ROTATION AND LIBRATION OF CELESTIAL BODIES

Nicolas Rambaux[1,2],

In collaboration with J. Castillo-Rogez[3], L. Cottereau[6], V. Dehant[4], O. Karatekin[4], A. Lemaitre[5], P. Robutel[2], J. Souchay[6], T. Van Hoolst[4], & J. Williams[3]…

1: University Pierre et Marie Curie– Paris 6, 2: IMCCE –Observatory of Paris
3: JPL/Caltech
4: Royal Observatory of Belgium, 5: FUNDP, Belgium
6: SYRTE, Observatory of Paris

Outline

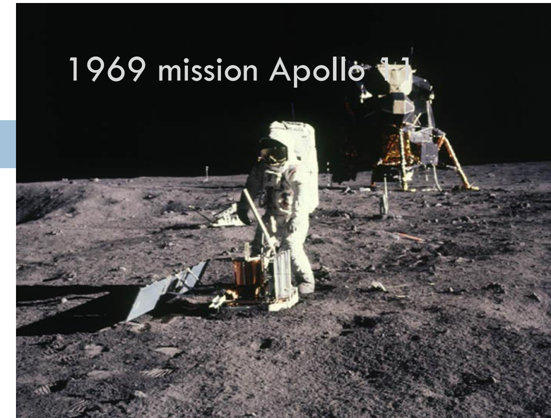
- Introduction
- Observation methods
- The Moon rotation
- Enceladus and other satellites
- Mercury, Venus
- Conclusion

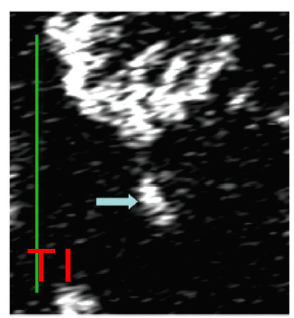
Rotational implications

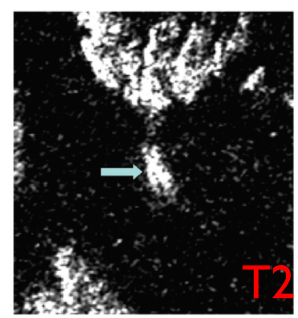
1. It is important for **cartographic coordinates** (e.g. Archinal etal 2011);
2. The knowledge of the rotational motion of bodies can be used to **sound the internal structure** by measuring the amplitudes of nutations/librations and precession, this idea comes from Hopkins 1839 (e.g. Mathews etal 2002; Williams etal 2001…). It is possible to distinguish between a differentiated/undifferentiated body or to detect internal liquid layer (e.g. Margot etal 2007, 2012…);

How to measure?

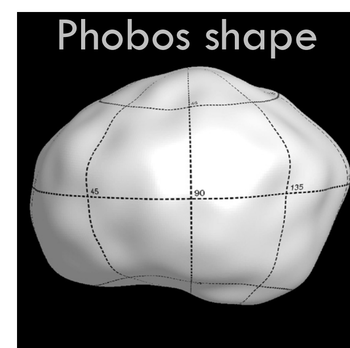
- Lunar Laser Ranging (Moon)
- Radar echoes
  - Range (Mercury, Venus…)
  - Radar interferometry (Mercury, Venus…)
- Control point network
  - Direct imagery (Mercury, Vesta…)
  - Radar (Titan/Cassini…)
  - Shape fit (small saturnian satellites, Phobos/MEX)
- Tracking landers (Mars)
- Gravity field (Vesta/Dawn..







(Stiles etal 2008)



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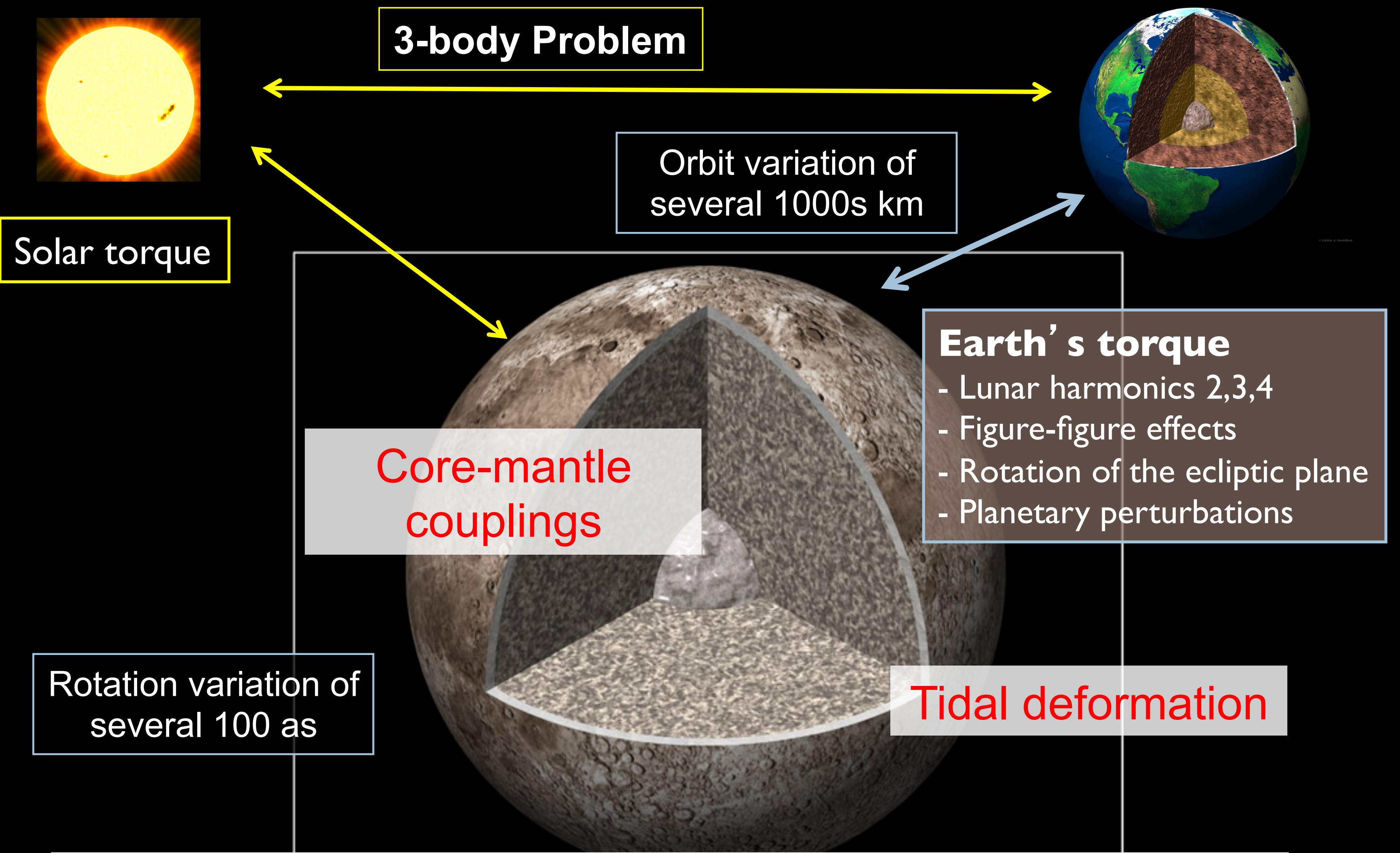
Rotation of the Moon is a complex dynamical system



Librations = departure from a uniform rotational motion

Lunar-Laser Ranging and ephemeries

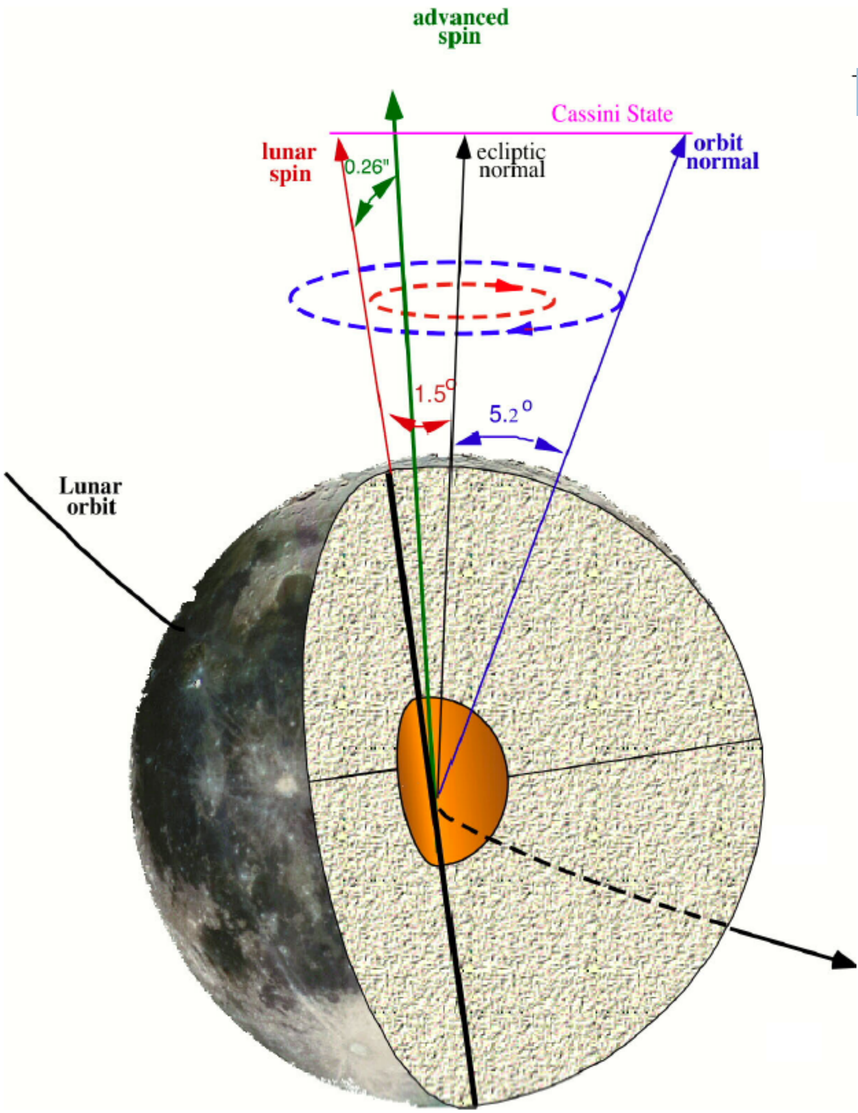
- Due to the high accuracy of the LLR observations and the large amount of data, the rotation is computed numerically in the ephemeries DE and INPOP (Williams et al. 71-today , Capallo et al. 1980; INPOP team Fienga, Laskar, et al. 2006-today).

- Lunar Laser Ranging Experiment -
(Williams *et. al.* & *Fienga et al.)*

- Accuracy of ***2 cm*** and ***1 mas*** in rotation over **39 years**.
- Fundamental physics, geophysics, selenophysics and **interior** of the Moon.

- These models are Joint numerical integration of the orbits of the Moon, the Earth, the planets and asteroids, and of the lunar rotation (Williams etal 2008; Folkner etal 2008; Fienga etal 2006; 2008; 2012).
- Dynamical partial derivatives of the orbits and lunar Euler angles with respect to solution parameters such as moment of inertia, gravity field, tides, dissipation, interaction with a fluid core and initial conditions.

Dynamical signature of the core



(Williams etal 2001)

✓**Mean moment of inertia** (Konopliv 1998)

$I/MR^2 = 0.3931 \pm 0.0002$

✓**k2 Love number** (Williams etal 2010)

$k2 = 0.021 \pm 0.003$ (Williams etal 2010)

$k2 = 0.0240 \pm 0.0015$ (Matsumoto etal 2012)

✓**Oblateness of the Core-Mantle Boundary**

✓**Dissipation in the Moon** (Williams etal 2001)

✓**Seismic signature** (Weber etal 2011, Garcia etal 2011)

Determination of free lunar librations

- Analysis of lunar ephemeries (DE421)

	Longitude blend	Longitude mode	Latitude mode	Wobble mode
Period (days)				
This paper	1056.21	1056.13	8822.88	27 257.27
Newhall *et al.* (1997)	1056.20	1056.12	8826.	27 258.
Chapront *et al.* (1999)	1056.13	-	8804.	27 259.29
Amplitude				
This paper	1.808”	1.296”	0.032”	8.196x3.312”
Newhall *et al.* (1997)	1.807”	1.37”	0.022”	8.19x3.31”
Chapront *et al.* (1999)	1.812”	-	0.022”	8.182”
Phase at JD 2451545.0				
This paper	223.5	207.0	160.8	161.63
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(Rambaux & Williams 2011, CMDA)

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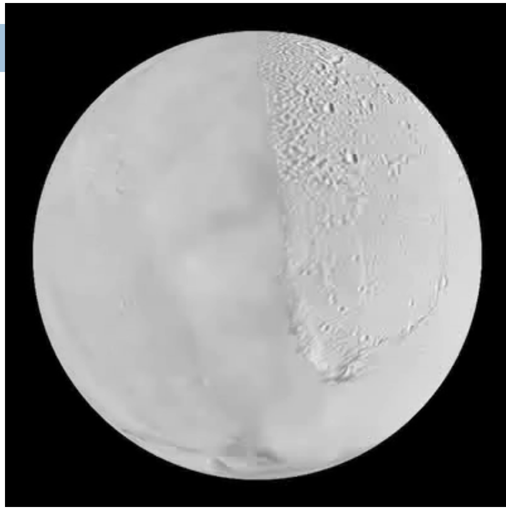
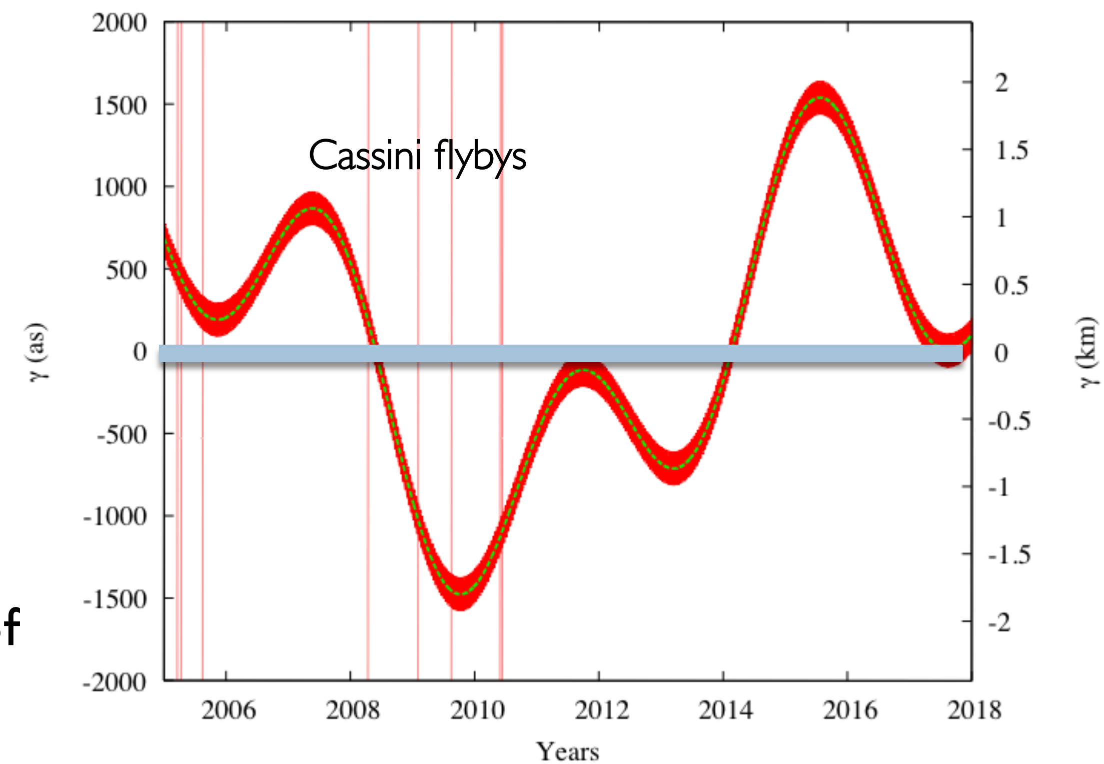
→ Yoder (1981) suggested a precession-driven turbulence by eddies at the CMB could excite the wobble mode;

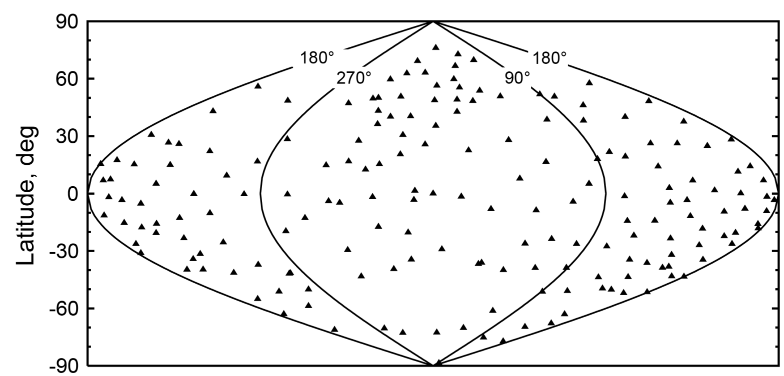
Enceladus rotation





- Modeling rotational motion of Enceladus by taking into account the orbital perturbation and the tidal effect (Rambaux etal 2011).

- Observational confirmation of predicted librations by Gliese etal (2011).

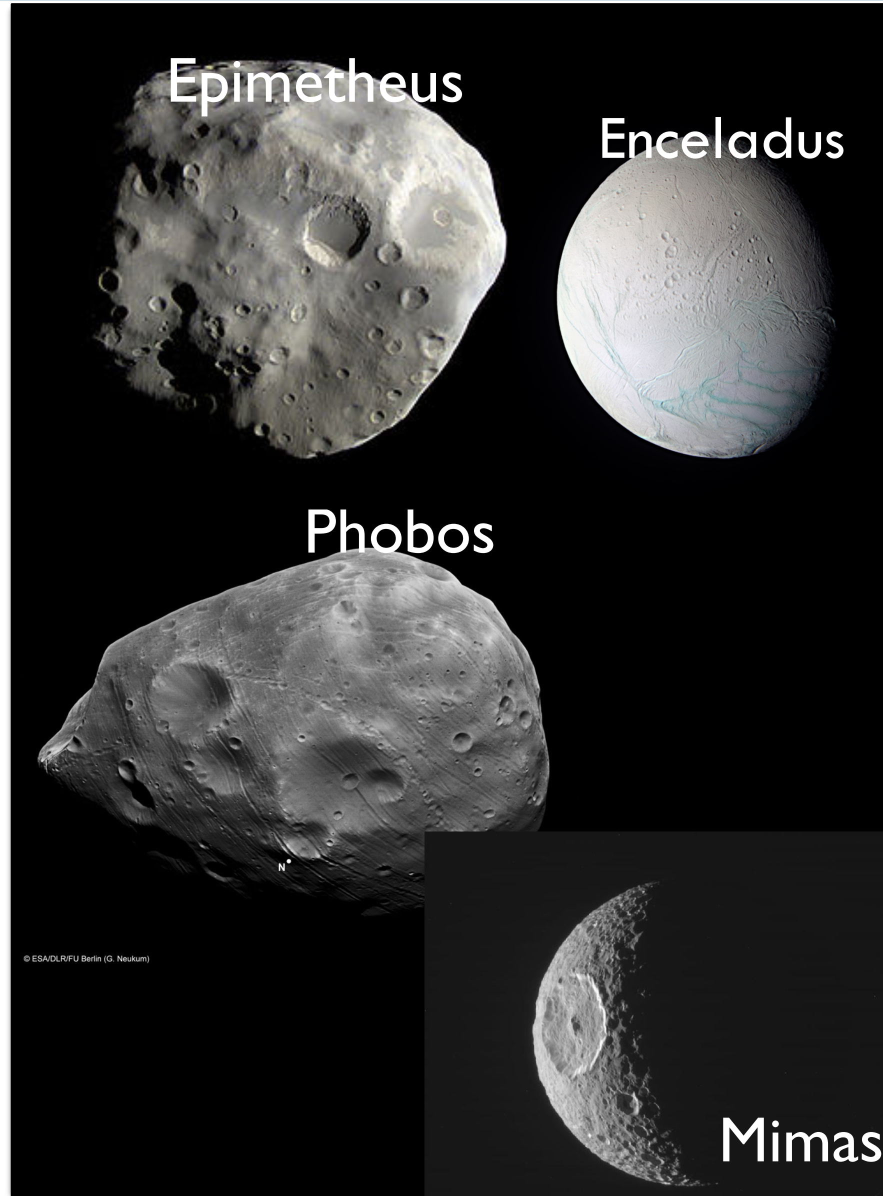


(Gliese etal 2011)

Detection of librations on other bodies ?

- At present :
  - **Phobos** (Duxbury 1989; Willner etal 2010; Rambaux etal 2012; Le Maistre etal 2013…)
  - **Epimetheus** (Tiscareno etal 2009; Noyelles 2010; Robutel etal 2010…)
  - **Enceladus** (Rambaux etal 2010; Giese etal 2011…)
  - **Mimas** (Noyelles etal 2011; Tajedinne etal 2013

- For Titan no firm detection of variation in the mean rotational motion (Stiles etal 2008, 2010, Merigolla and less 2012). Prediction models (e.g. Noyelles 2008; Bills and Nimmo 2011; Van Hoolst etal 2013…)



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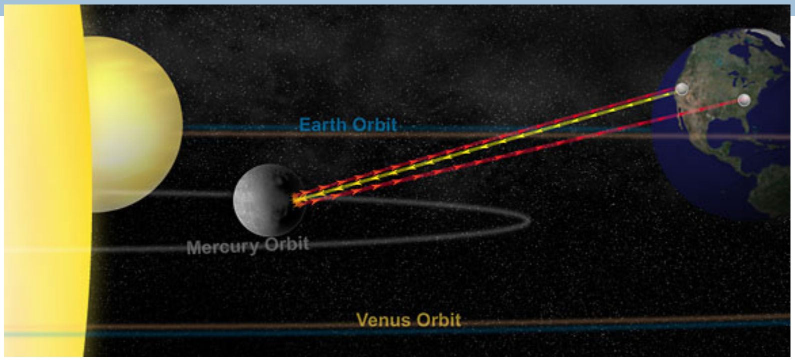
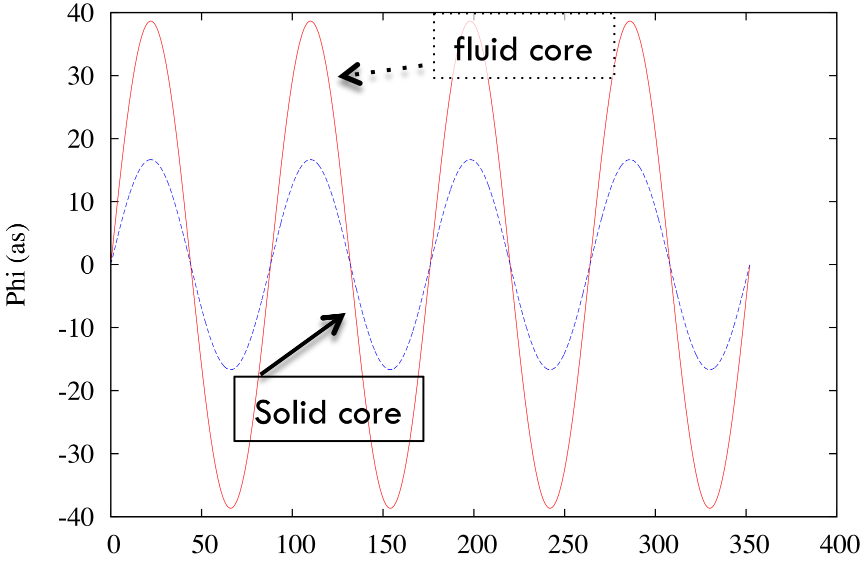
The molten core of Mercury

- Observations by radar interferometry (Holin 1988, Margot etal 2007, 2012);
- Determination of the amplitude of the forced libration 38.5 ± 1.6” (455 m)
- Origin of residues ?
  - free librations,
  - long planetary period forcing,
  - interior coupling ?

  (Peale etal 2009; Koning and Dumberry 2011; Van Hoolst etal 2012; Yseboodt etal 2013,…)

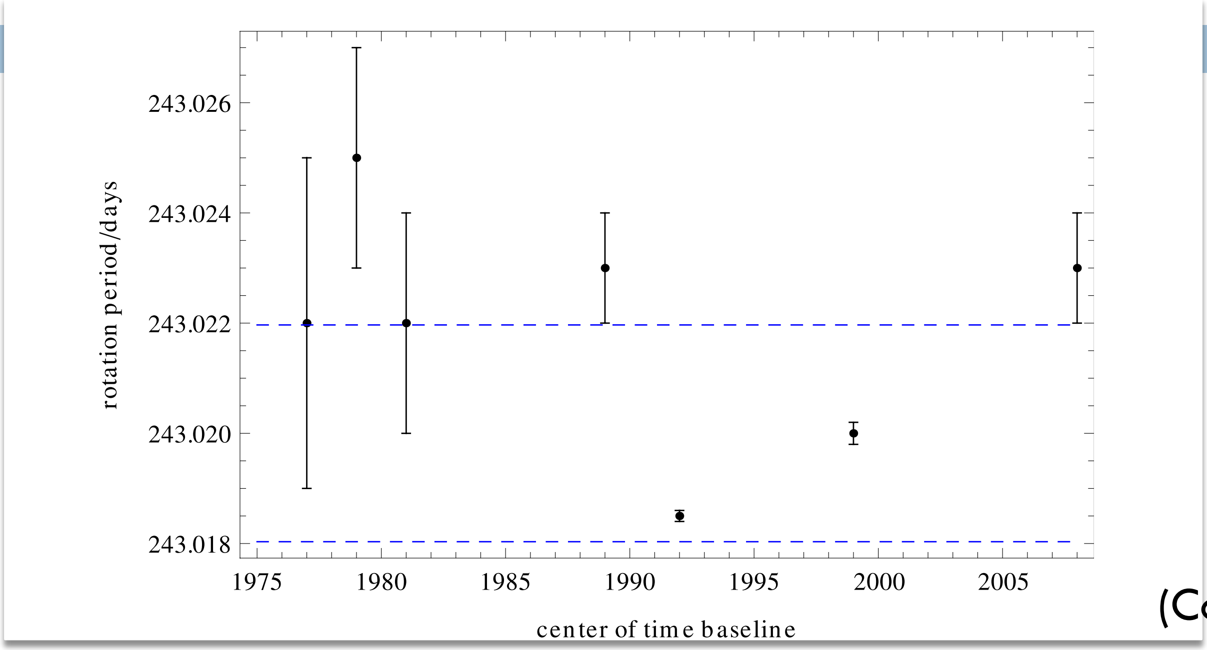
(Bill Saxton, NRAO/AUI/NSF)





$$\varphi = \frac{3}{2}\frac{(B-A)}{C_m} f(e) \sin nt$$

And Venus ?



(Cottereau etal 2011)

- A discrepancy has been measured between the lod of Magellan and VEX space mission of 6.5 minutes (Mueller etal 2011);
- Suggestions: atmospheric coupling (Karatekin etal 2011), triaxiality, presence of the core (Cottereau etal 2011) but modeling effects are too small. It is an open problem.

- The nutations of Mars have been detected but the core has not yet show its signature in the rotation (e.g. Le Maistre etal 2012)

Conclusion for the comparative planetology

- The rotation is a powerful tool to investigate the interior of planets and natural satellites ;

- The detection of Mercury's librations by radar interferometry argued for a molten core (Margot etal 2007; Rambaux etal 2007, Peale etal 2008; Margot etal 2012, Yseboodt etal 2013, etc.)
- Detection of the main libration for Phobos, Epimetheus, Enceladus, and Mimas (Duxbury 1989; Willner etal 2010; Tiscareno etal 2009; Robutel etal 2010; Rambaux etal 2010; Giese etal 2011; Tajedinne etal 2013, etc.)
- The comparison of the rotation with models for Venus and Titan appears to be open problems (Mueller etal 2011; Cottereau etal 2011; Stiles etal 2010; Meriggiola and Iess 2012; Van Hoolst etal 2013, etc.)