Basic properties

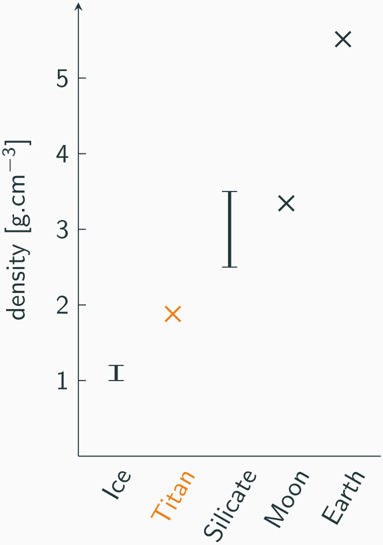
Physical properties : radius



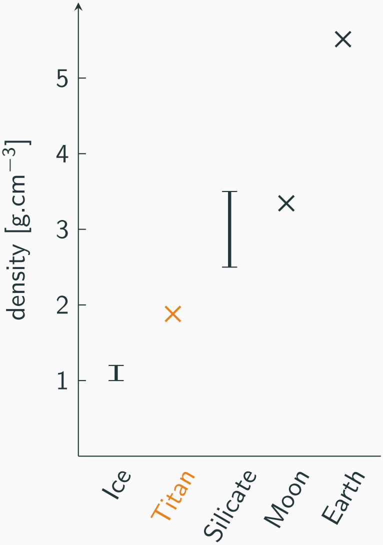
Physical properties : mass



Physical properties : density



Physical properties : density



Volumetric fraction of Ice

$$x = \frac{\rho_{\rm silicate} - \bar{\rho}}{\rho_{\rm silicate} - \rho_{\rm ice}} \in [0.48, 0.65]$$

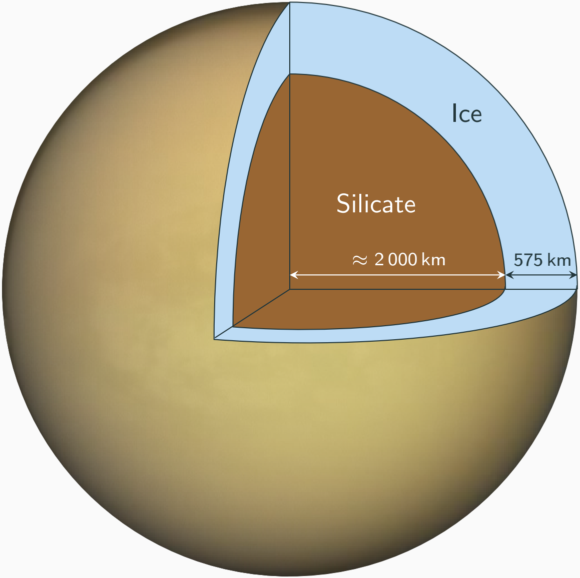
Mass fraction of Ice

$$\eta = \frac{\rho_{\rm ice}}{\bar{\rho}} x \in [0.30, 0.35]$$

Rock radius

$$\frac{R_{\rm rock}}{R} = (1 - x)^{1/3} \in [0.71, 0.81]$$

Physical properties : simple model



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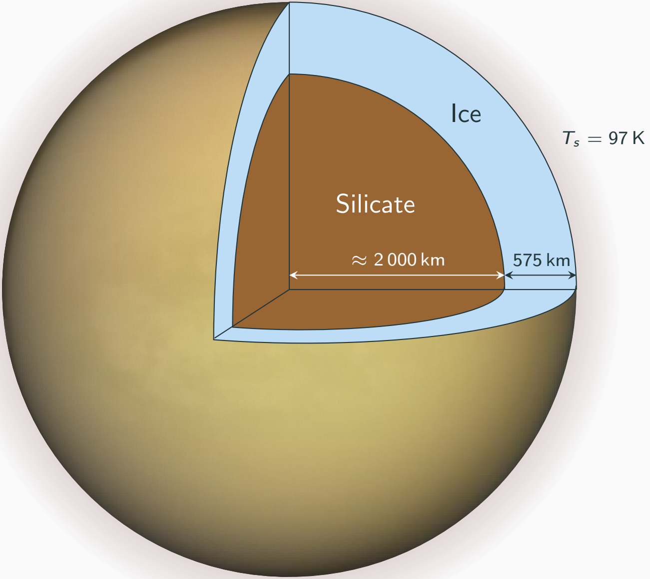
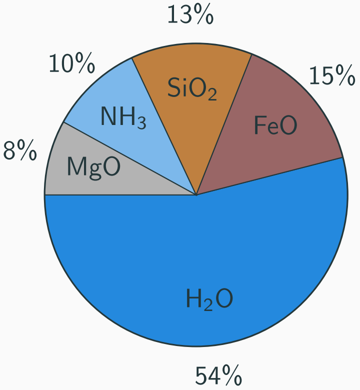


Is there an ocean below the surface ?

Thermodynamical argument

Titan's composition (Lewis 1971)

Solar-proportion mixture (by mass)



$$\bar{\rho} = 1.8\,\mathrm{g.cm^{-3}}$$

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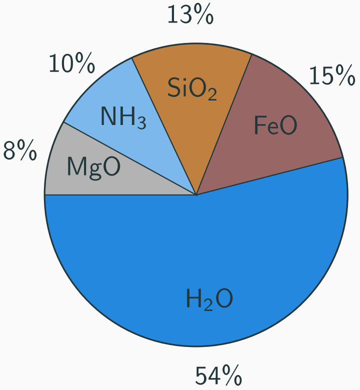

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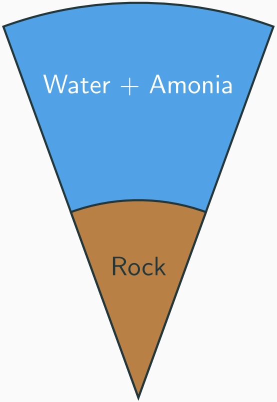

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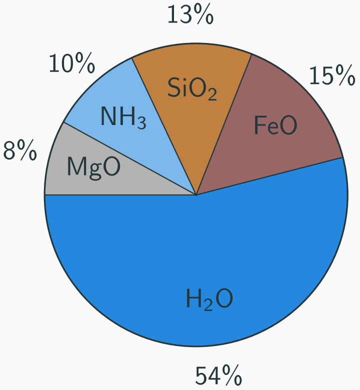

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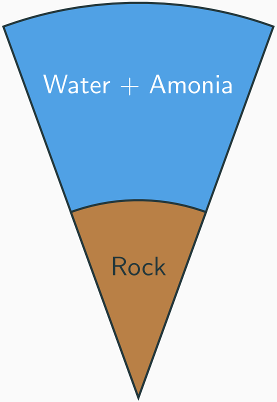
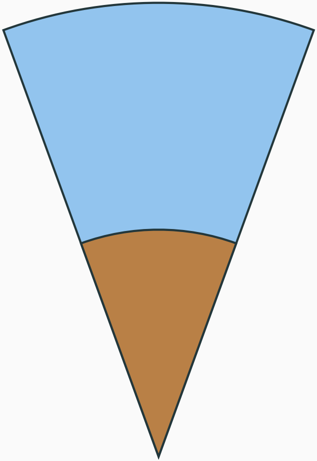
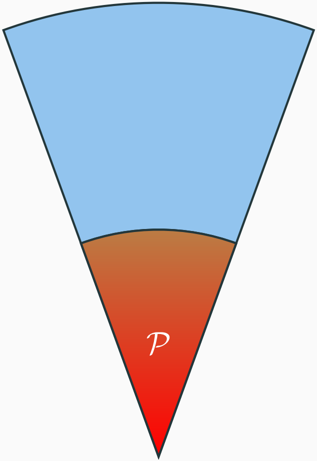


$\bar{\rho} = 1.8\,\mathrm{g.cm^{-3}}$

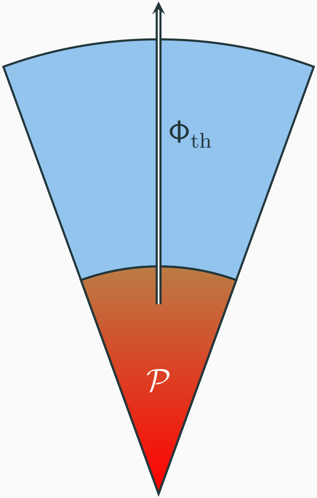
$T_{\mathrm{melt}} = 173\,\mathrm{K}$





Radiogenic heat production

$$\mathcal{P} \approx 250\,\mathrm{GW}$$



Radiogenic heat production

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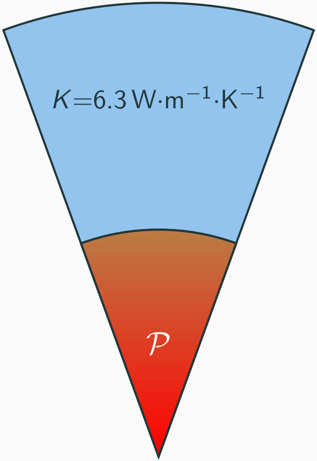
Thermal equilibrium

$$\Phi_{\rm th} \approx 250\,\mathrm{GW}$$

Liquid water (Lewis 1971)



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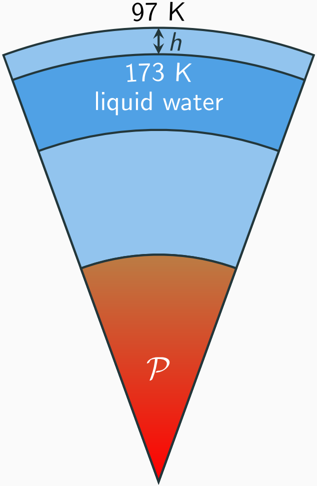
Fourier's law

$$\frac{\mathrm{d}T}{\mathrm{d}r} = \frac{\Phi_{\mathrm{th}}}{4\pi R^2 K} = 0.5\ \mathrm{K{\cdot}km^{-1}}$$



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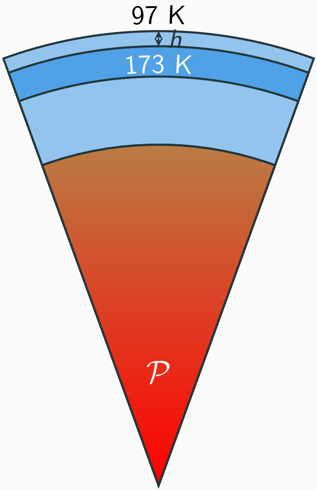
Ice shell thickness

$$h = 150\,\mathrm{km}$$



Radiogenic heat production

$$\mathcal{P} \approx 450\,\text{GW}$$

Thermal equilibrium

$$\Phi_{\mathrm{th}} \approx 450\,\text{GW}$$

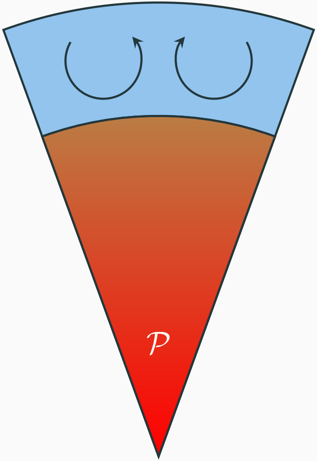
Fourier's law

$$\frac{\mathrm{d}T}{\mathrm{d}r} = \frac{\Phi_{\mathrm{th}}}{4\pi R^2 K} = 0.85\ \text{K}\cdot\text{km}^{-1}$$

Ice shell thickness

$$h = 90\,\text{km}$$

Solid-state convection in the ice (Reynolds & Cassen 1979)



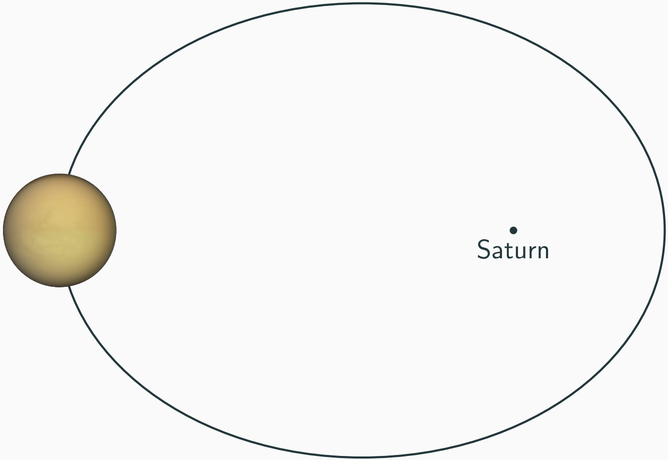
Ice convection

$$\left.\frac{\mathrm{d}T}{\mathrm{d}r}\right|_{\mathrm{conv}} \ll \left.\frac{\mathrm{d}T}{\mathrm{d}r}\right|_{\mathrm{cond}}$$

$$\Downarrow$$

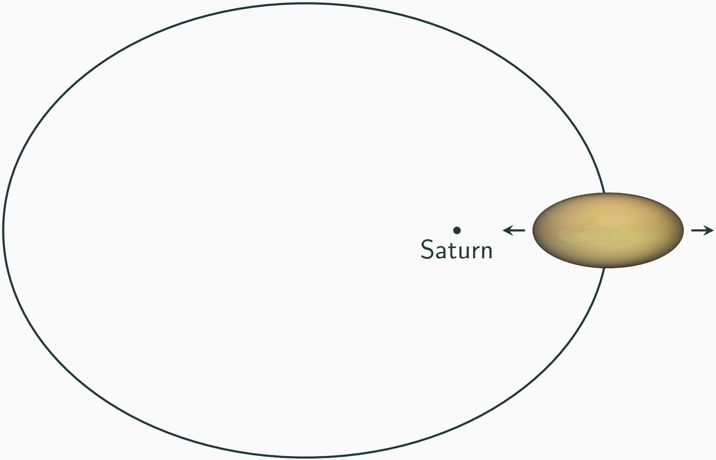
no liquid water

Tidal heat (Peale, Cassen & Reynolds 1979)



eccentricity : $e = 0.028$

Tidal heat (Peale, Cassen & Reynolds 1979)



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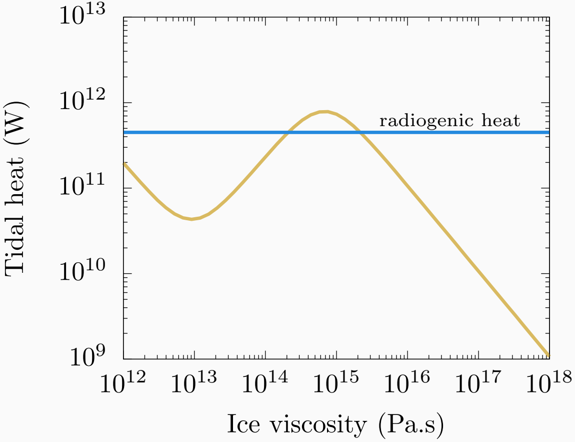
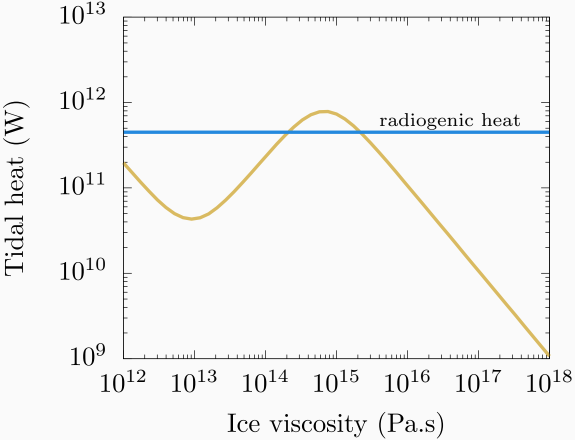
Tidal heat



radiogenic heat
Tidal heat (W)
Ice viscosity (Pa.s)
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}

Tidal heat

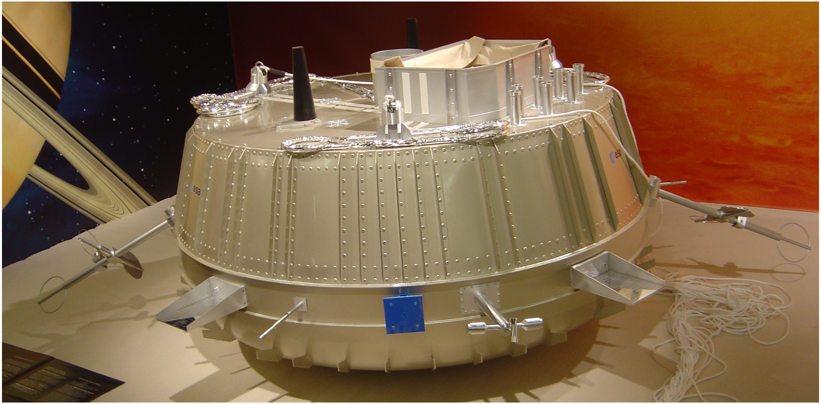


enough to maintain a liquid ocean ?

Electromagnetic clue

Huygens spacecraft ESA/ASI

Landing date : January 14, 2005



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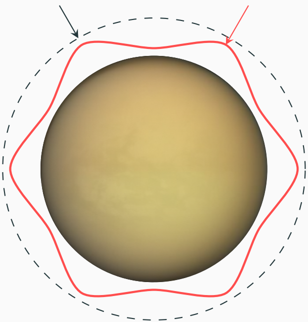
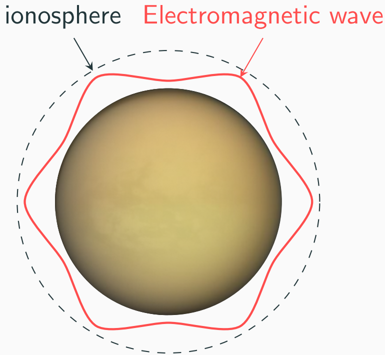


Huygens detection

signal at 36 Hz

Schumann resonance (Béghin et al. 2010, 2012)

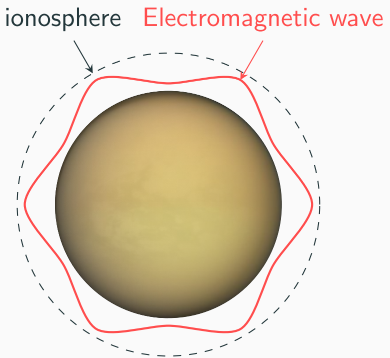


Huygens detection

signal at 36 Hz

Fundamental mode ($\lambda = 2\pi R$)

$$\nu = \frac{c}{2\pi R} \approx 18\,\text{Hz}$$



Huygens detection

signal at 36 Hz

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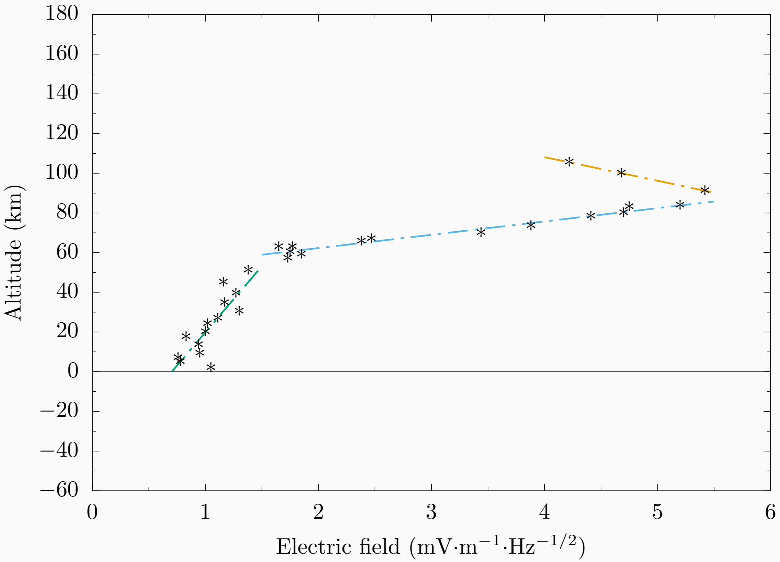
$\longrightarrow$ signal = 2nd harmonic

Electric field profile (Béghin et al. 2010)



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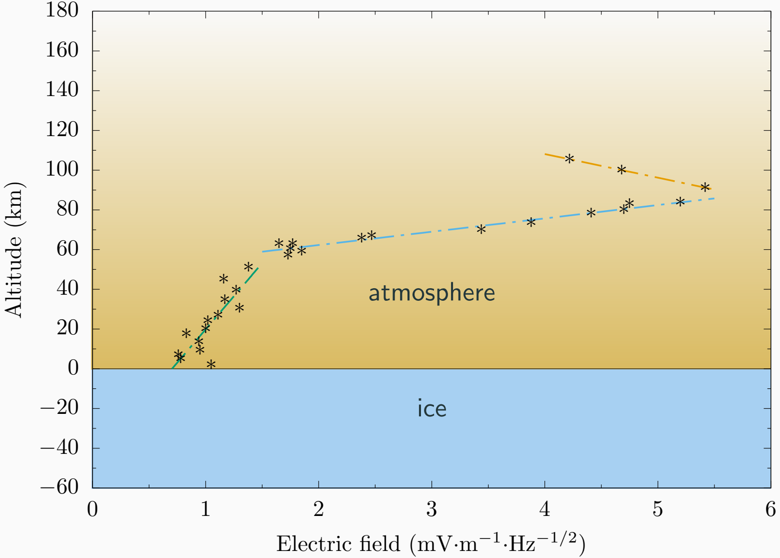

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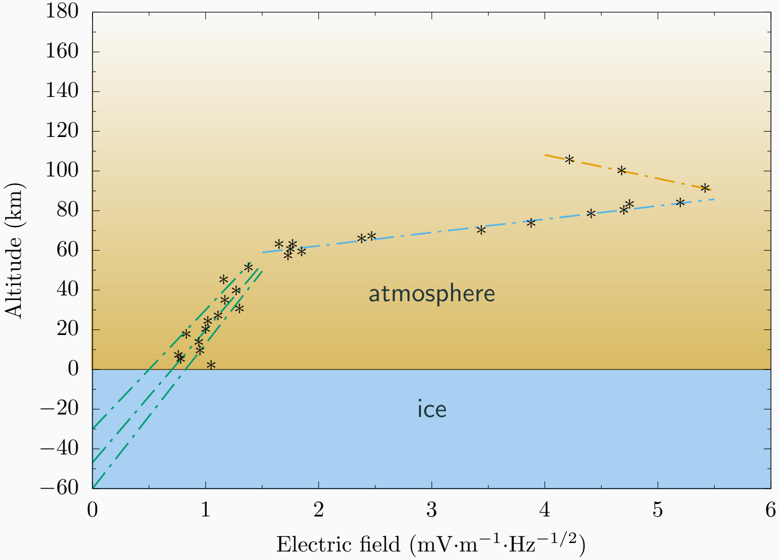

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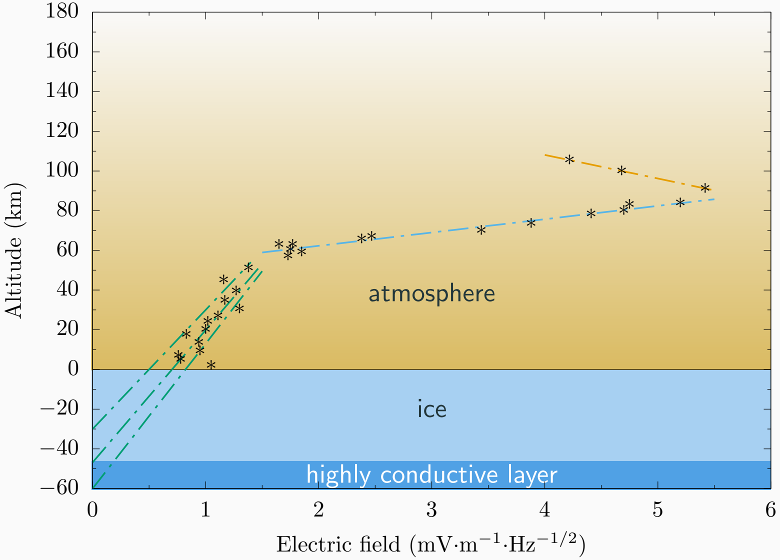


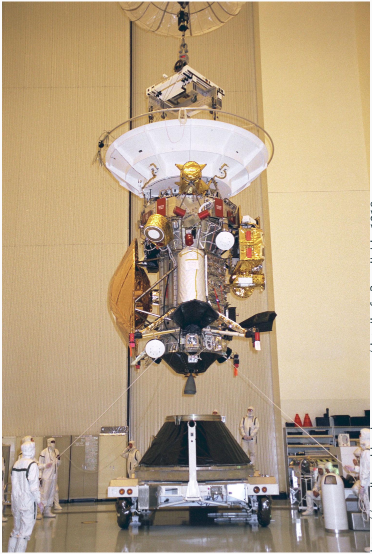
Geophysical evidence

Cassini-Huygens NASA/JPL/ESA/ASI

Launch date
October 15, 1997

Orbital insertion
July 1, 2004

Last contact
September 15, 2017



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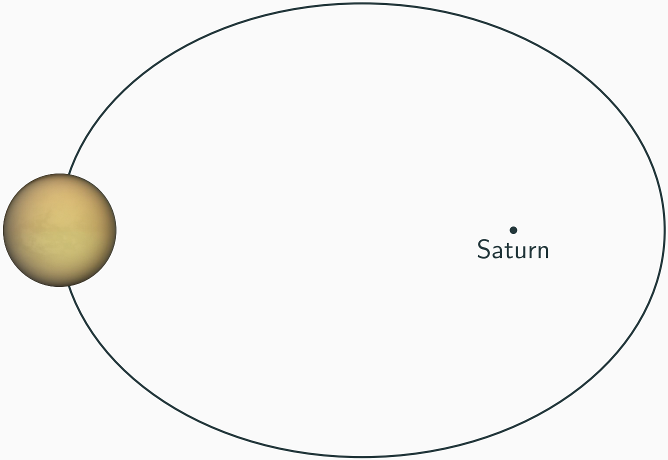

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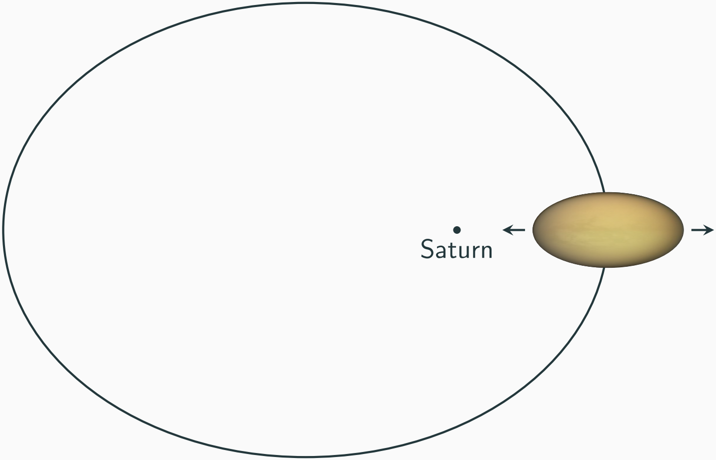
Tidal deformation (Iess et al. 2012)



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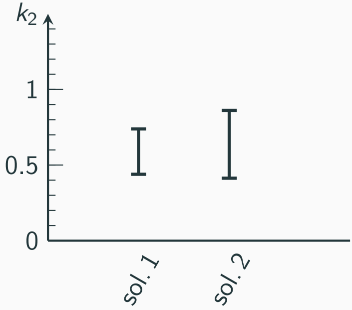
Tidal deformation (Iess 2012)

	Love number	
solution 1	$k_2 = 0.589 \pm 0.150$	Iess et al. 2012
solution 2	$k_2 = 0.637 \pm 0.224$	Iess et al. 2012



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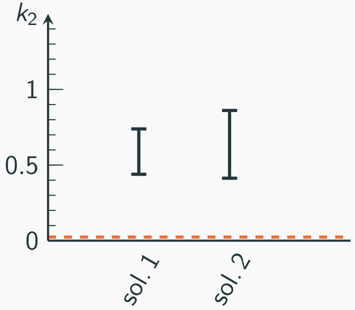

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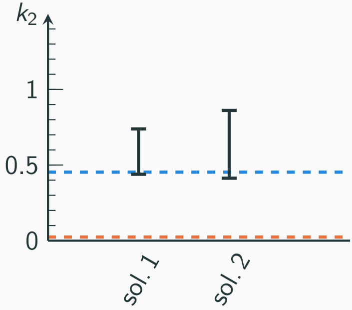
model with ocean	$k_2 = 0.453$	

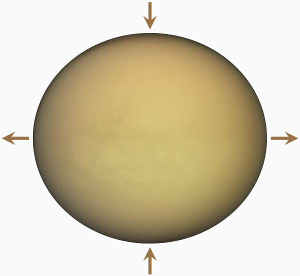


Classical mechanics puzzle

Additional information about Titan (1/2)

Titan's gravity field (Iess et al. 2012, SOL1a)

- Rotation → $J_2 = (33.599 \pm 0.332) \times 10^{-6}$
- Tidal deformation → $C_{22} = (10.121 \pm 0.029) \times 10^{-6}$



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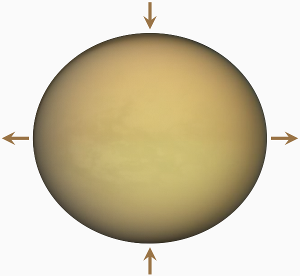

$J_2/C_{22} \approx 10/3 \quad \Rightarrow \quad$ hydrostatic equilibrium

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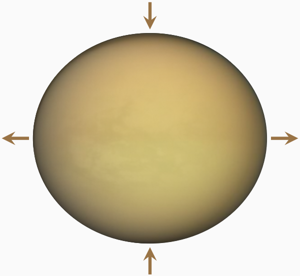
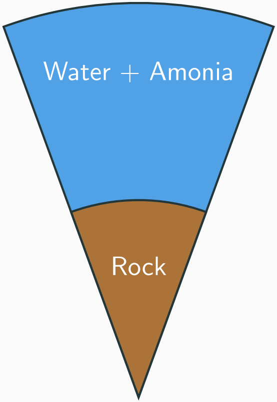


$J_2/C_{22} \approx 10/3 \quad \Rightarrow \quad$ hydrostatic equilibrium

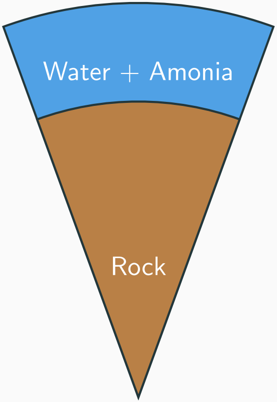
Amplitude $J_2 \quad \Rightarrow \quad I \approx 0.34\, mR^2$

Mass distribution



$I = 0.30\, mR^2$

$J_2 = 25 \times 10^{-6}$



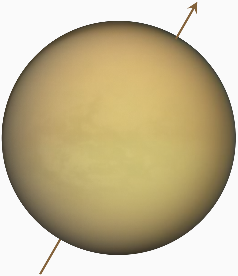
$I = 0.34\, mR^2$

$J_2 = 34 \times 10^{-6}$

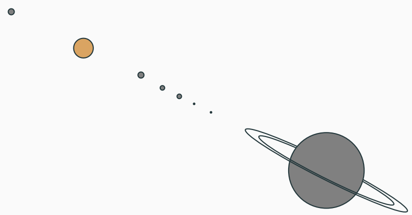
Additional information about Titan (2/2)

Titan's spin orientation (Stiles et al., 2008, 2010)

- Tilt amplitude → 0.32° obliquity
- Tilt direction → Cassini state

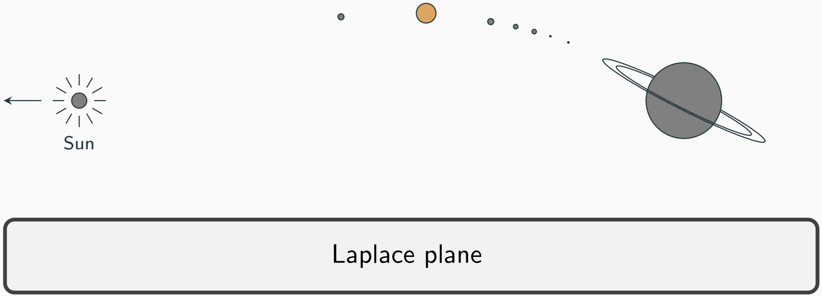


Laplace plane, Inclination and Obliquity



Regular satellites

Laplace plane, Inclination and Obliquity



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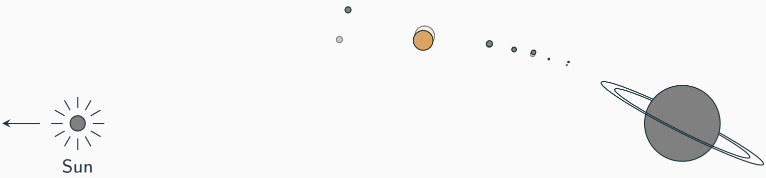
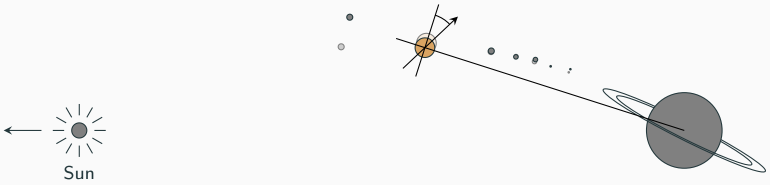


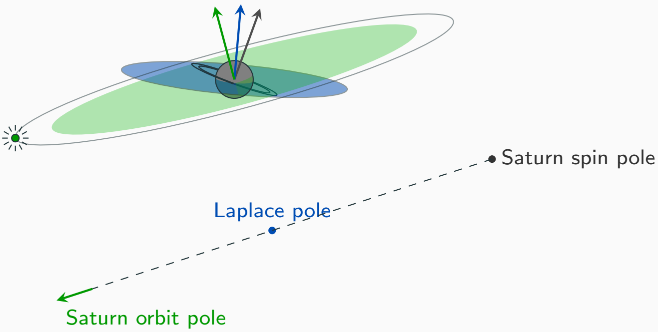
Orbital inclination

Laplace plane, Inclination and Obliquity



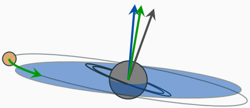
Titan’s obliquity

Pole positions



Orbit poles

Pole positions



• Saturn spin pole

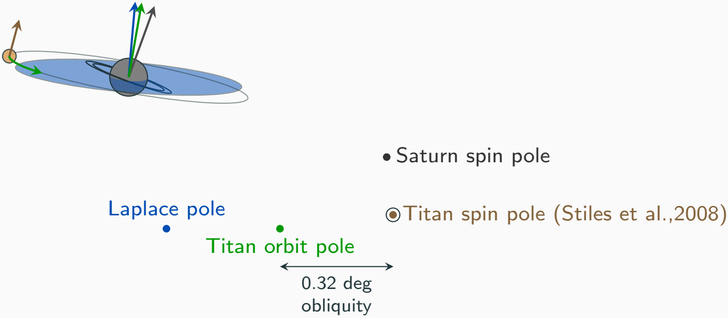
Laplace pole

Titan orbit pole

0.32 deg
inclination

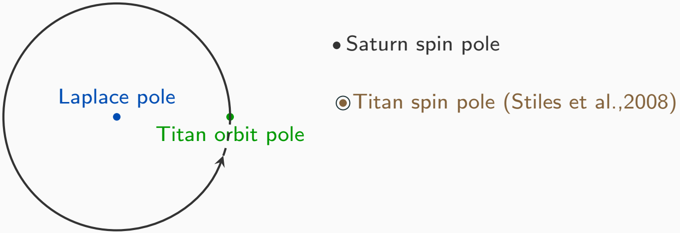
Orbit poles

Pole positions



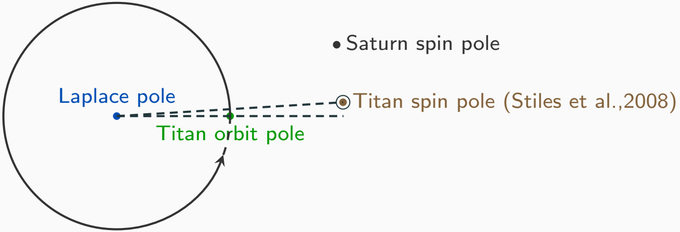
Orbit poles + Titan spin

Pole positions



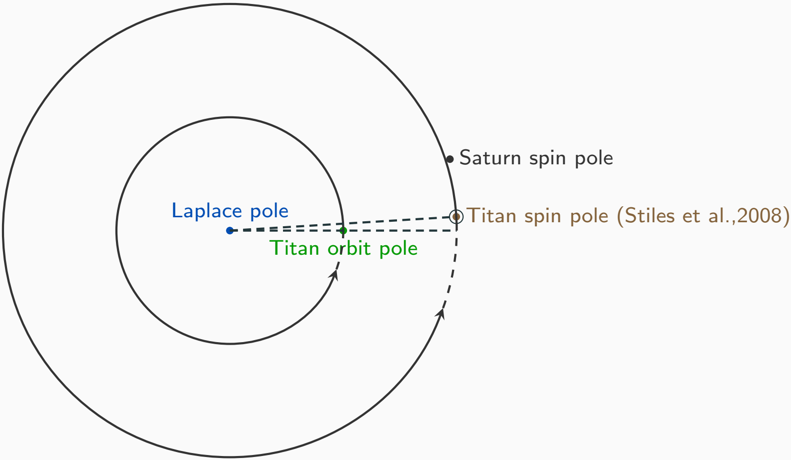
Titan's orbital precession (703 years)

Pole positions



Cassini state alignment + perturbations

Pole positions



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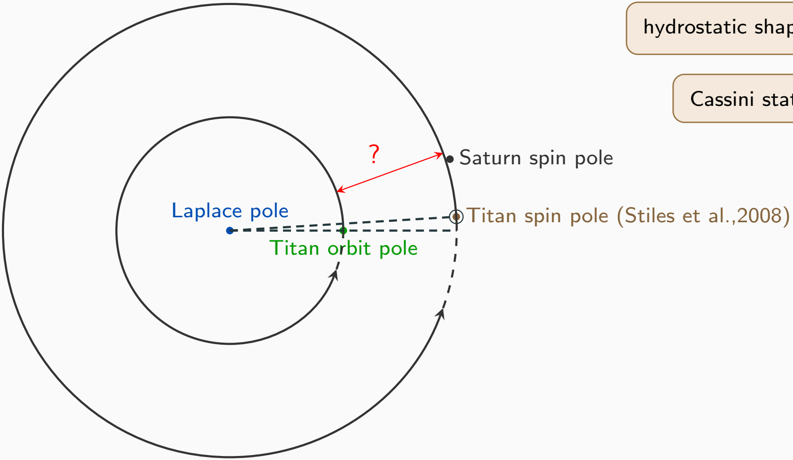
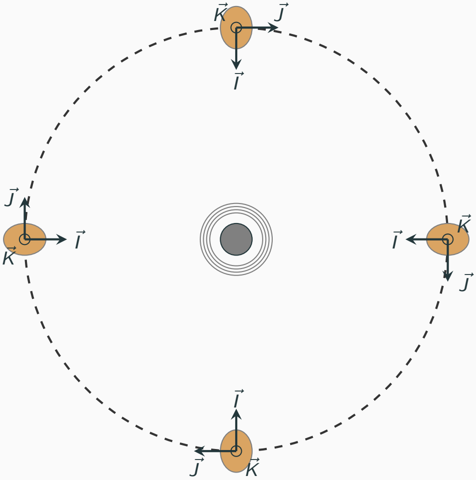


hydrostatic shape

Cassini state

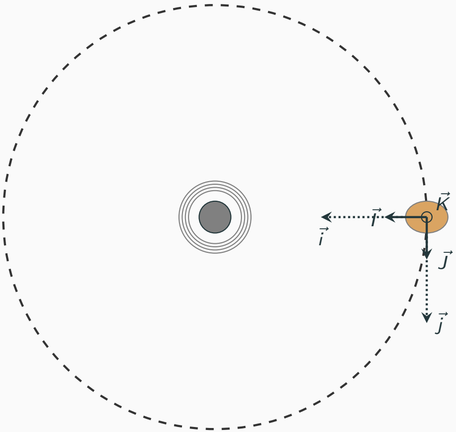
What's the expected obliquity ?

Synchronous rotation



Synchronous rotation

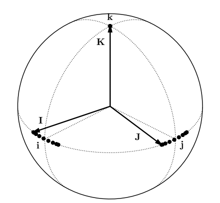
Synchronous rotation



Rotating frame

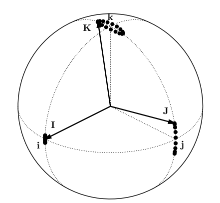
Rigid case

Eigenmodes



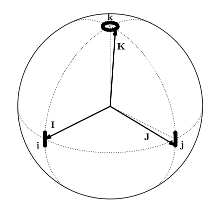
Libration in longitude

2.3 years



Wobble

275.6 years

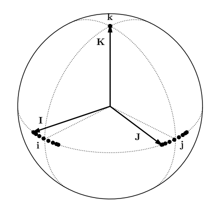


Libration in latitude

185.7 years

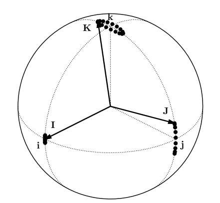
Rigid case

Eigenmodes



Libration in longitude

2.3 years



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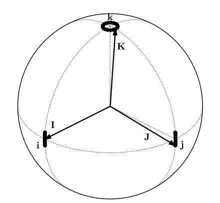
275.6 years



Libration in latitude

185.7 years

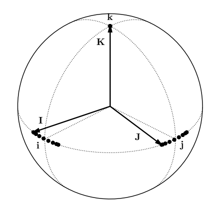
Orbital excitation

precession period (Vienne & Duriez, 1995)

703.5 years

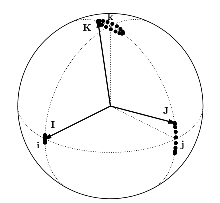
Rigid case

Eigenmodes



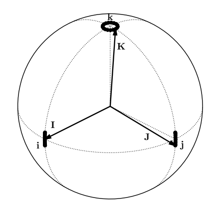
Libration in longitude

2.3 years



Wobble

275.6 years



Libration in latitude

185.7 years

Orbital excitation

precession period (Vienne & Duriez, 1995)

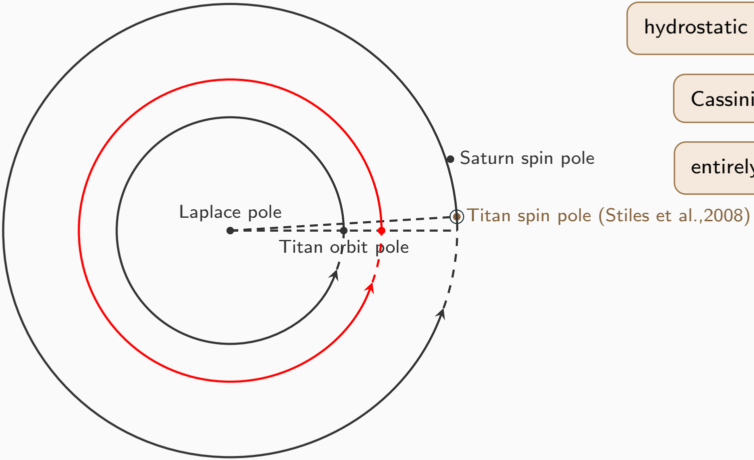
703.5 years

Forced obliquity

(Bills & Nimmo, 2011)

0.113 deg

Back to the pole position



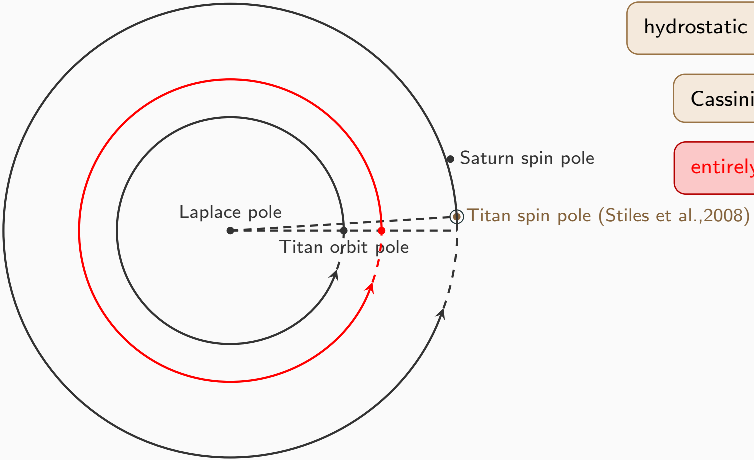
hydrostatic shape

Cassini state

entirely rigid

Forced obliquity

Back to the pole position



hydrostatic shape

Cassini state

entirely rigid

Titan is not rigid

Hint of a global sub-surface ocean

Frequency of libration in latitude = function of

- Mean moment of inertia $I/(mR^2)$
- Gravity field coefficients J_2, C_{22}

Hint of a global sub-surface ocean

Frequency of libration in latitude = function of

- Mean moment of inertia $I/(mR^2)$
- Gravity field coefficients J_2, C_{22}

Bills & Nimmo (2011)

$$\text{obliquity} = 0.32^\circ \quad \Leftrightarrow \quad I = 0.45\, mR^2$$

Hint of a global sub-surface ocean

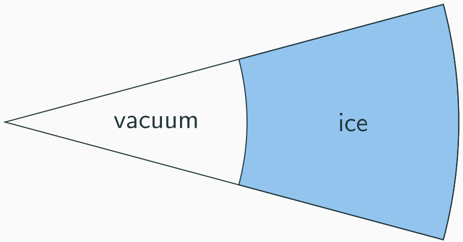
Frequency of libration in latitude = function of

- Mean moment of inertia $I/(mR^2)$
- Gravity field coefficients J_2, C_{22}

Bills & Nimmo (2011)

$$\text{obliquity} = 0.32^\circ \qquad \Leftrightarrow \qquad I = 0.45\, mR^2$$

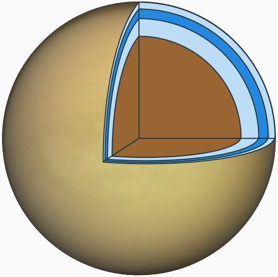
Example of body with $I = 0.45\, mR^2$



A global sub-surface ocean

Bills & Nimmo (2011)

> [. . .] strongly suggest that Titan does not precess as a rigid body, but has a surface shell which is partially decoupled (e.g. by an ocean) from the deeper interior. However, the precessional dynamics of a thin shell, overlaying a global subsurface ocean, are not yet fully understood (Noir et al., 2009).



A global sub-surface ocean

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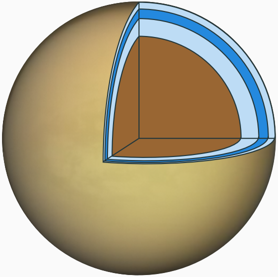


Three layer models

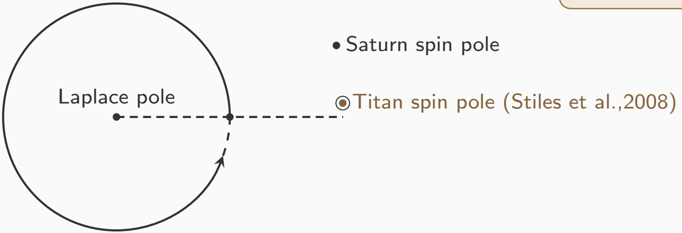
- Baland et al. (2011, 2014)
- Noyelles & Nimmo (2014)

Results

- Baland et al. (2011)
- Noyelles & Nimmo (2014)

hydrostatic shape

Cassini state



Results

- Baland et al. (2011)
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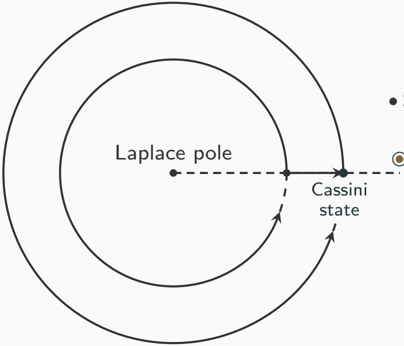
hydrostatic shape

Cassini state

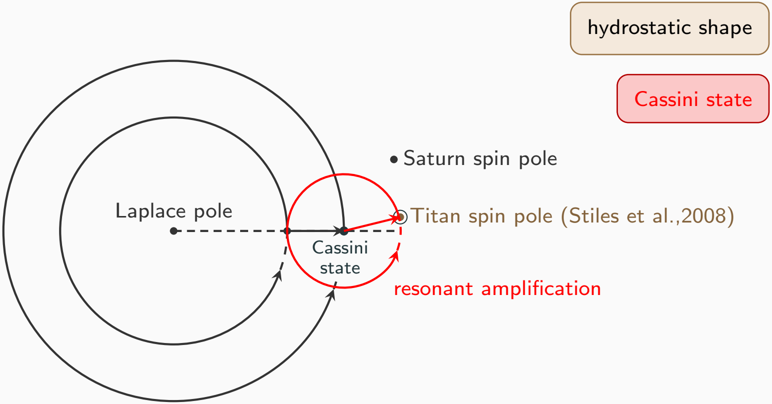


• Saturn spin pole

⊙ Titan spin pole (Stiles et al.,2008)

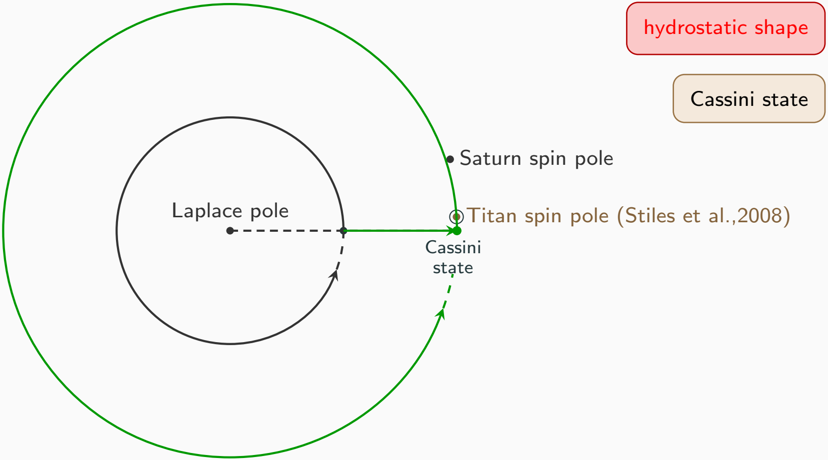
Results

- Baland et al. (2011)
- Noyelles & Nimmo (2014)



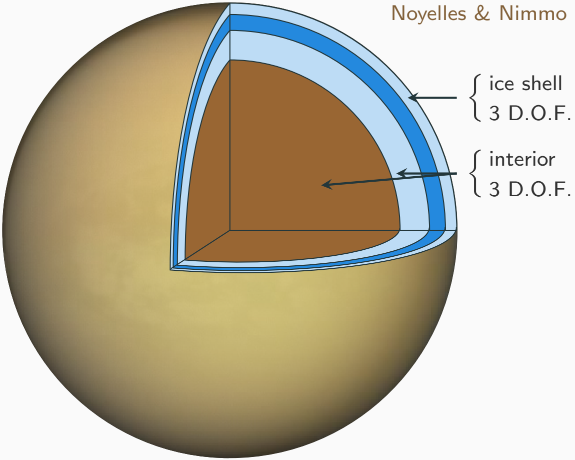
Results

- Baland et al. (2011)
- Noyelles & Nimmo (2014)
- Baland et al. (2014)

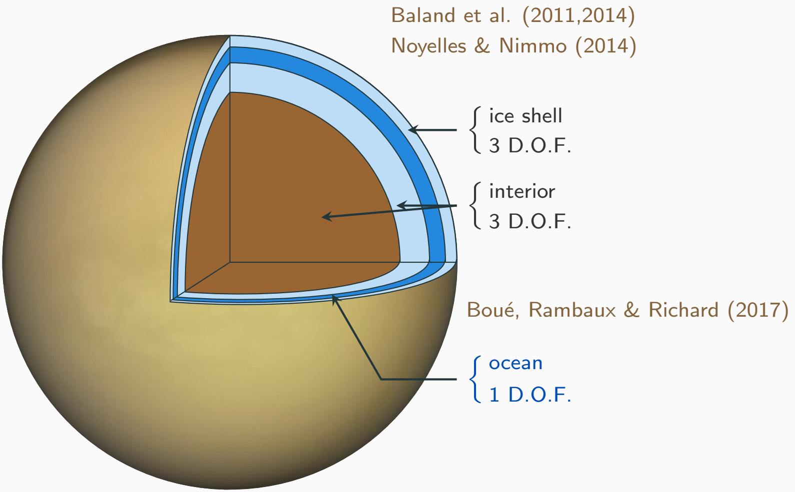


Dynamical model

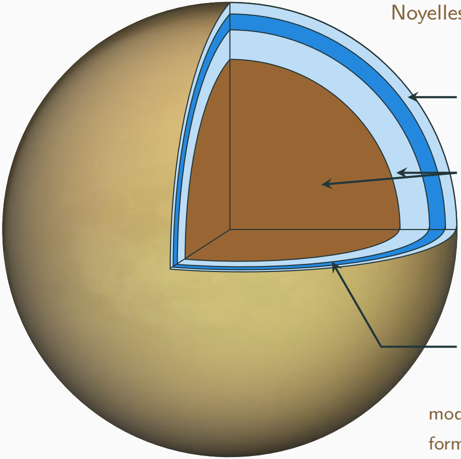
Baland et al. (2011,2014)
Noyelles & Nimmo (2014)



Dynamical model



Dynamical model



Baland et al. (2011,2014)

Noyelles & Nimmo (2014)

ice shell
3 D.O.F.

interior
3 D.O.F.

Boué, Rambaux & Richard (2017)

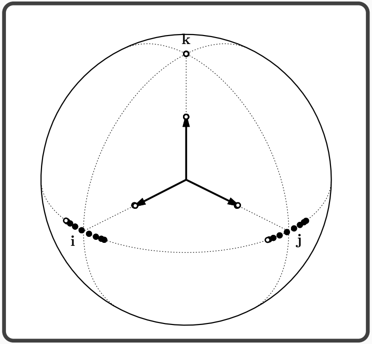
ocean
1 D.O.F.

model: Mathews (1991)

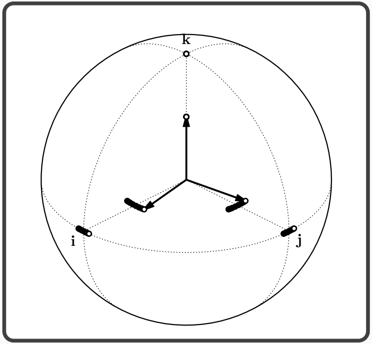
formalism: adapted from Poincaré (1901,1910)

Eigenmodes (Boué et al. 2017)

Libration in longitude



0.8 years

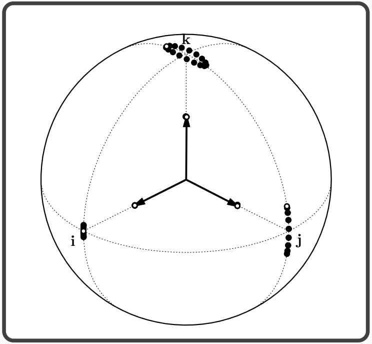


2.6 years

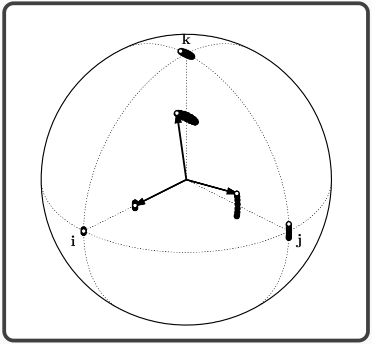
Using the "Light-ocean" interior model of Fortes (2012)

Eigenmodes (Boué et al. 2017)

Wobble



32.4 years

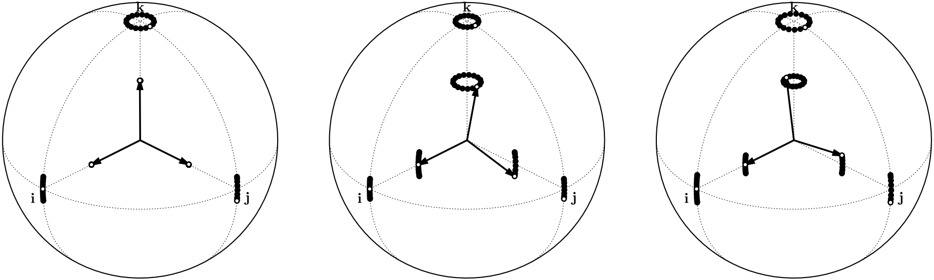


353.0 years

Using the "Light-ocean" interior model of Fortes (2012)

Eigenmodes (Boué et al. 2017)

Libration in latitude



15.6 years 244.4 years 930.5 years

Using the "Light-ocean" interior model of Fortes (2012)

Result (Boué et al. 2017)

Table 1: Obliquity of Titan's layers in degree.

	rigid	static ocean	rotating ocean
interior	0.113		
ocean	0.113		
shell	0.113		

Result (Boué et al. 2017)

Table 1: Obliquity of Titan's layers in degree.

	rigid	static ocean		rotating ocean
		F1	**F2**	
interior	0.113	0.149	0.207	
ocean	0.113			
shell	0.113	0.062	0.064	

F1 Light-ocean model of (Fortes, 2012)
F2 Dense-ocean model of (Fortes, 2012)

Result (Boué et al. 2017)

Table 1: Obliquity of Titan's layers in degree.

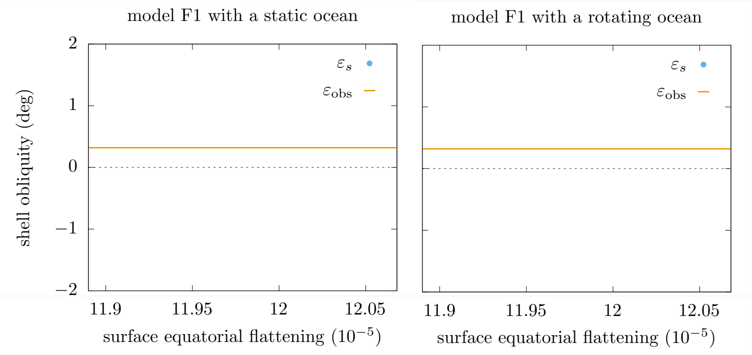
	rigid	static ocean		rotating ocean	
		F1	**F2**	**F1**	**F2**
interior	0.113	0.149	0.207	0.294	0.272
ocean	0.113			-0.477	0.207
shell	0.113	0.062	0.064	0.004	0.108

F1 Light-ocean model of (Fortes, 2012)
F2 Dense-ocean model of (Fortes, 2012)

Effect of a tiny deformation of the shell (Boué et al. 2017)

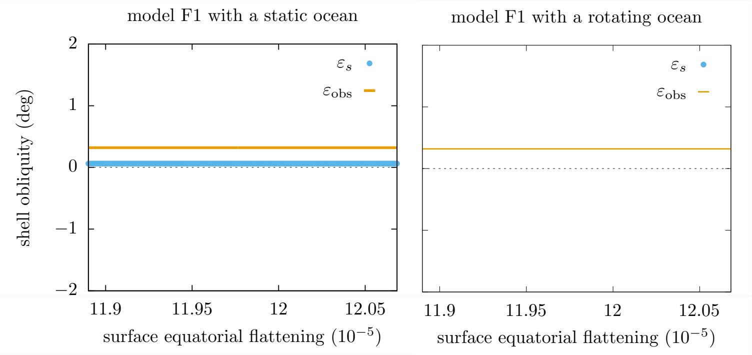
6 D.O.F

7 D.O.F.



Effect of a tiny deformation of the shell (Boué et al. 2017)

6 D.O.F 7 D.O.F.



Effect of a tiny deformation of the shell (Boué et al. 2017)

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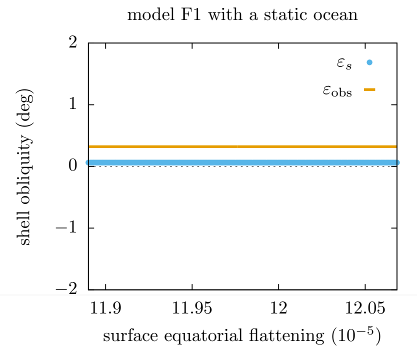
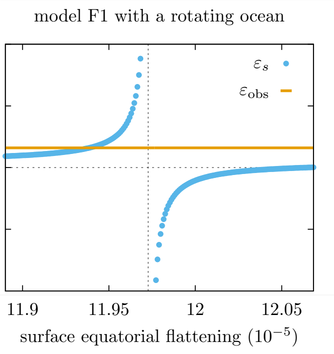




Concluding remarks

Summary

The presence of the ocean is

inferred from

- temperature profile (Lewis 1971)

detected through

- intensity of the atmospheric electric field (Béghin et al. 2010)
- amount of tidal deformation (Iess 2012)
- orientation of the spin axis (Boué et al. 2017)

Summary

The presence of the ocean is

inferred from

- temperature profile (Lewis 1971)

detected through

- intensity of the atmospheric electric field (Béghin et al. 2010)
- amount of tidal deformation (Iess 2012)
- orientation of the spin axis (Boué et al. 2017)

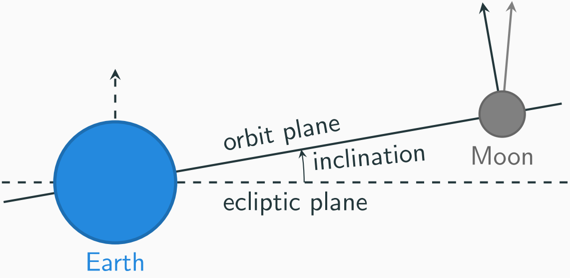
potentially detectable through

- libration in longitude (Richard et al. 2014)

Three famous laws (Cassini 1643)

Moon's rotation characteristics

1. the rotation rate is synchronous with the orbital mean motion
2. the inclination of the lunar equator plane to the ecliptic is constant
3. the spin axis and the normals to the ecliptic and orbit plane remain coplanar



Generalisation for an axially symmetric body (Colombo 1966)

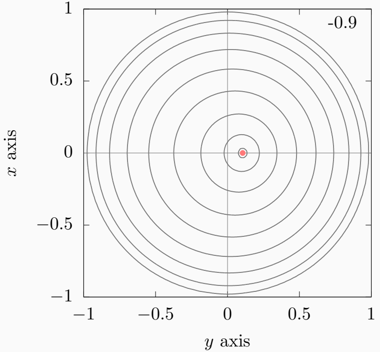


Figure 1: Trajectory of the spin-axis in a frame rotating at the orbital precession rate.

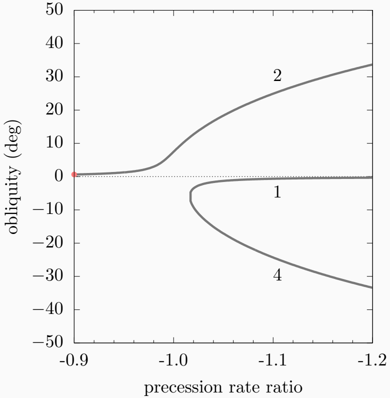
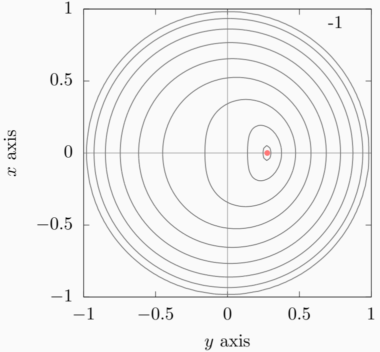


Figure 2: Equilibrium obliquity.

Generalisation for an axially symmetric body (Colombo 1966)



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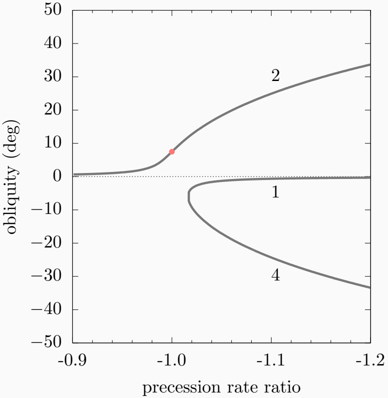

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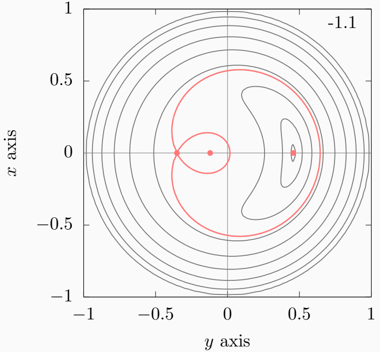

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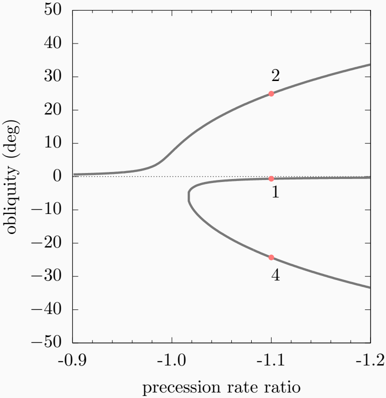

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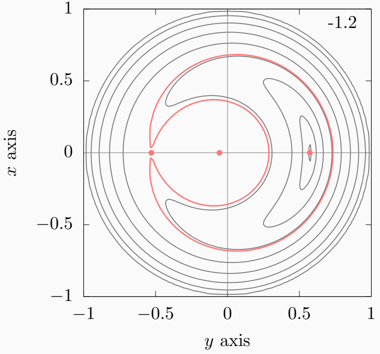

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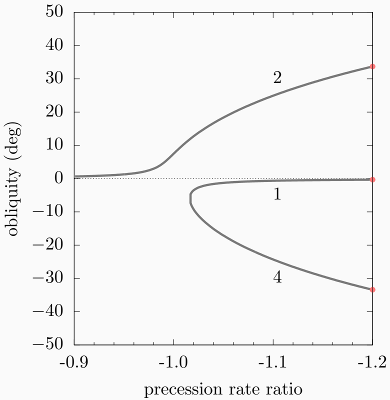

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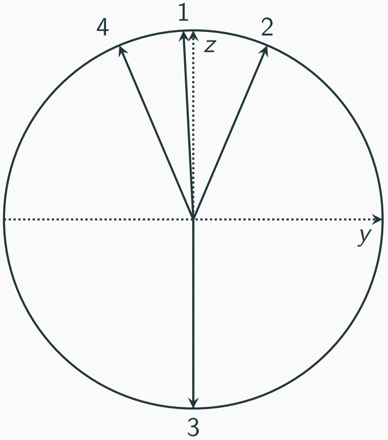
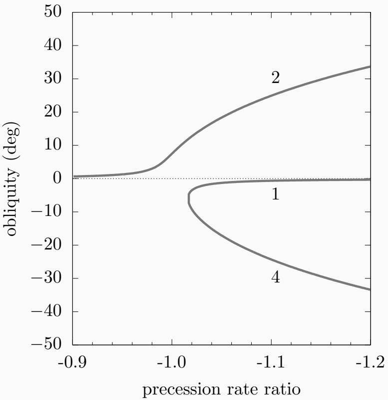


Figure 1: Numbering of the 4 Cassini states.



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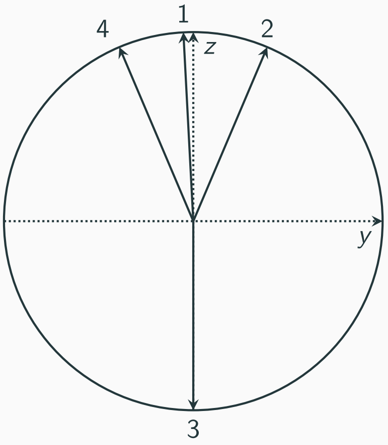


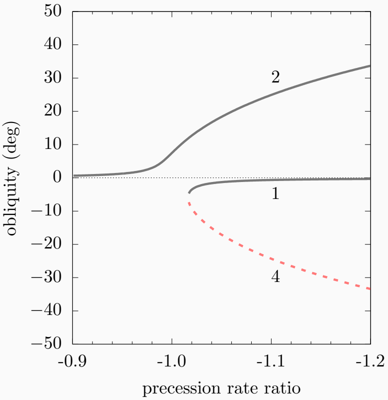
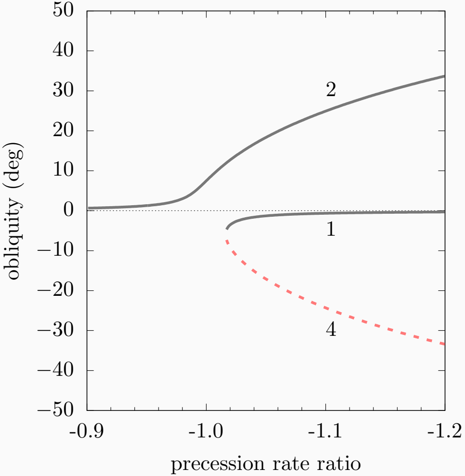
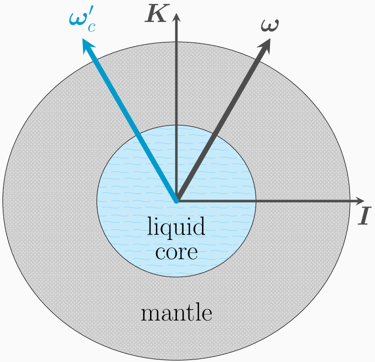


Figure 1: Equilibrium obliquity.

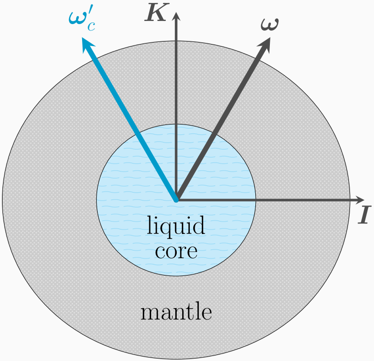
Axial asymmetry and spin-orbit resonances (Peale 1969)



4 Cassini states

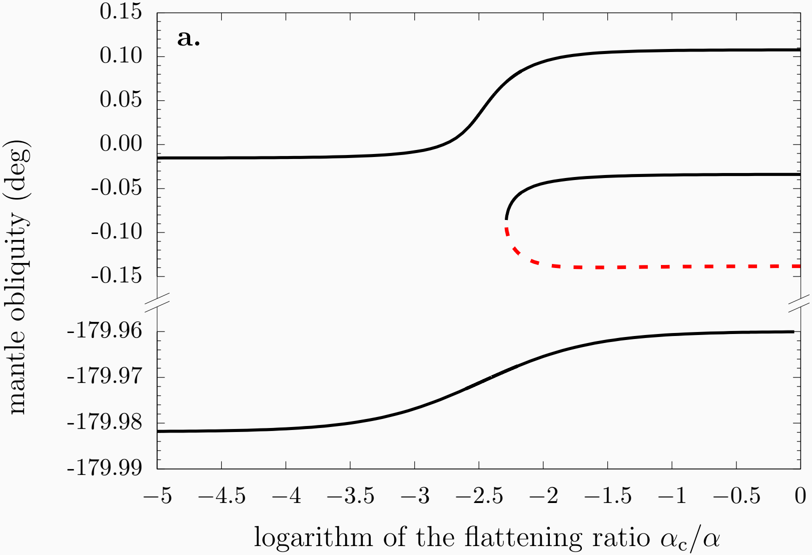

ω'_c
K
ω
I
liquid
core
mantle

Body with a liquid core (Boué in prep.)



Up to 16 Cassini states !

Body with a liquid core (Boué in prep.)



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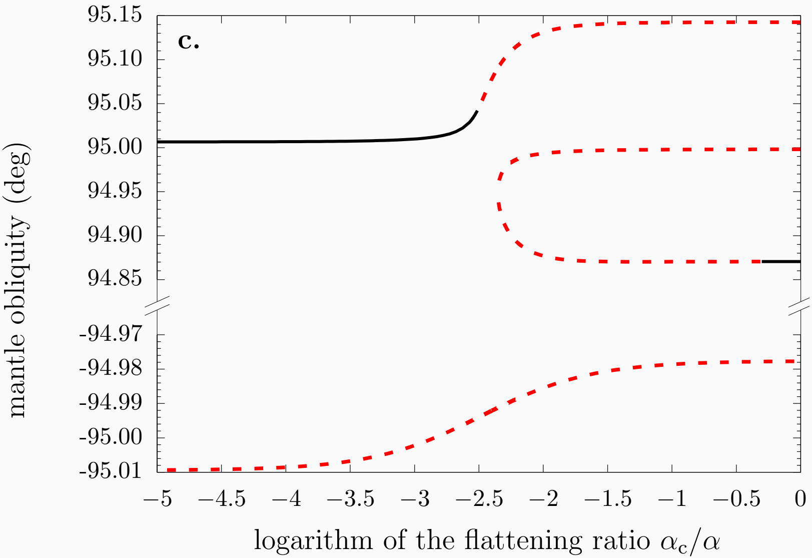

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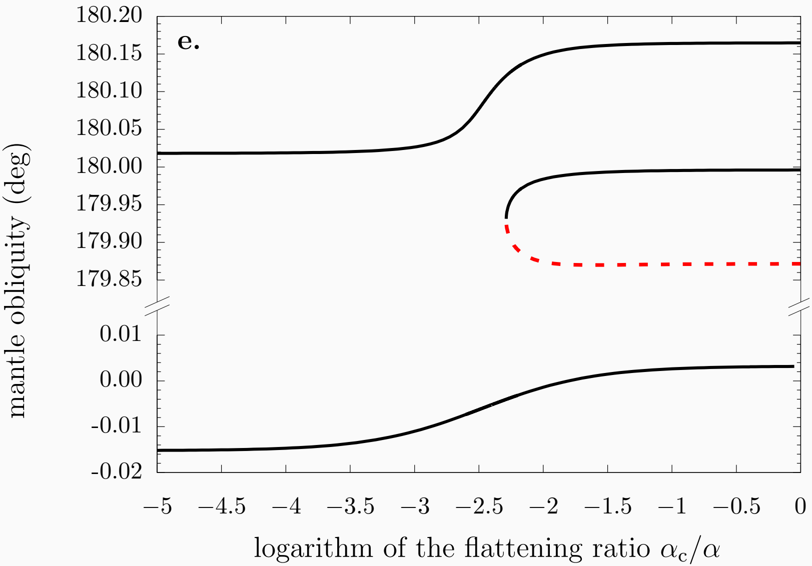
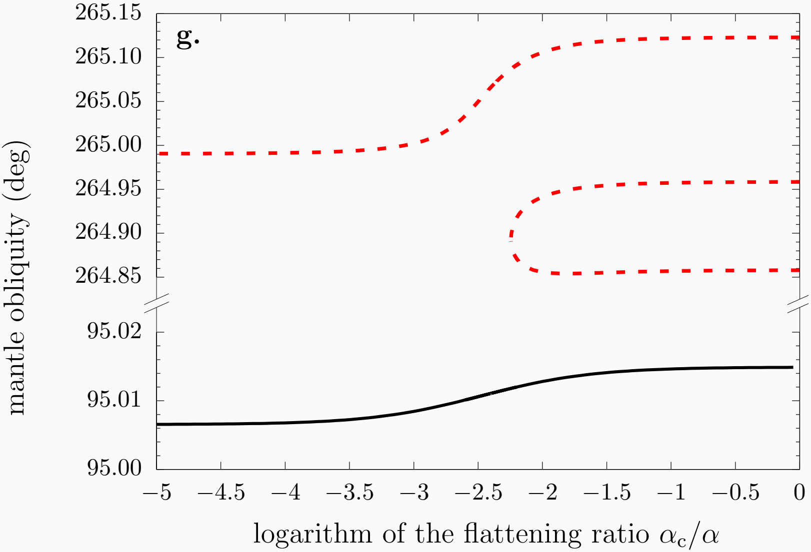
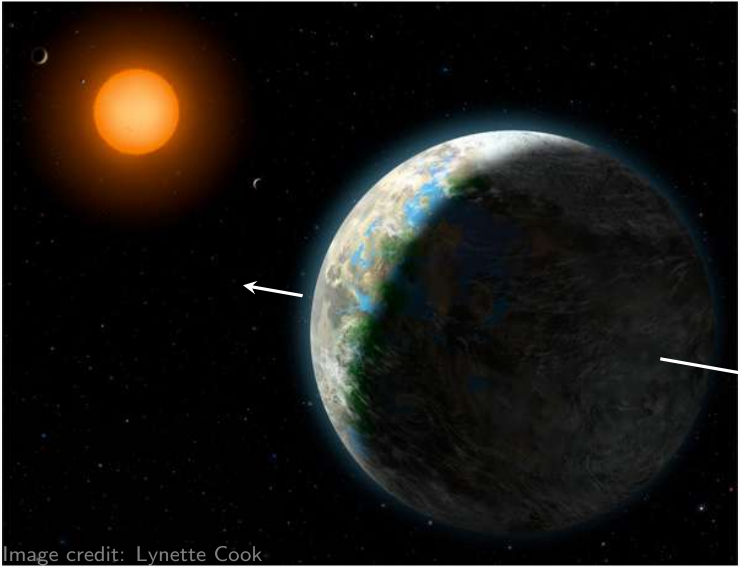



g.
mantle obliquity (deg)
265.15
265.10
265.05
265.00
264.95
264.90
264.85
95.02
95.01
95.00
−5
−4.5
−4
−3.5
−3
−2.5
−2
−1.5
−1
−0.5
0
logarithm of the flattening ratio α_c/α

Exoplanet orientation ?



Exoplanet orientation ?