ROYAL OBSERVATORY
OF BELGIUM

ASSESSING THE STRUCTURE OF PLANETARY INTERIORS FROM SATELLITE AND GROUND-BASED GEOPHYSICAL DATA

A COMPARATIVE STUDY OF VENUS, EARTH AND MARS

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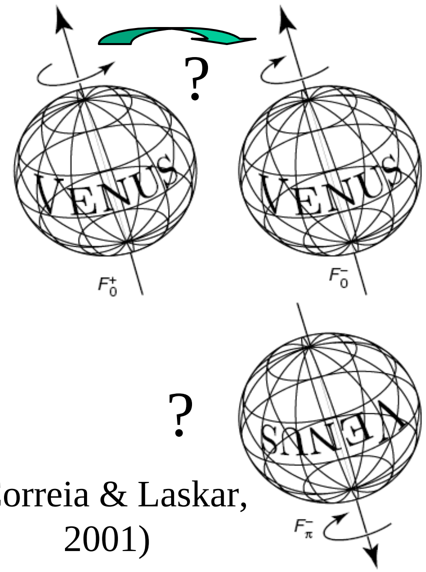
Assessing the structure of planetary interiors

- Why is it necessary ?
- Some key questions
- Comparative planetology

Atmosphere – interior structure and rotation



(Correia & Laskar, 2001)

Dense atmosphère (Correia & Laskar, 2001)

&

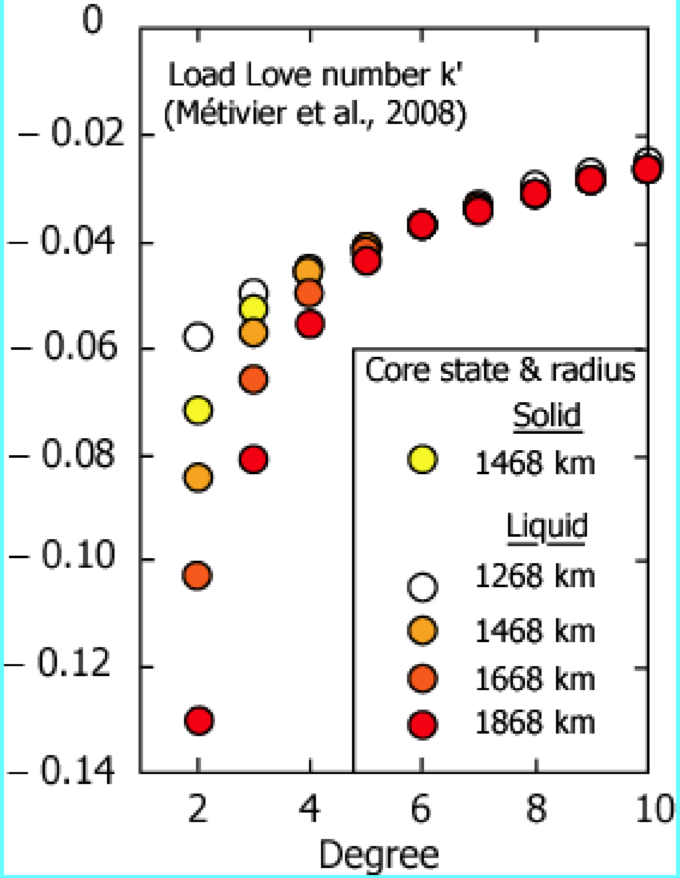
Friction at the core-mantle boundary (e.g., Yoder, 1995)

See also Karatekin et al., in this meeting

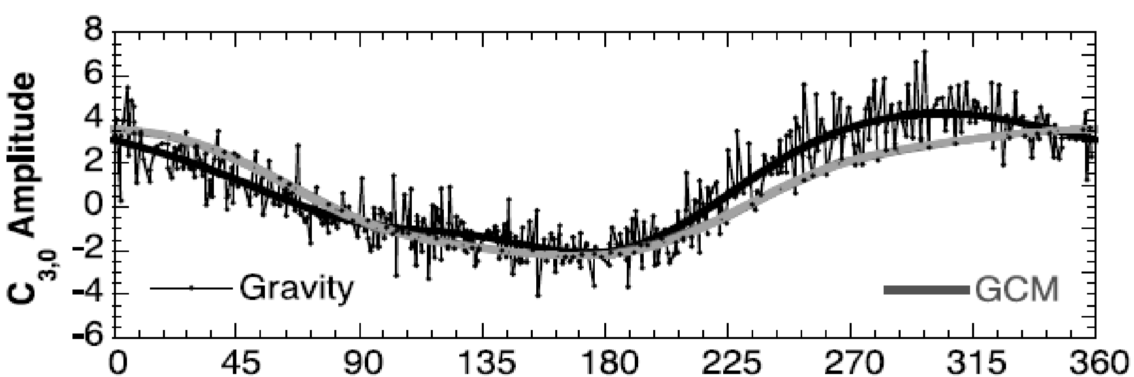
Mass transfers & loading (short time-scale)

(e.g., Yoder & Standish, 1997; Zuber et al., 2007; Métiver et al., 2008)

Instantaneous response to surface loading

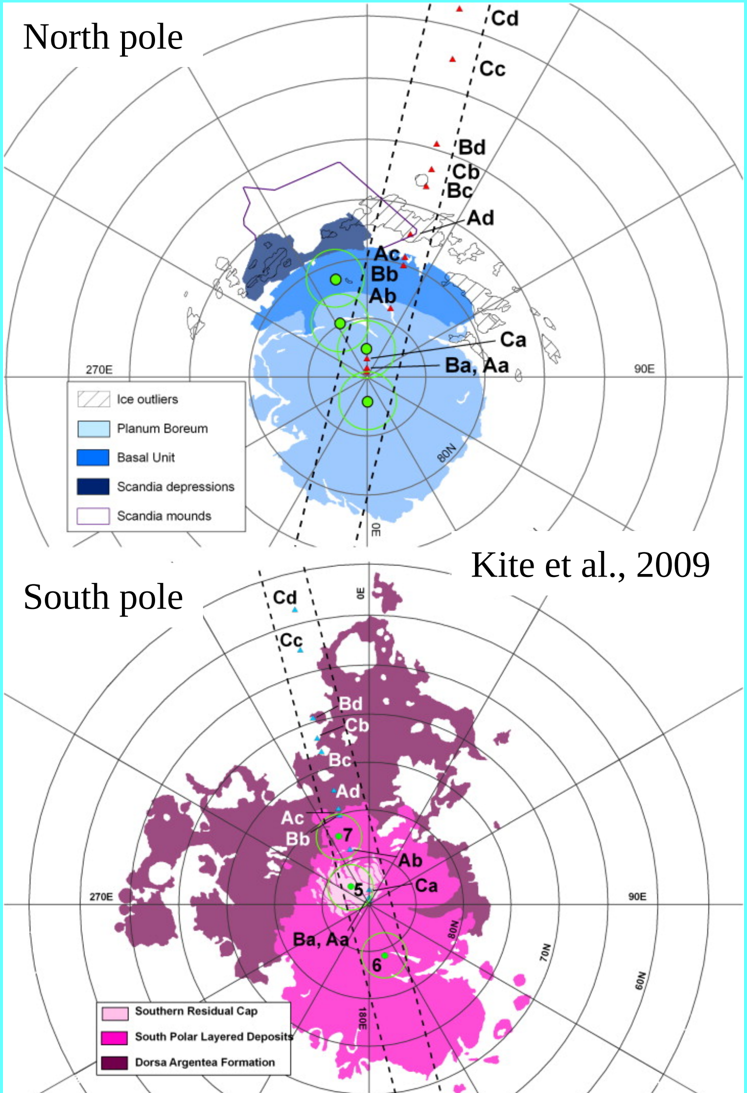


Atmospheric mass transfers



Seasonal variation in gravity (Zuber et al., 2007)

Mass transfers & loading (long time scale)



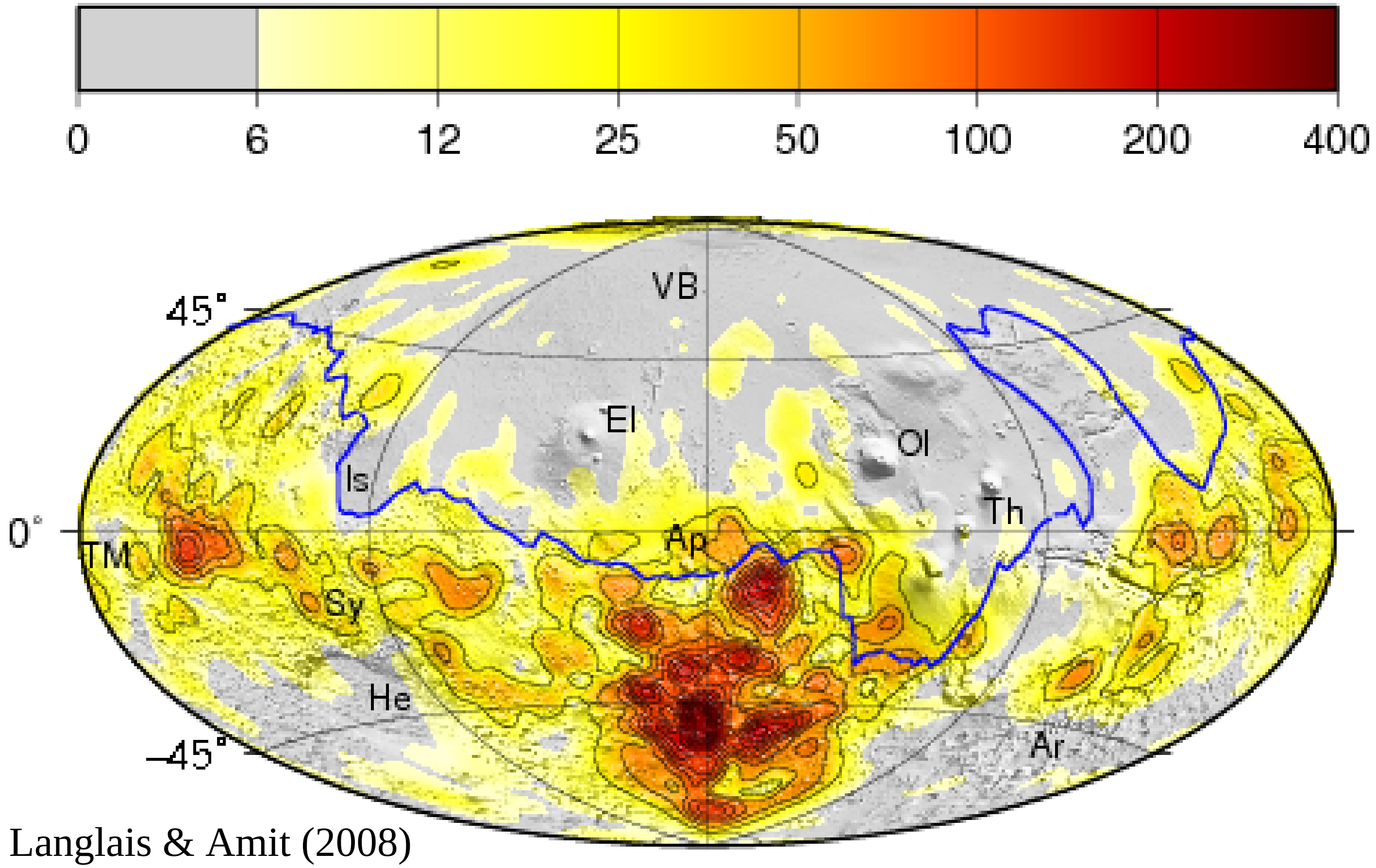
- True polar wander (Murray & Malin, 1973)
(e.g., Roberts & Zhong, 2007; Daradich et al., 2008; Rouby et al., 2008)
Contributions by surface and internal loads
  - ➢ Crust & lithosphere thicknesses ?
  - ➢ Thermal evolution and convection pattern ?

- Mars' response to obliquity changes
  - ➢ Long time scale mass tranfers
  - ➢ Core radius ? Mantle viscosity ?

Mars' magnetic field

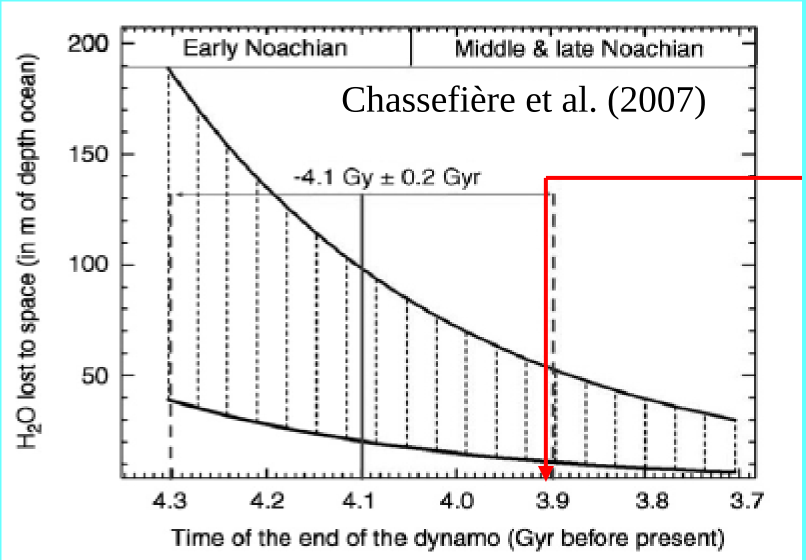
Relationships with tectonics and cratering history

Predicted intensity (nT) at 300 km altitude



Langlais & Amit (2008)

Magnetic field history vs. H_20 & CO_2 escape



Late Heavy Bombardment

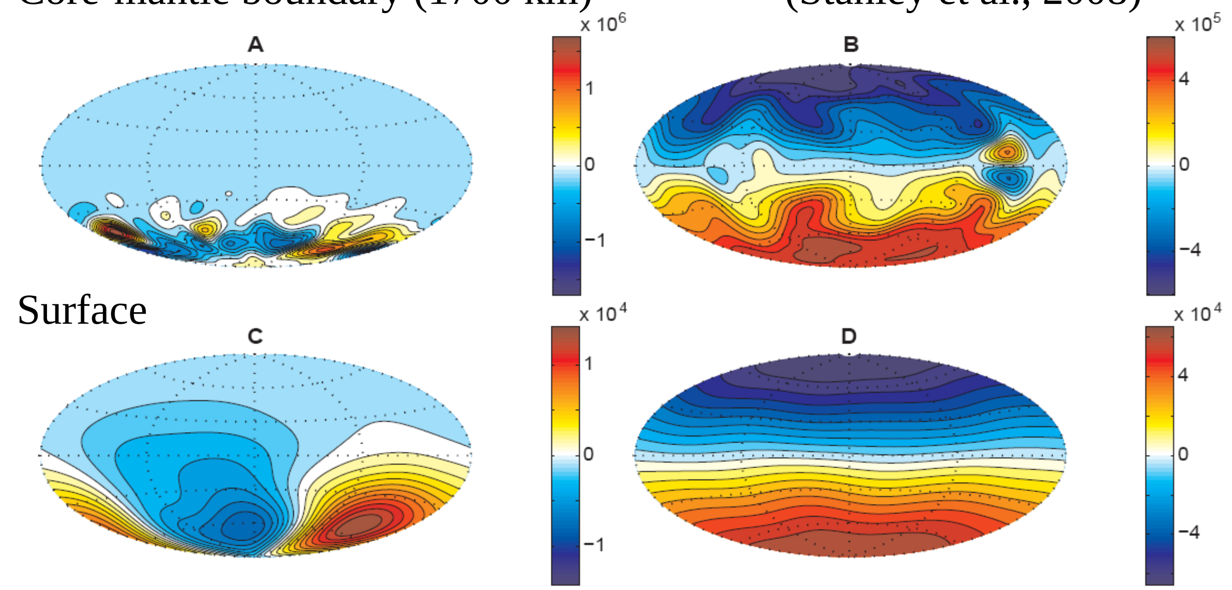
- Similar age for magnetic field and dichotomy

- Hemispheric scale pattern :

mantle circulation and/or large impact(s) ?

Core-mantle boundary (1700 km)

(Stanley et al., 2008)



Predicted magnetic field
(radial component, nT)

A & C : Degree-1 heat flux

B & D : Homogeneous heat flux

➢ Instantaneous view valid on long time scales ?

Magnetic field & planetary interiors (1)

for a review, see, e.g. Stevenson, 2003 & U. Christensen 2009 (this meeting)

Venus

- Liquid core (Yoder, 1995)
- No observation of magnetic field of internal origin
- Predicted dynamo > 2 x observational upper bound
  - ➢ Neither thermal nor compositional convection inside liquid core
  - ➢ No inner core ? (Stevenson et al., 1983)
  - ➢ Not cooling inner core ?
  - ➢ Venus' interior hotter than Earth's one ?

    (stagnant lid regime e.g., Nimmo, 2002)
  - ➢ Transitional convection regime ?

Earth

Magnetic field & planetary interiors (2)

- Liquid outer core (Oldham, 1906; Gutenberg, 1913)
- Solid inner core (Lehmann, 1936) younger than 2.5 Ga

  (~ 1± 0.5 Ga ? Labrosse et al., 2001)
- Magnetic field of internal origin older than 3.8 Ga

  (McElhinny & Sennayake, 1980)
- Growth of inner core:
  - ➢ Sustain convection
  - ➢ Strengthen dynamo field

Magnetic field & planetary interiors (3)

Mars

• Liquid core (e.g., Yoder et al., 2003)

• Now extinct magnetic field of internal origin existed in early Mars

(~ 4.1 ± 0.5 Ga)

• Extinction of the dynamo

➢ Convection → conduction & no inner core formation (Stevenson et al., 1983) ?

➢ Thermal evolution of the mantle → too small heat flux at core-mantle boundary ?

Some key questions

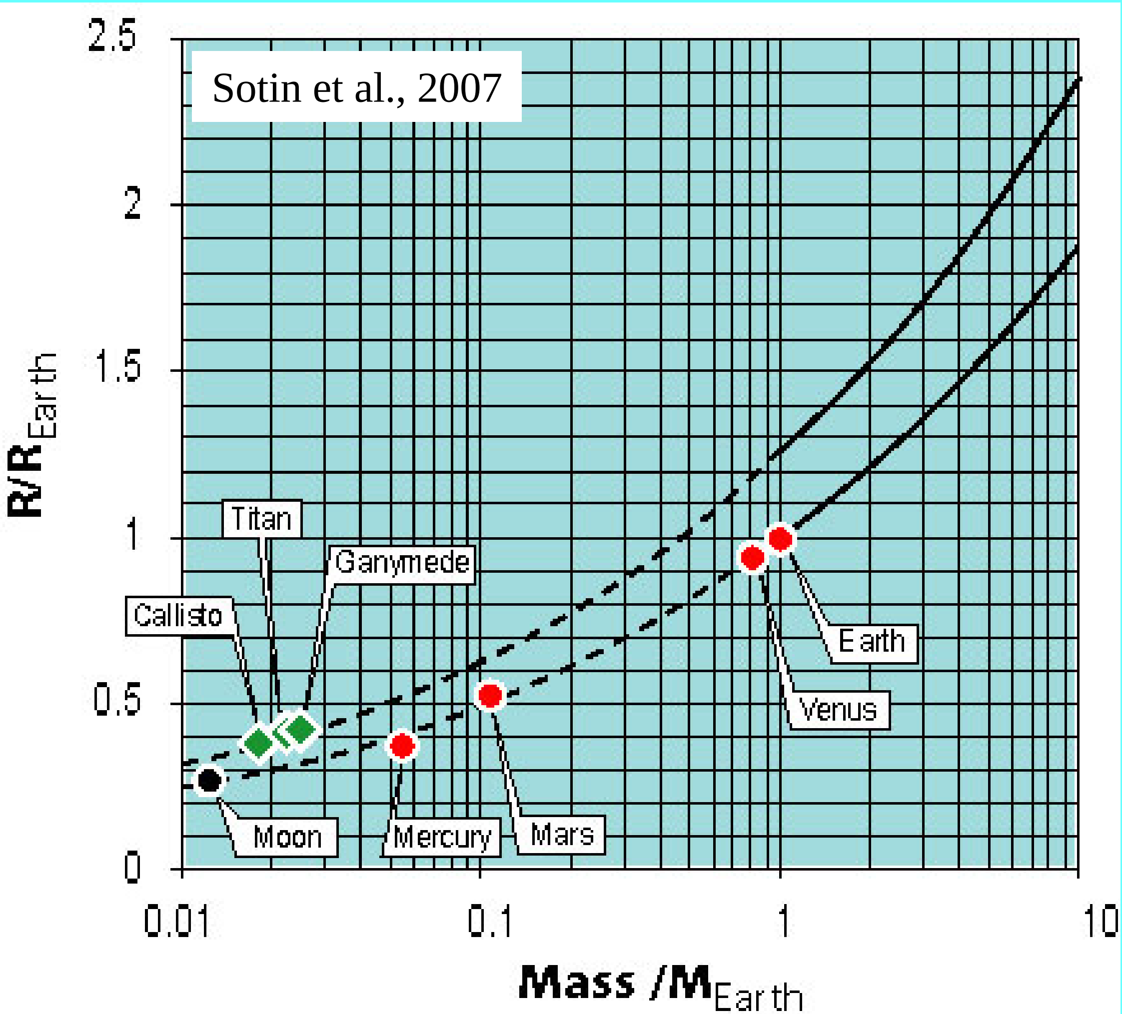
- Liquid core : size, composition & thermal state
- Conditions for growth of inner core
- Thermal regime of the mantle

  → heat flux at core-mantle boundary

  →lid thickness
- Link to surface observations: crust thickness and density

Comparative planetology

Zeroth order of approximation: consistency of mass-radius relationships



Model :
- Sun composition:
  Fe/Si ; Mg/Si ; Mg/(Mg+Fe)
- Equations of state

<u>Earth-like planets</u>:

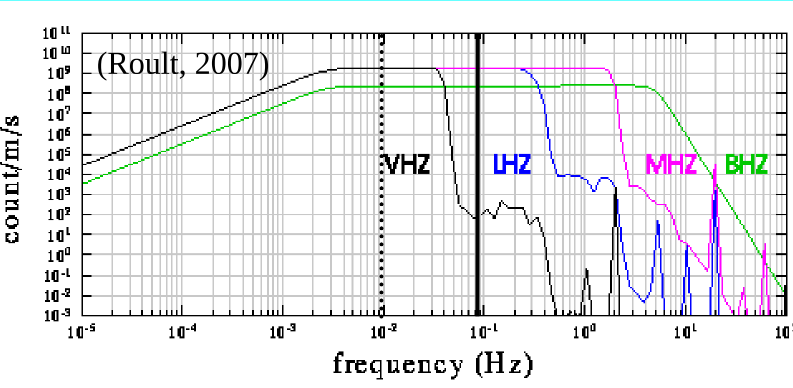
$\mathbf{R/R_{earth} \sim (M/M_{Earth})^{0.3}}$

Mars: $\delta R/R = -1.5\%$
→ Iron-rich mantle: agreement with analysis of SNC meteorites

Venus: $\delta R/R = +0.1\%$

The Earth as a reference planet

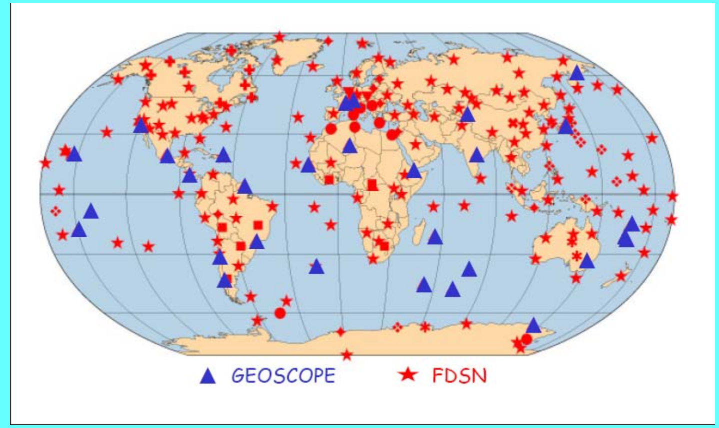
Range of observations

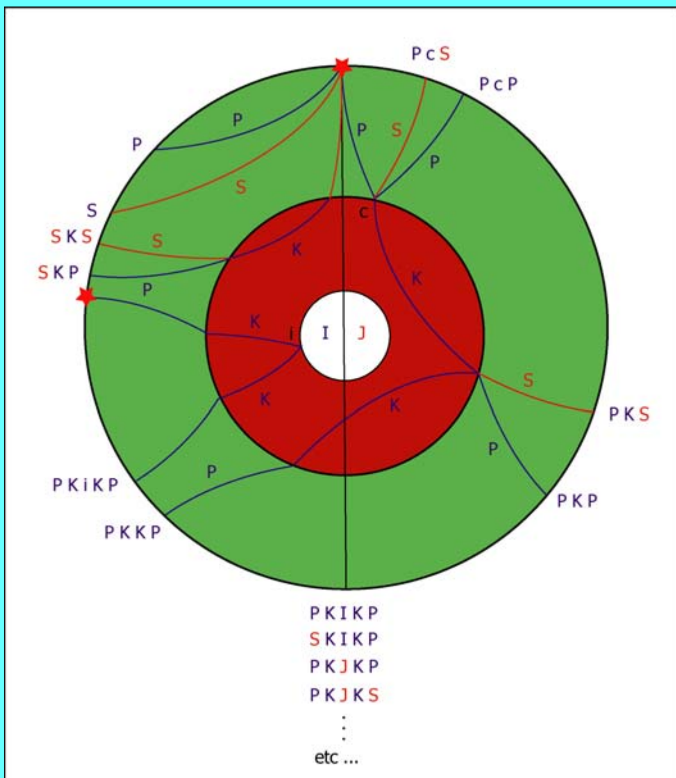


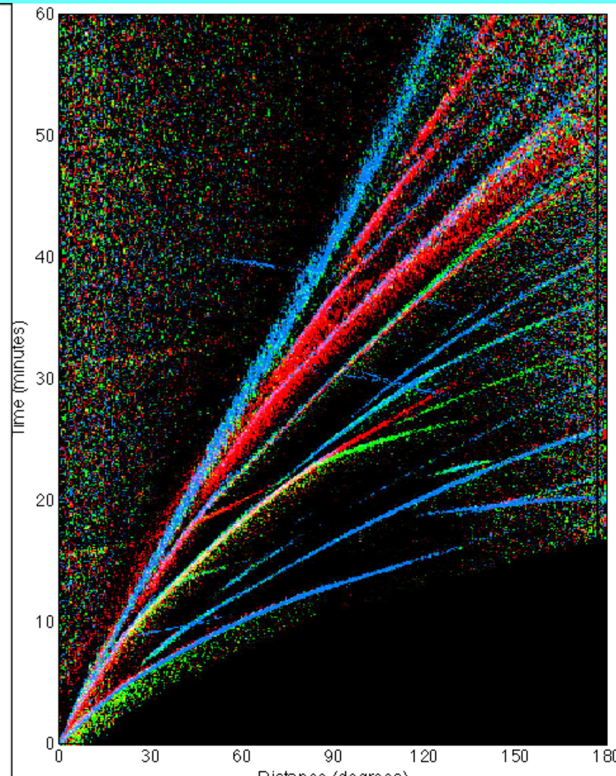
Free oscillations

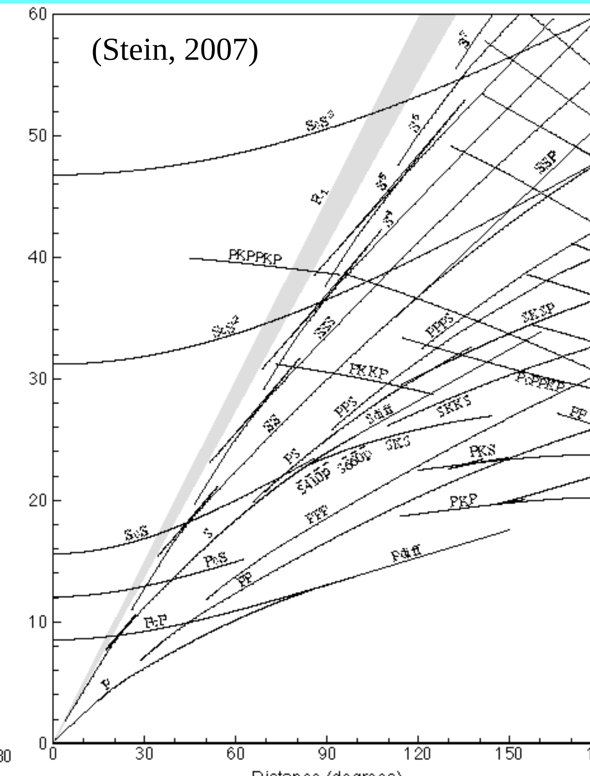
Surface waves

Body waves





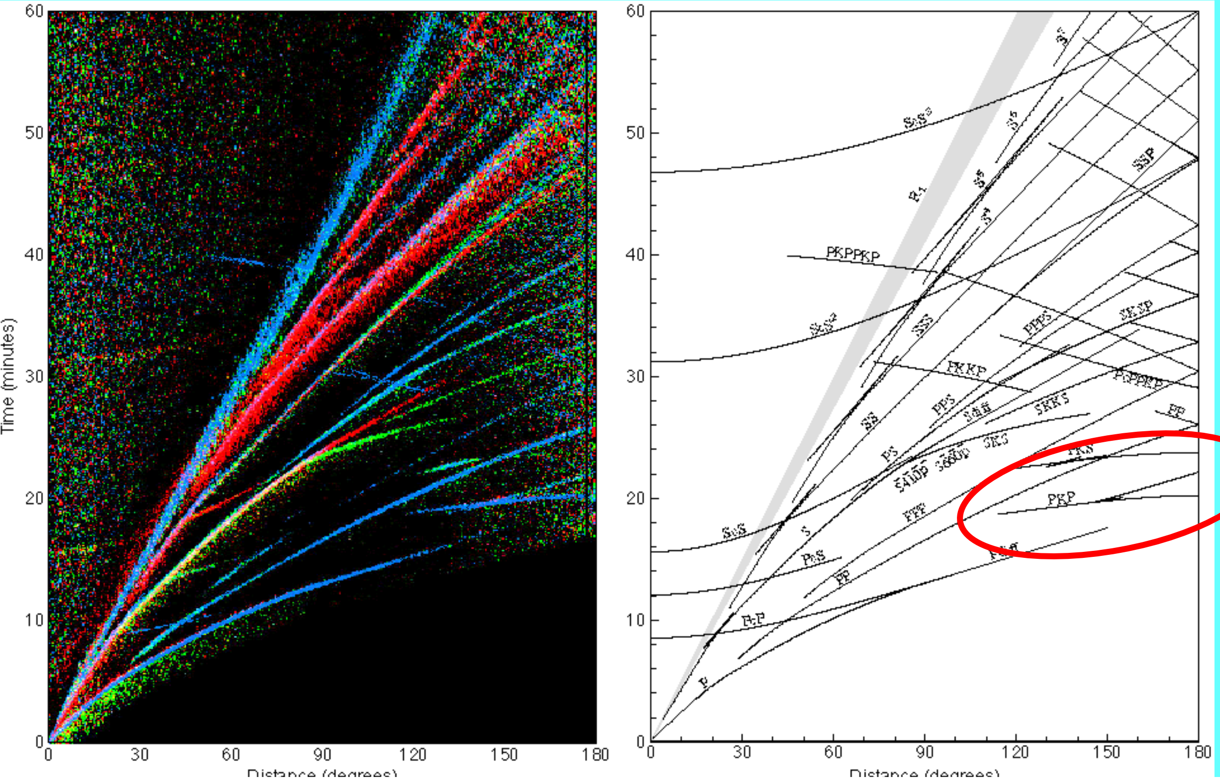


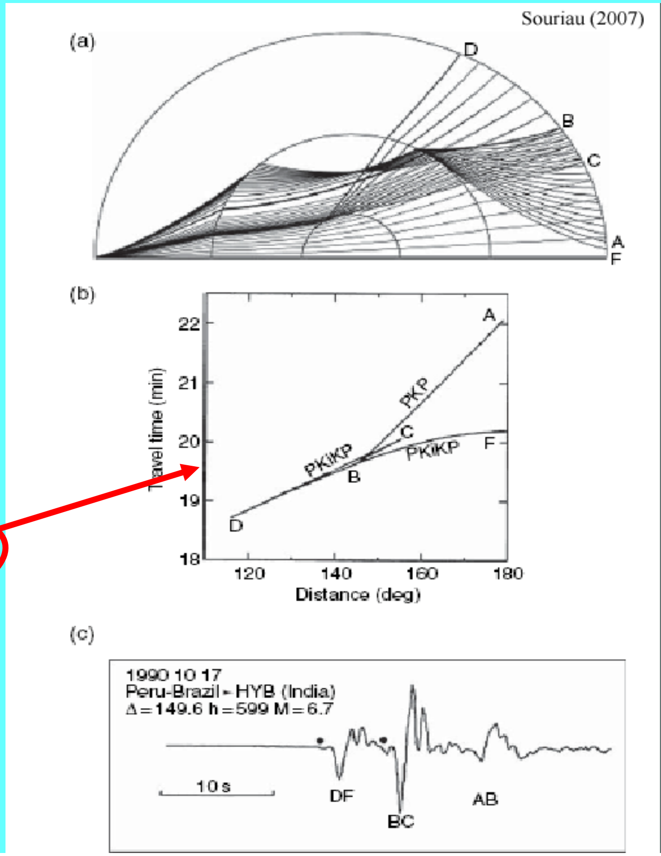


(Stein, 2007)

Outer and inner cores

Accurate information on laterally averaged radial structure





Discovery of the core: Oldham (1906)

<u>Outer core radius</u>:

- Gutenberg (1913) 3470 km
- Dziewonski & Anderson (1981) 3480 km
- Kennett et al. (1995) 3479.5 km

➢ Accuracy of ~ 1 km

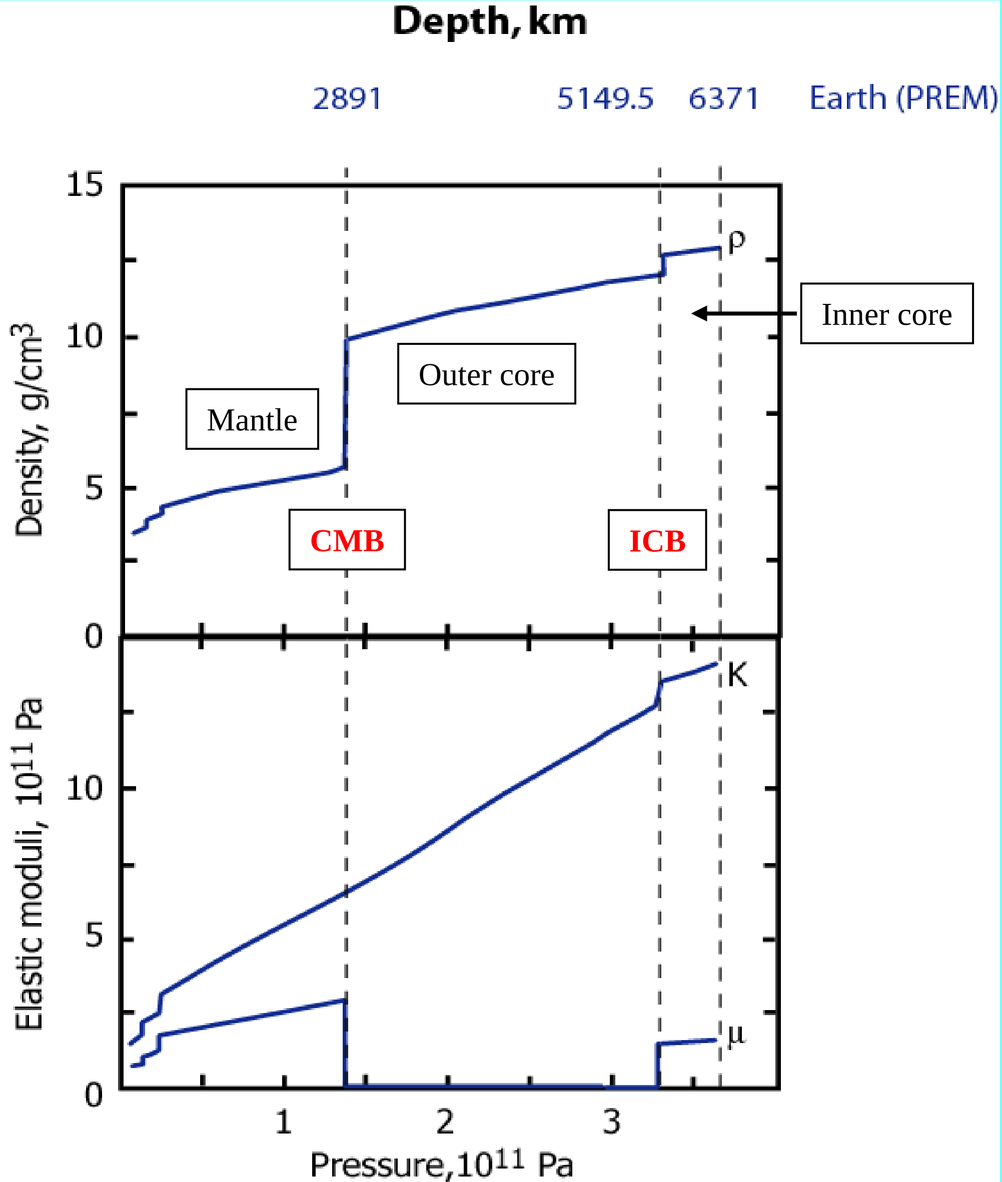
Discovery of the inner core: Lehmann (1936)

<u>Inner core radius</u>:

-Dziewonski & Anderson (1981) 1221.5 km
- Kennett et al. (1995) 1217.5 km

➢ Accuracy of ~ 4-5 km

Earth-like reference models



PREM : Dziewonski & Anderson (1981)
ak135 : Kennett et al. (1995)

- > 30 seismic stations
  - ~ 900 normal modes
  - ~ 2,000,000 P-wave arrival times
  - ~ 250,000 S-wave arrival times
- Radius: 6371 km
- Mass: 5.974×10^{24} kg
- I/MR^2 : 0.3308

Joint inversion of different geophysical data sets

Only one type of geophysical data → strong trade-off between temperature and composition

- Electromagnetic data mostly constrain temperature and iron content
- Density and seismic wave speeds mostly constrain mineralogical composition

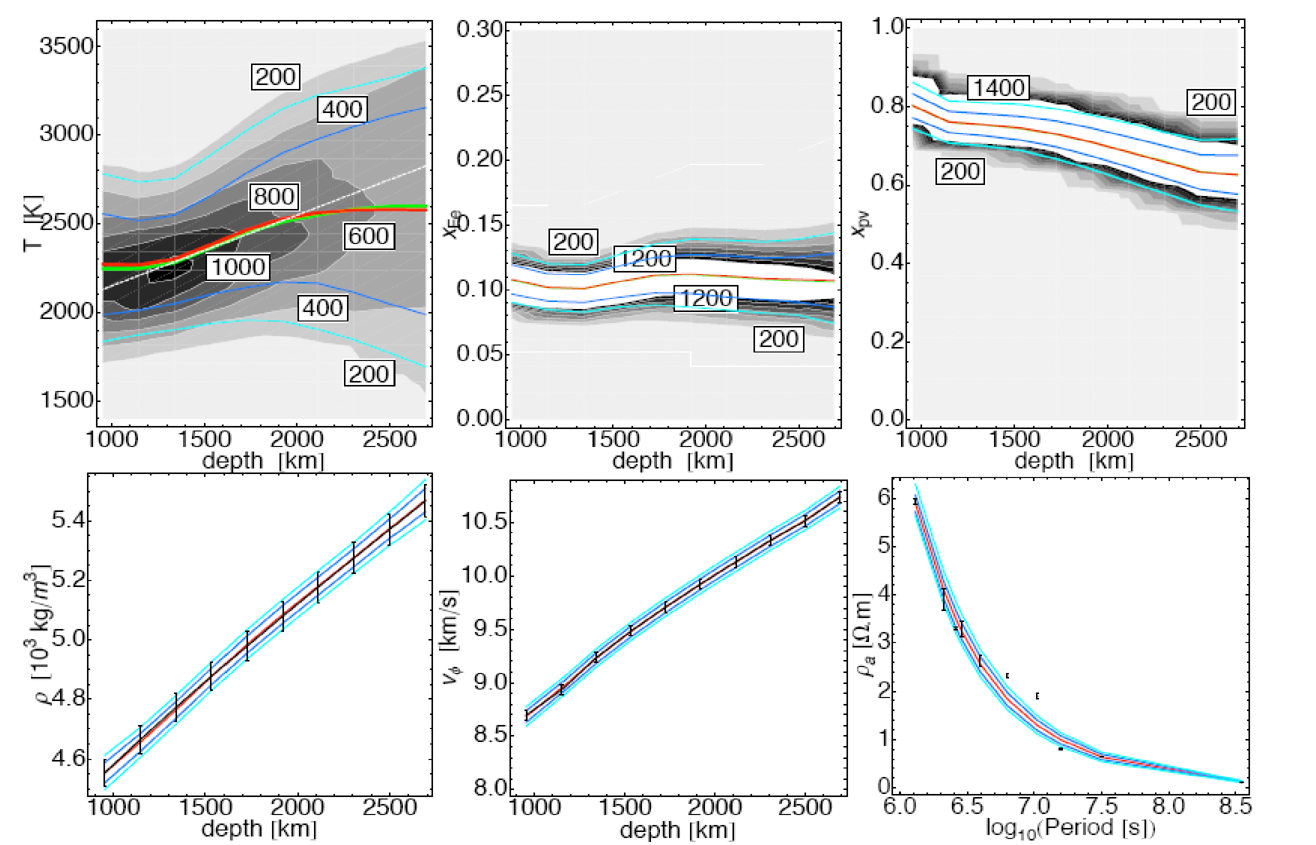
Earth's lower mantle
(Verhoeven et al., 2009)

dT/dz : 0.4 K/km

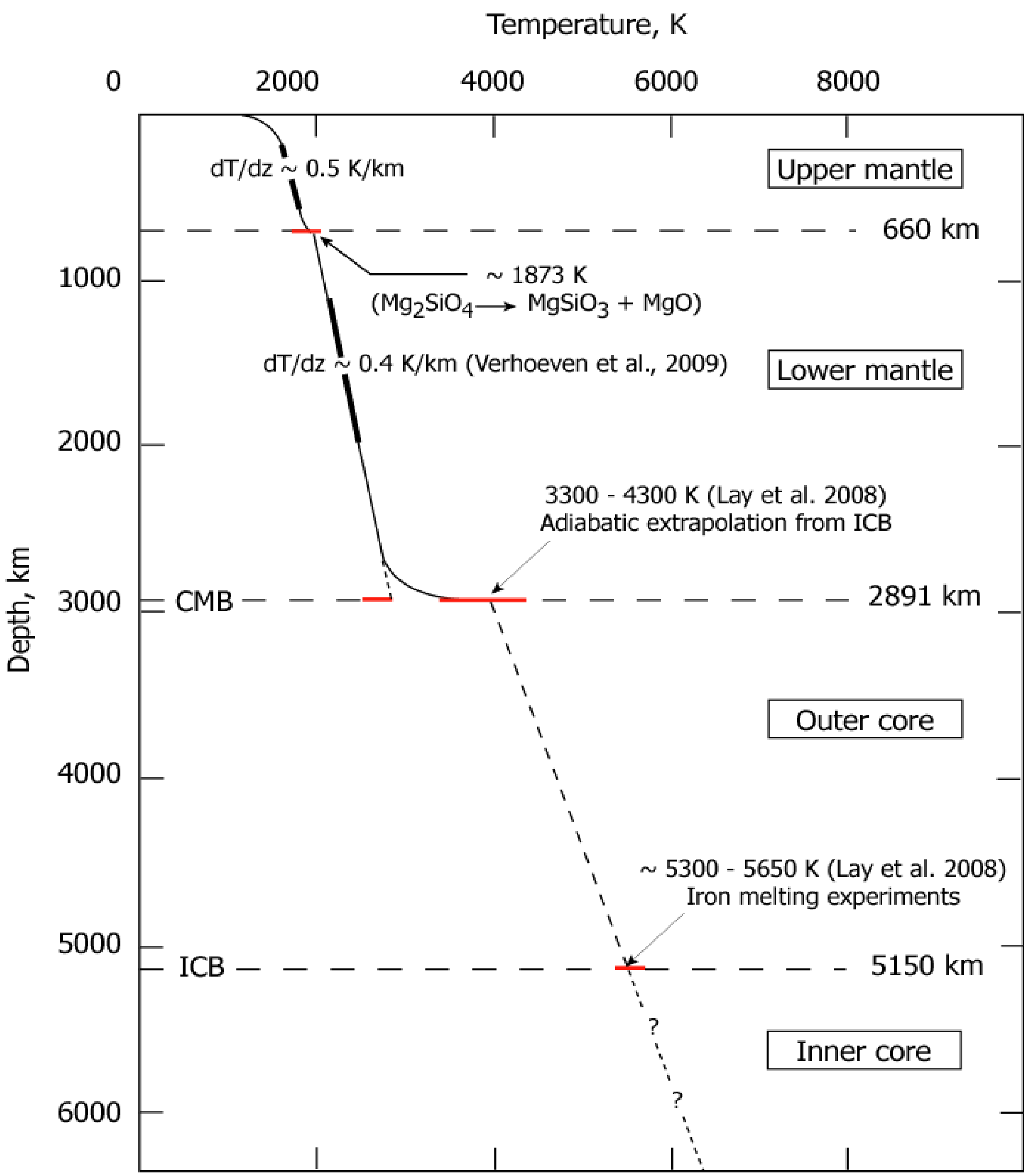
Constant iron content (10%)

Mg-perovskite content
[80% → 65%]

Effect on lower mantle dynamics (Deschamps & Tackley in this session)



Schematic temperature profile of the Earth

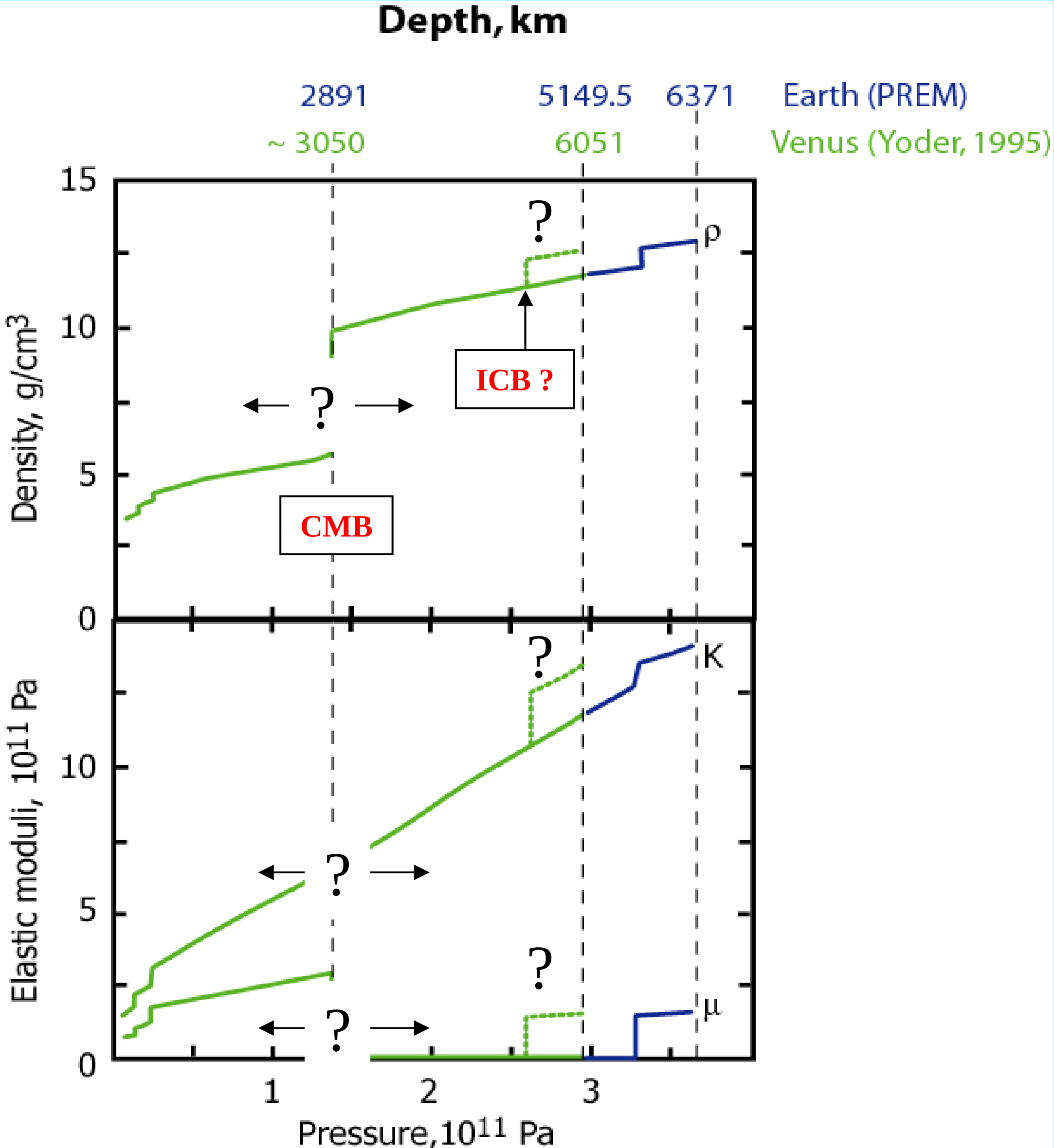


<u>Importance of Thermal Boundary Layers</u>
(TBL)

- Plate tectonics and slab deflection inside transition zone

- Temperature contrast between mantle and core

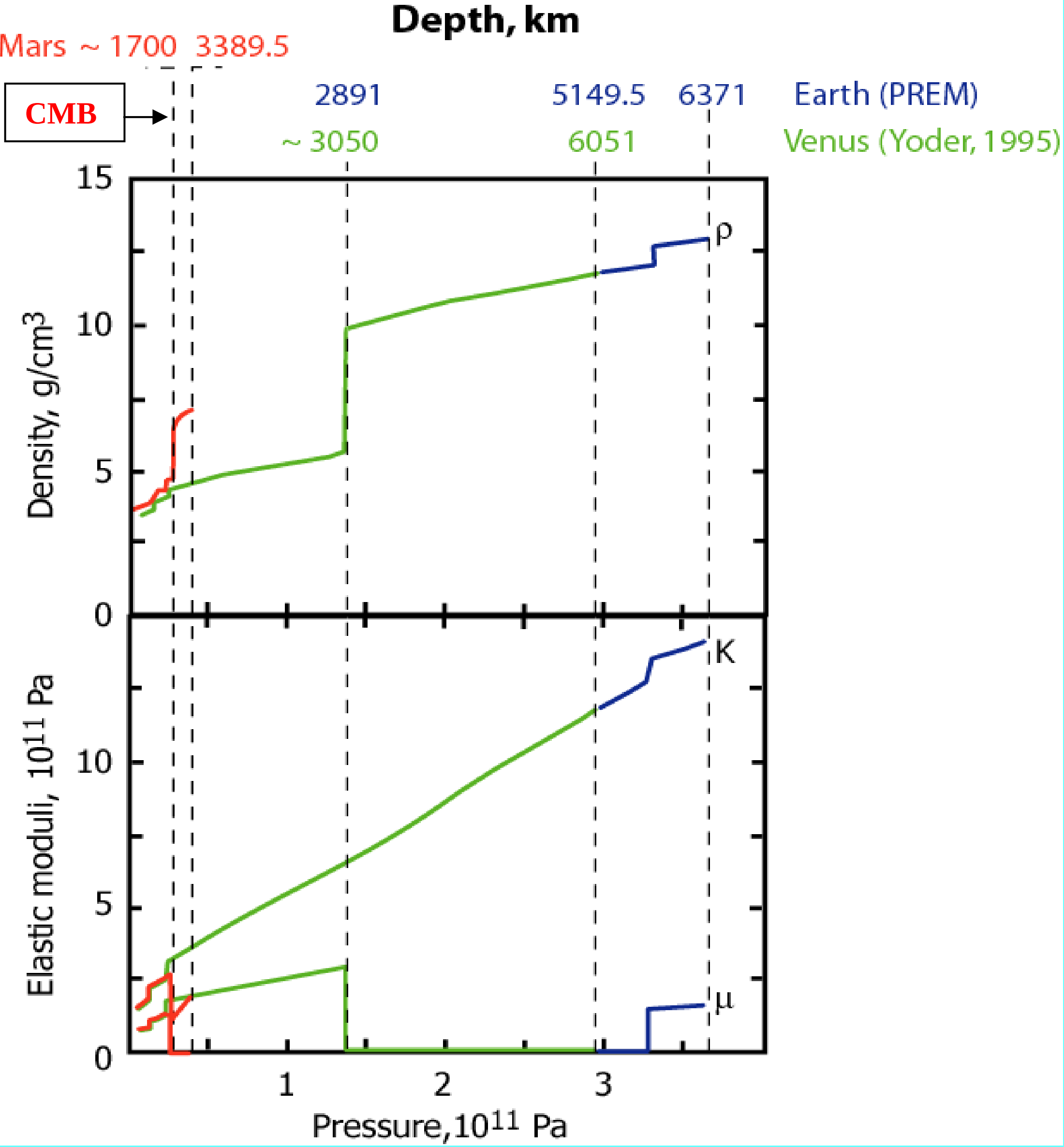
Earth-like reference models applied to Venus



Venus : Yoder (1995)

- Radius: 6051 km
- Mass: 4.869 x 10^{24} kg
- I/MR^2 : ~ 0.33
- Analogy with Earth's structure, composition & mineralogy
- High-pressure – high temperature experiments
- Rotation, geodesy and gravimetry

Earth-like reference models applied to Mars



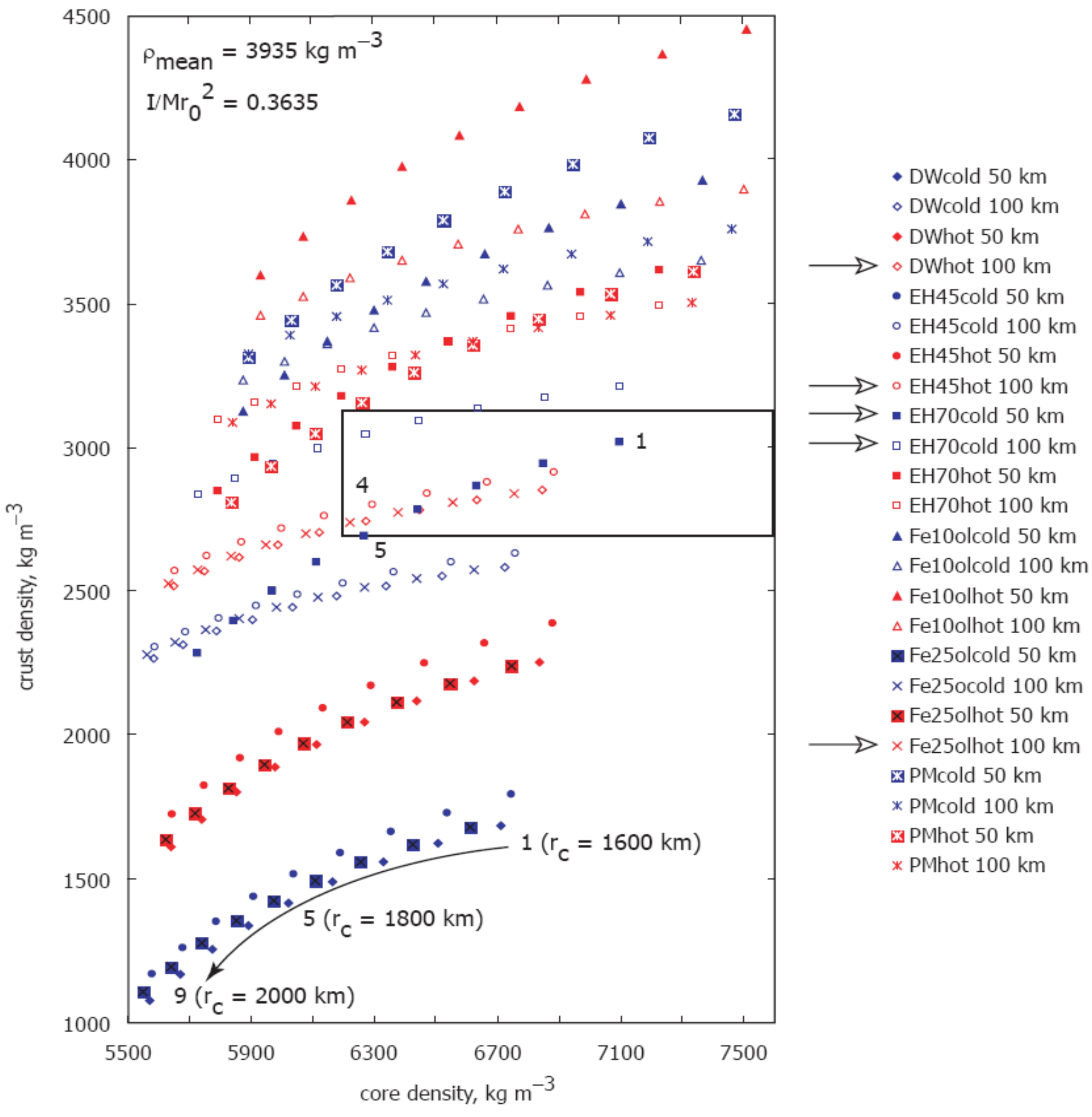
Mars : p.e. Zarkov & Gudkova (2005)

- Radius: 3389.5 km
- Mass: 0.642 x 10^{24} kg
- I/MR^2 : 0.3635 +/– 0.0012
- Analogy with Earth's structure, composition & mineralogy
- High-pressure – high temperature experiments
- Rotation, geodesy and gravimetry
- SNC meteorites:
  Geochemical arguments (Fe content)

➢ Spinel-Perovskite transition phase at the base of the Martian mantle ?
➢ Consequences for lower mantle dynamics (*see Tackley et al. in this session*)

Uncertainties on Mars' interior

(see e.g., Sohl et al., 2005; Verhoeven et al., 2005; Zharkov & Gudkova, 2005; Lognonné & Johnson, 2007)



- Unknown mantle temperature
- Olivine-rich or pyroxene-rich mantle ?
- Large range of variation for
  - core radius
  - crust thickness & density

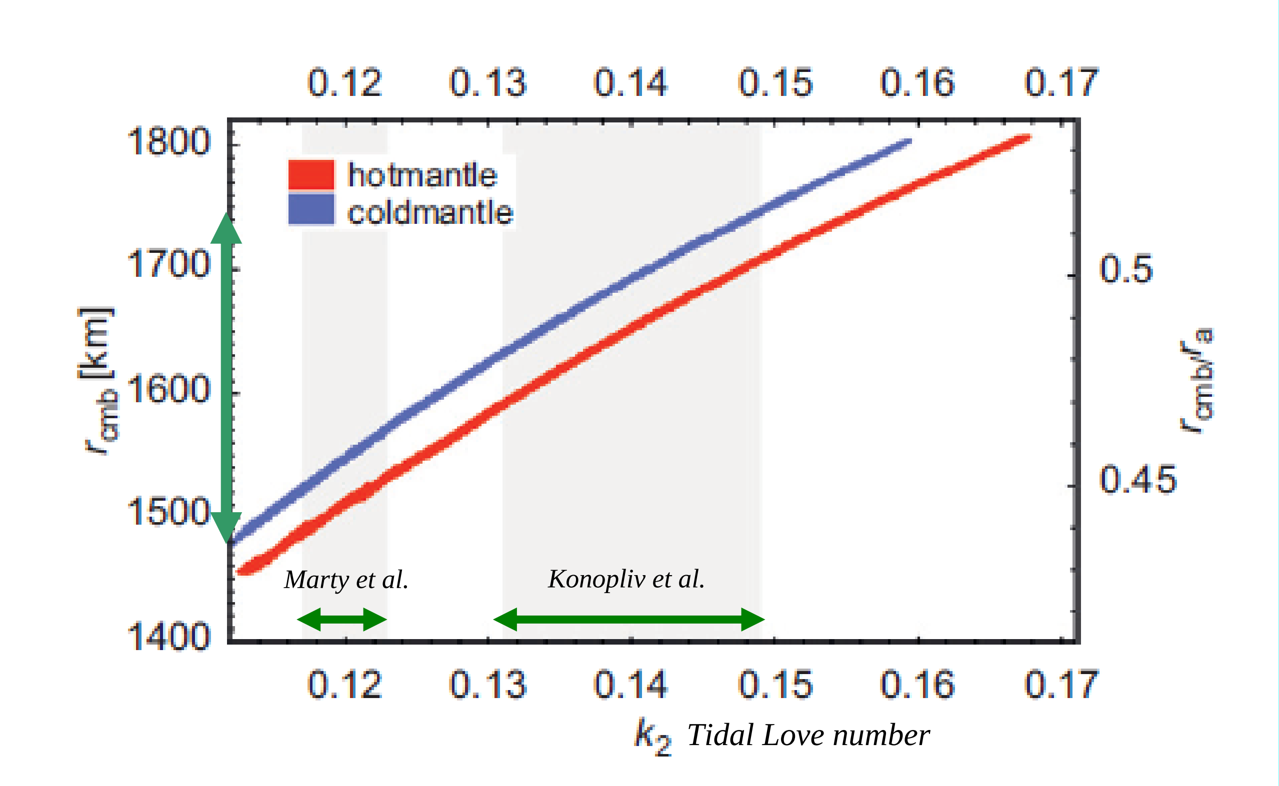
See also Rivoldini et al.'s poster in this session

Need for ground-based
- ➢ Geodetic data
- ➢ Seismological data
- ➢ Electromagnetic data

Core radius by seismology see Knapmeyer in this session

Current knowledge of the Martian core from geodetic data

(e.g. Yoder et al., 2003; Konopliv et al., 2006; Marty et al., 2009)



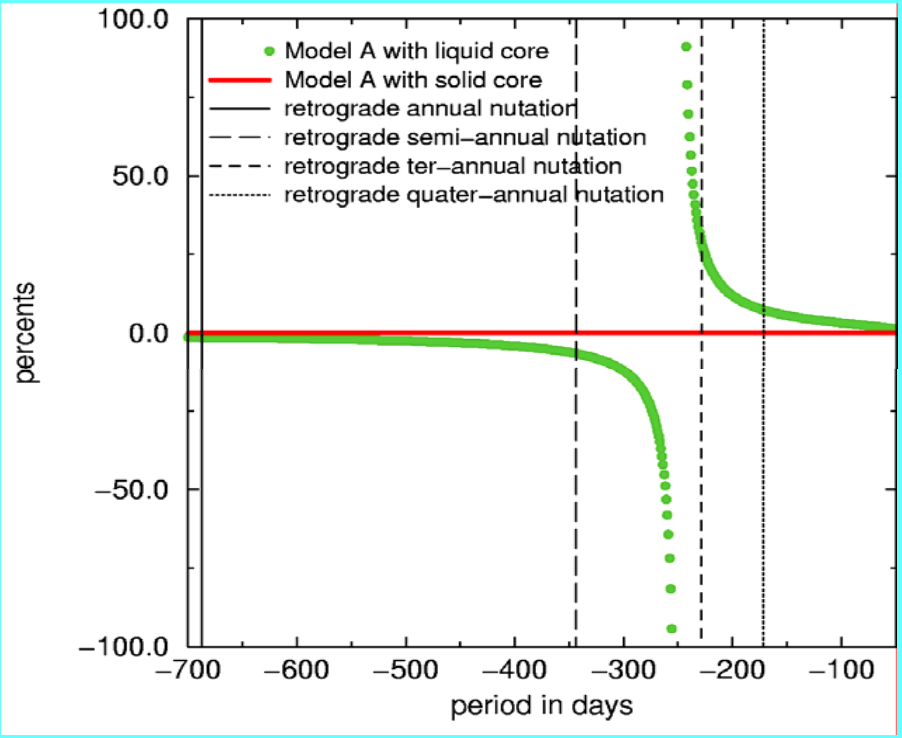
Core radius estimates given possible mantle temperature end-members, mantle rheology, and crust density and thickness range.

See also Rivoldini et al.'s & Rosenblatt et al.'s poster in this session

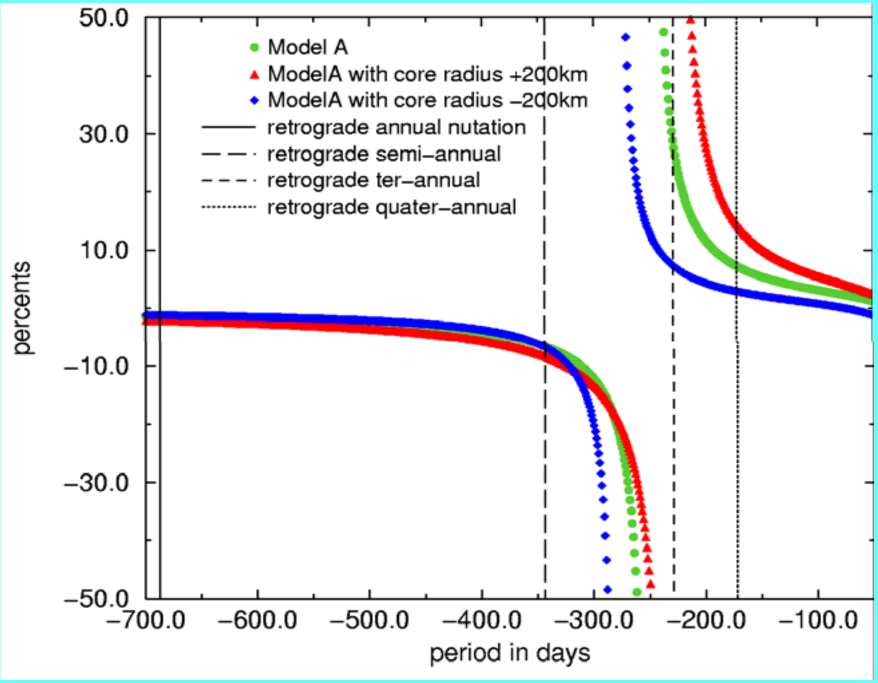
Discrepancy between different studies.
Large uncertainty for core radius: +/- 250 km.
Needs to be improved → Monitoring the nutations
(variations of the orientation of Mars' rotation axis)

Mars’ deep interior from its nutations (1)

Free Core Nutation (FCN) resonance with the retrograde ter-annual period

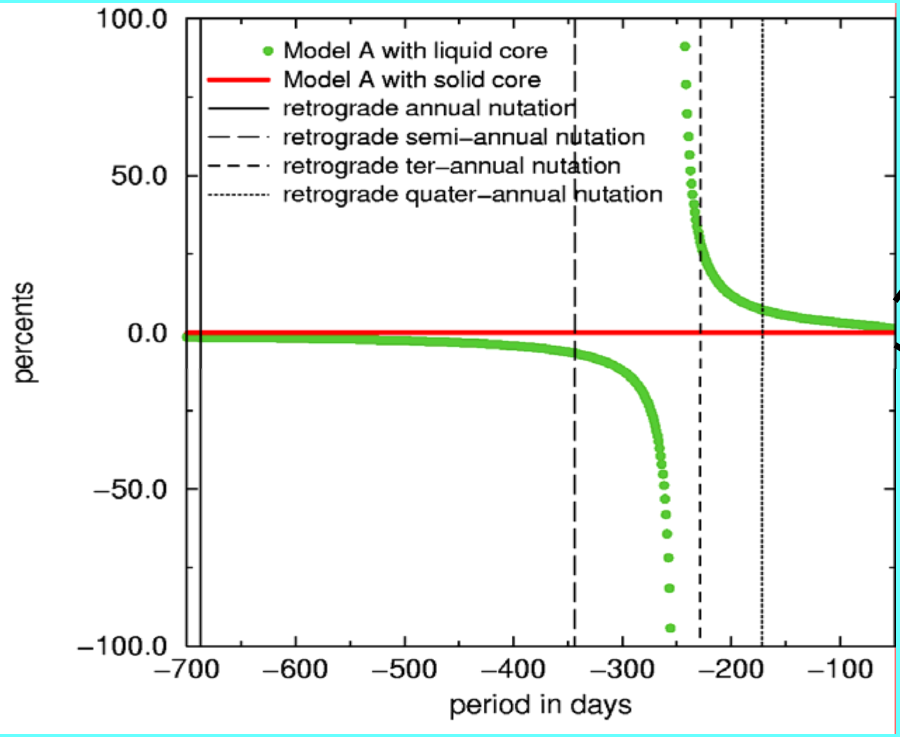


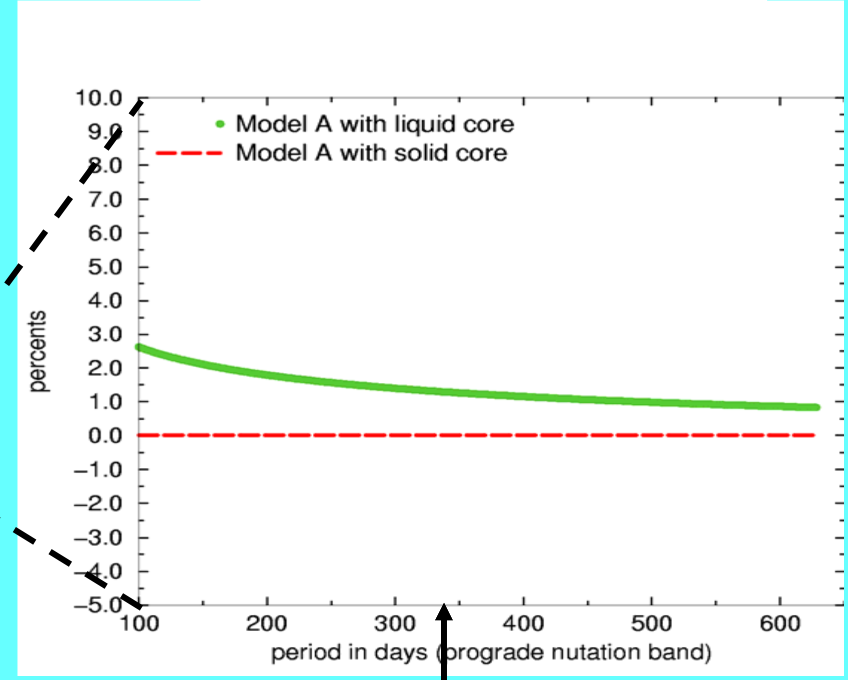
Response of the planet Mars with a liquid core (green) or a solid core (red). The Free Core Nutation resonance can be observed (*see Dehant et al., this meeting)*



New constraints on the size of the Martian core.

Mars' deep interior from its nutations (2)





prograde semi-annual nutation

The prograde semi-annual nutation is far from the resonance but its amplitude is sufficiently high to observe the core contribution in the data.

In addition, if an inner core exists, it is expected to cancel the effect of the FCN on the semi-annual nutation, thus allowing to detect the inner core.

Conclusion (1)

- Good knowledge of Earth’s radial structure (thanks to numerous seismic data)
- More constraints from additional electromagnetic data and gravimetric data *(see Rosenblatt et al.’s poster in this session)*

→ Earth as a reference planet

- Earth’s observations + High pressure-high temperature experiments + geochemical arguments = tools for the interpretation of observations on Mars and Venus

➢ But cannot substitute these observations

Conclusion (2)

- Mars and Venus interior structures are less well known than the Earth's one 100 years ago !

- Long-standing ground-based geophysical data are mandatory

  to characterize the structure of planetary interiors

  to interpret satellite and surface observations

  to constrain scenarios of planetary evolution on the short and long time scales.

We thank B. Langlais, H. Amit, S. Le Mouëlic and A. Rivoldini for fruitfull discussion about the magnetic field and planetary interior modeling