The interior structure and dynamics of Mercury

(*my own sober spin based on gravity and rotation observations*)

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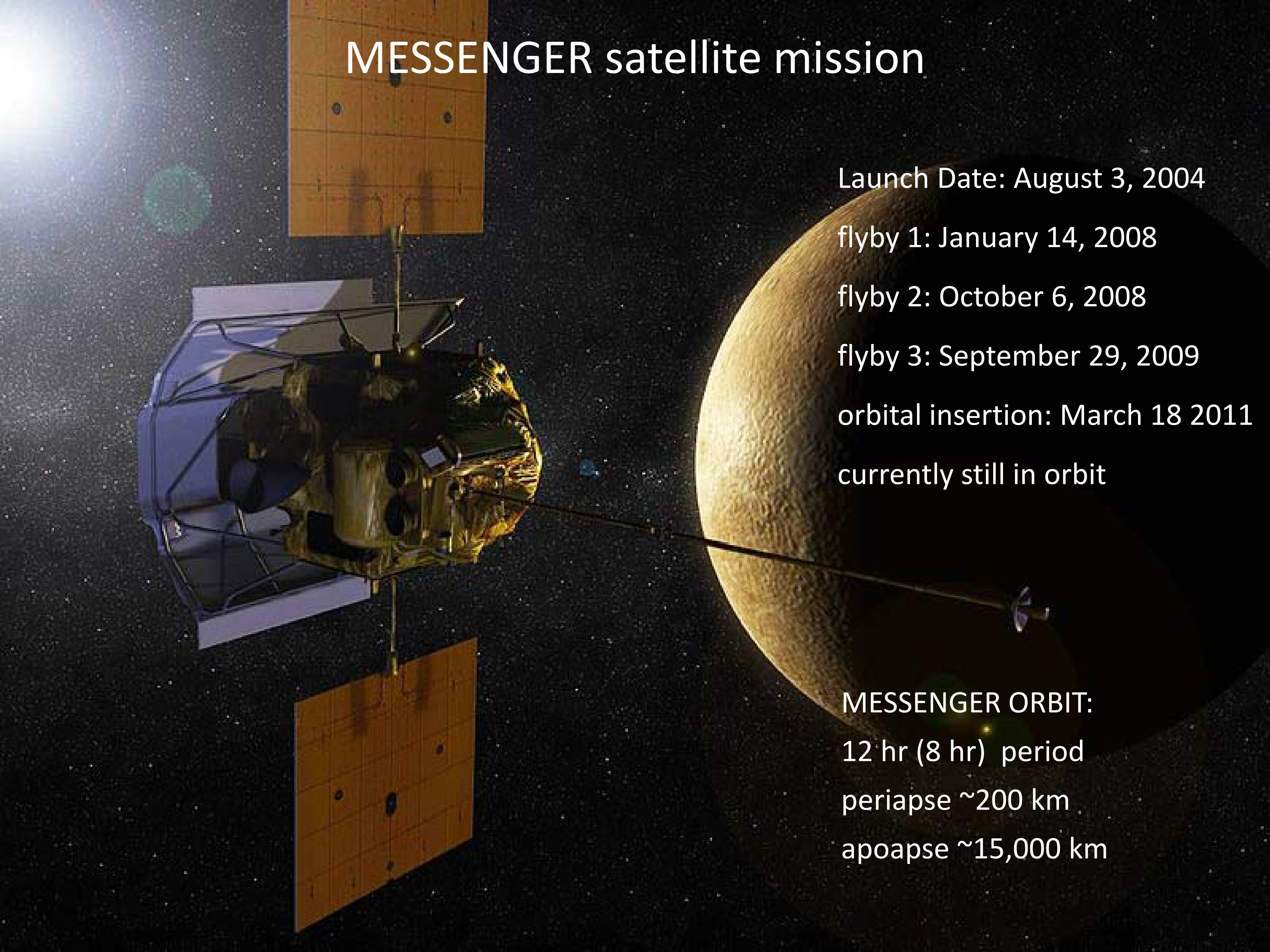
MESSENGER satellite mission



Launch Date: August 3, 2004

flyby 1: January 14, 2008

flyby 2: October 6, 2008

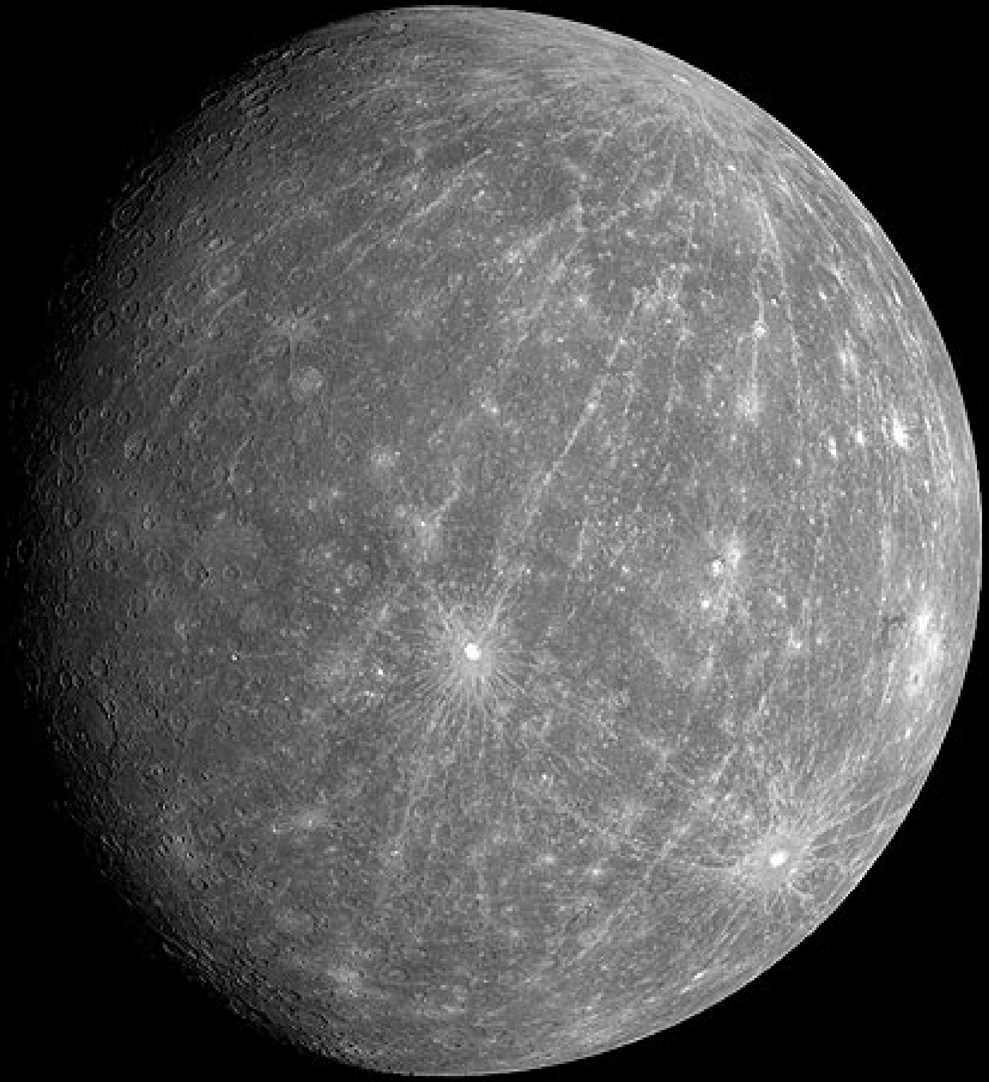
flyby 3: September 29, 2009

orbital insertion: March 18 2011

currently still in orbit

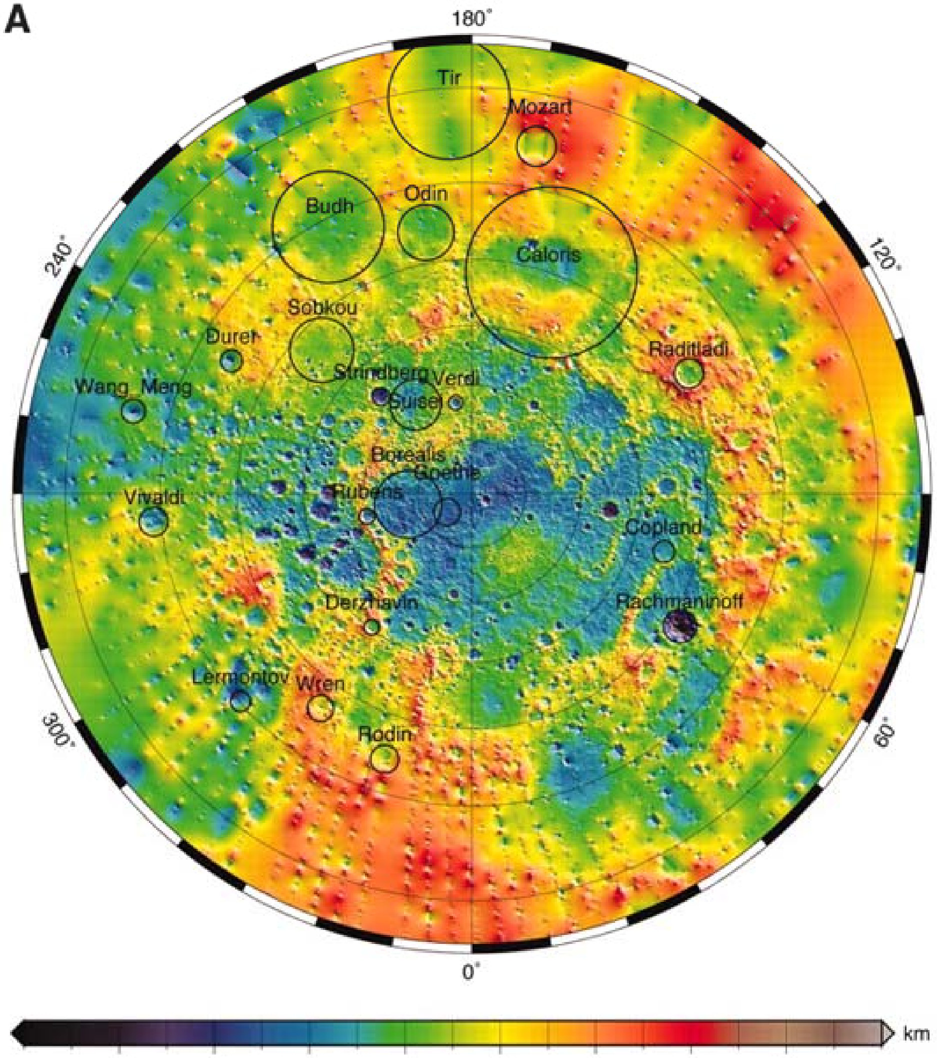
MESSENGER ORBIT:
12 hr (8 hr) period
periapse ~200 km
apoapse ~15,000 km

Spectacular images



Spectacular images

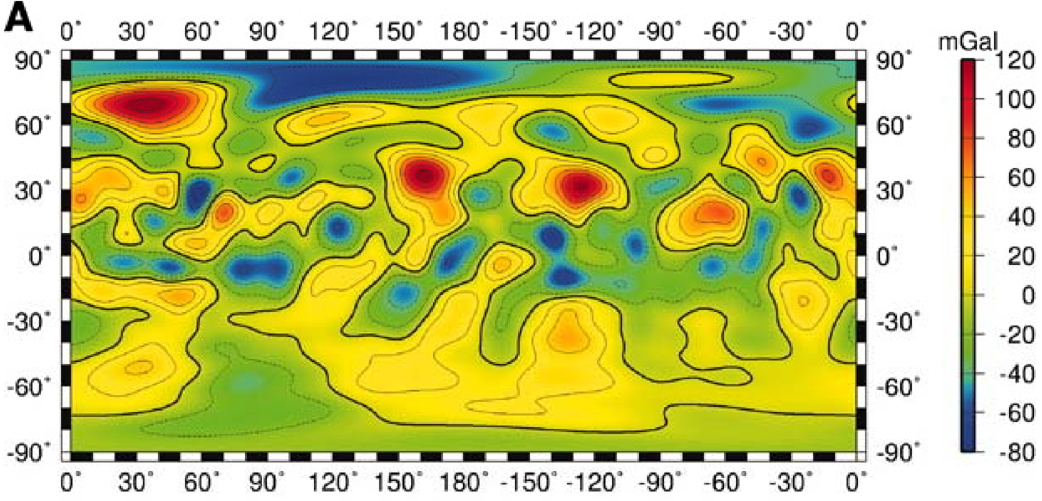
Topography of Mercury from MESSENGER



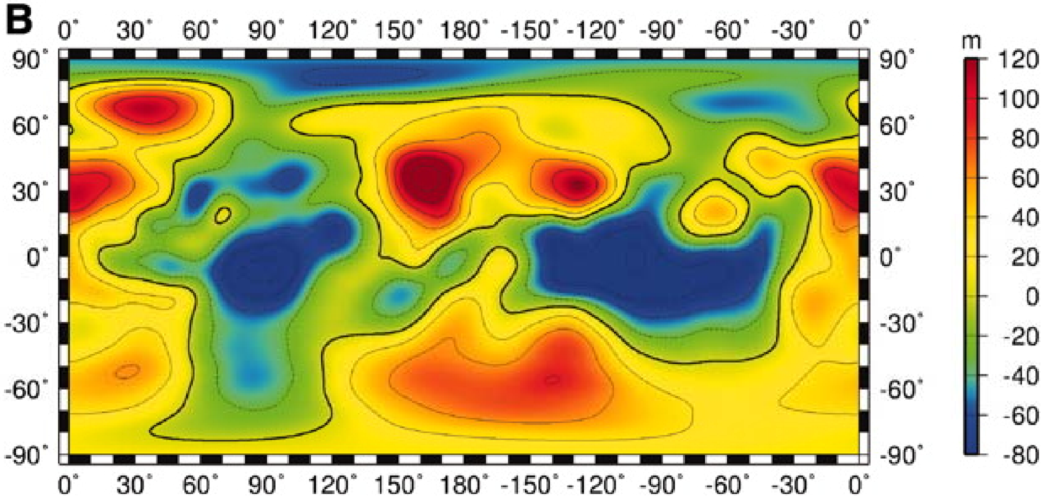
Zuber et al., Science, 2012

Mercury gravity, geoid from MESSENGER

Free air gravity anomaly



Geoid



$B > A =$ equatorial moments of inertia

$C =$ polar moment of inertia

$M, R =$ mass, radius

$$J_2 = \frac{C - \frac{1}{2}(A+B)}{MR^2}$$

$$= (5.03 \pm 0.02) \times 10^{-5}$$

$$C_{22} = \frac{B-A}{4MR^2}$$

$$= (0.81 \pm 0.01) \times 10^{-5}$$

Smith et al., Science, 2012

Earth-Mercury comparison: size, interior structure

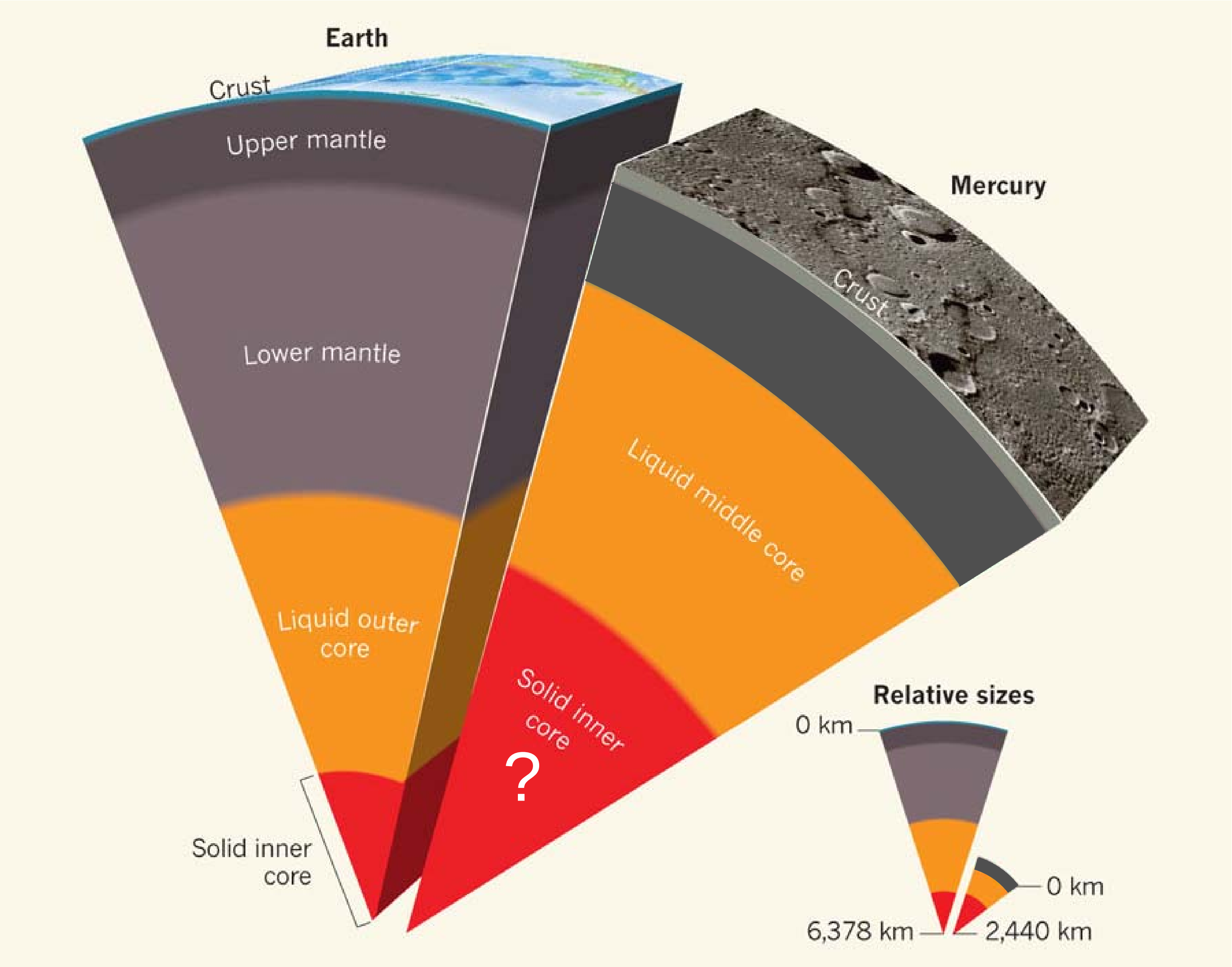


Image adapted from *Stevenson, Nature, 2012*

Earth-Mercury comparison: mantle convection

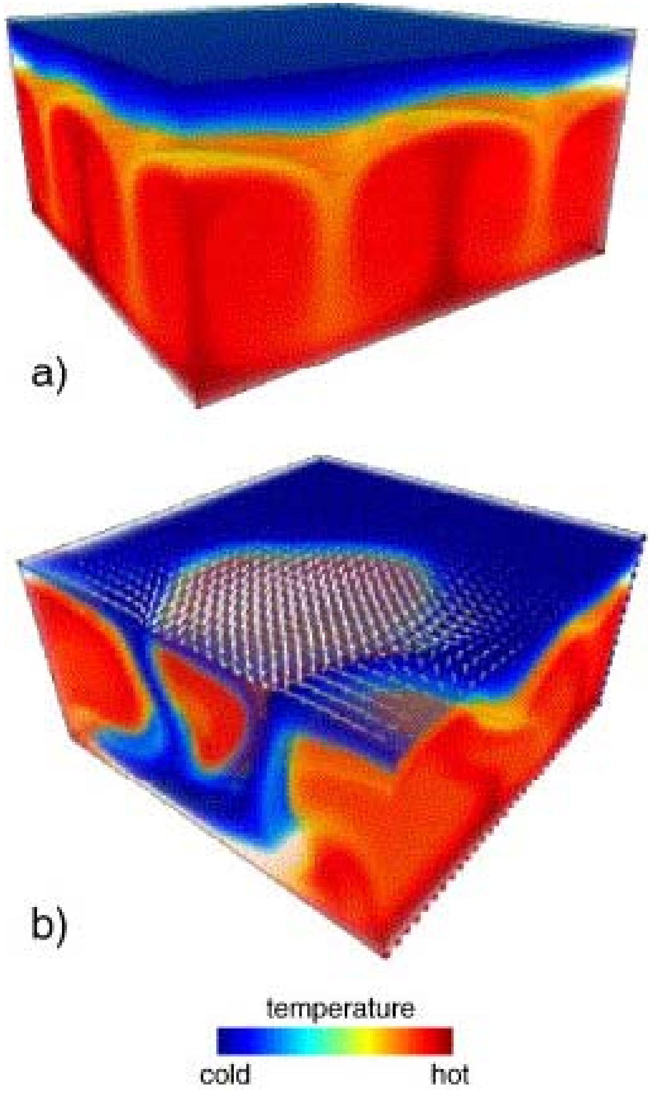
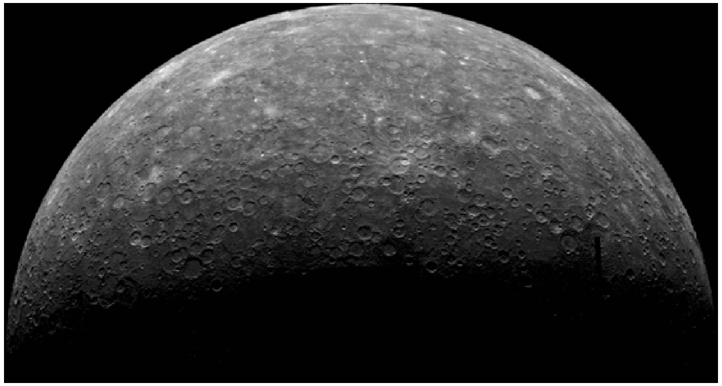
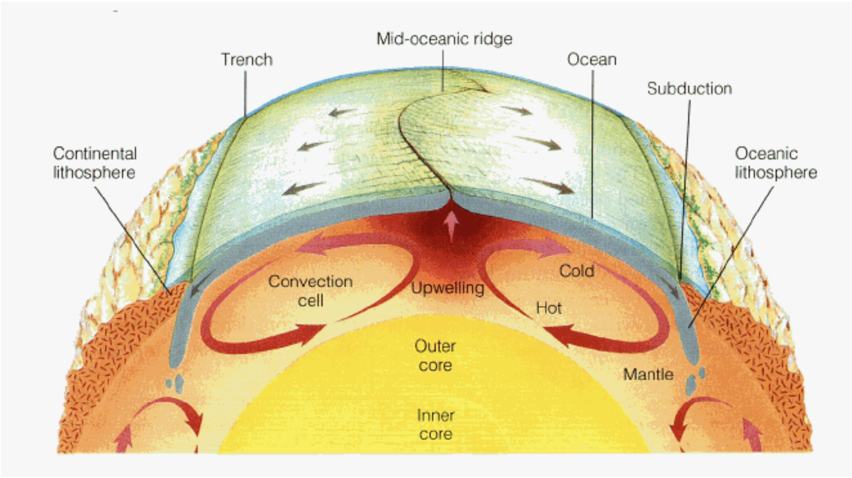


Image from *Loddoch et al., EPSL, 2006*

Mercury: stagnant lid convection?



Earth: plate tectonics



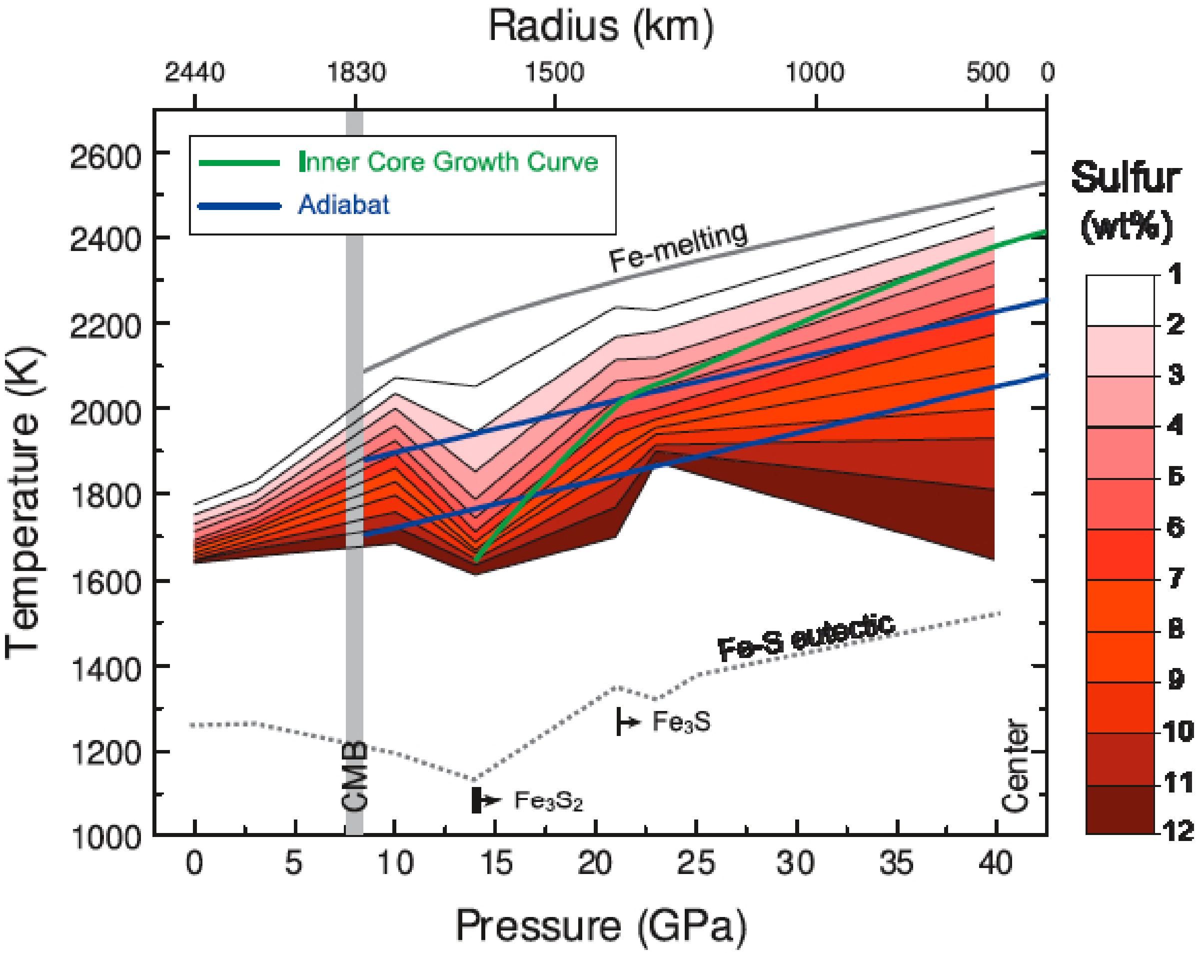
High heat flux through CMB

depth, pressure

Low heat flux through CMB

depth, pressure

Fe-FeS Liquidus



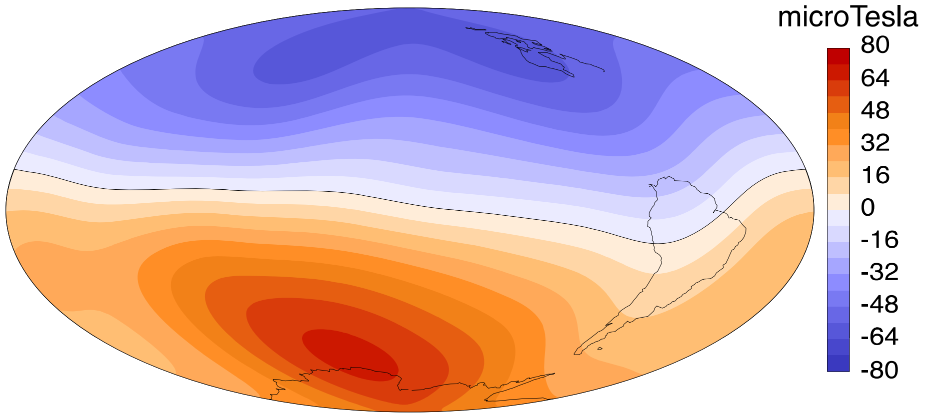
Chen et al, GRL, 2008

Snow regime

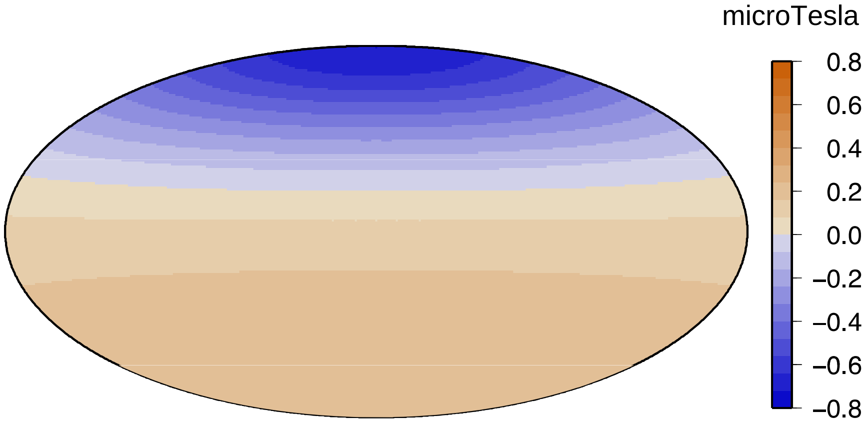
Snow regime

Earth-Mercury comparison: magnetic field

Earth surface

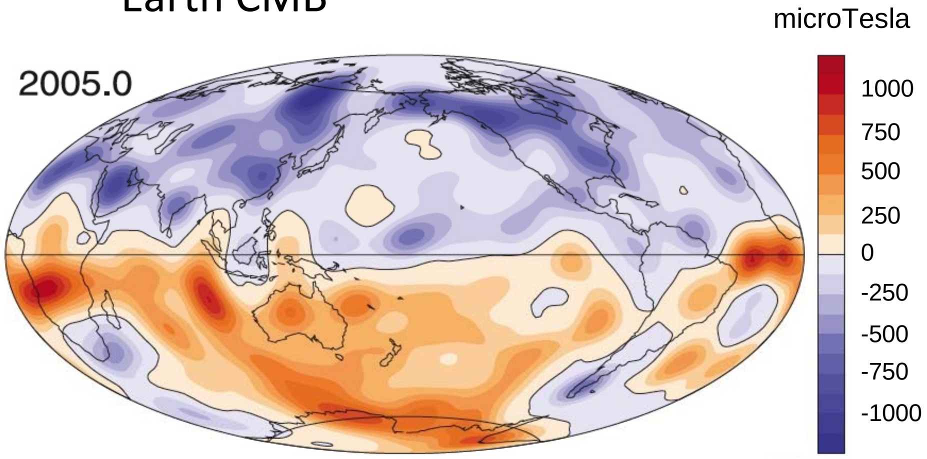


Mercury surface



from *Anderson et al, JGR, 2012*

Earth CMB



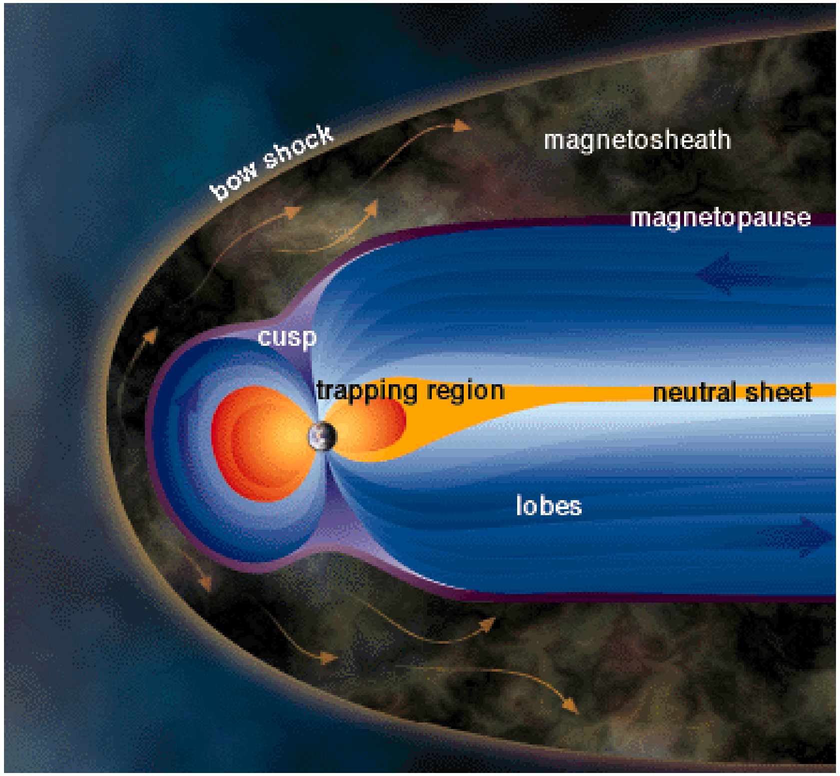
Finlay et al, GJI, 2012

- Field strength of Mercury

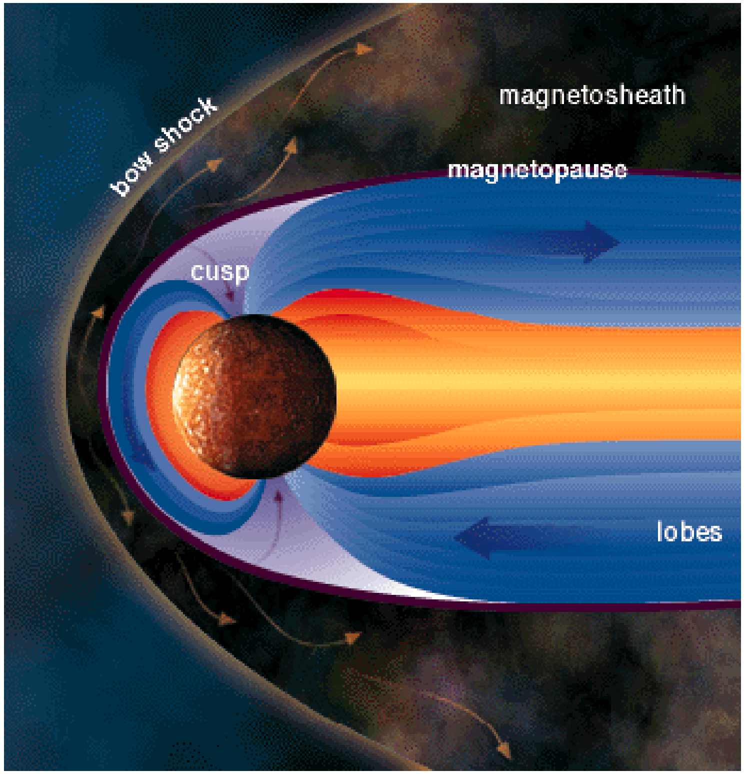
  = 1% of Earth
- Axially symmetric
- Large quadrupole
- Tilt < 0.8^o

Earth-Mercury comparison: magnetosphere

Earth



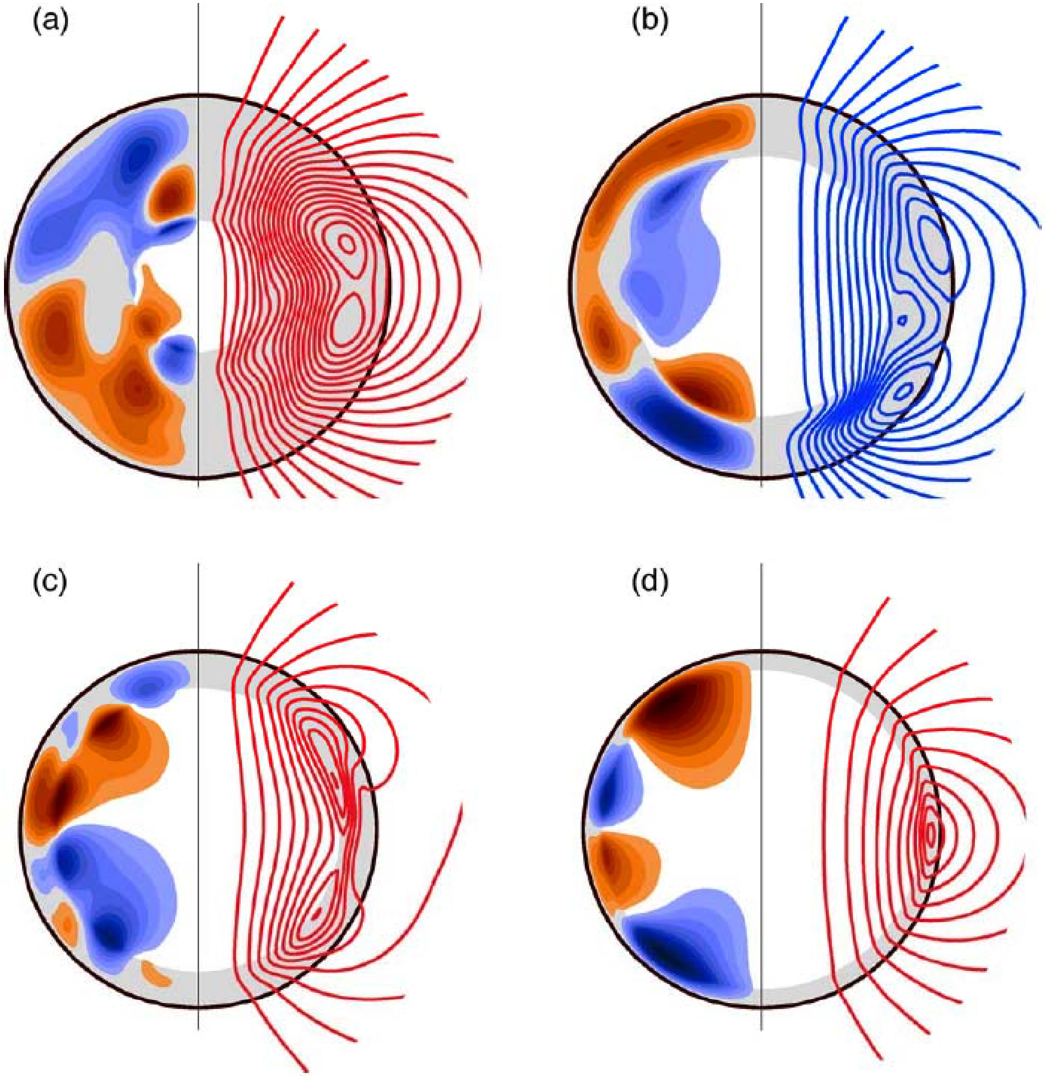
Mercury



Original artwork by Windows to the Universe staff.

Magnetic field of Mercury

1) Thin shell dynamo

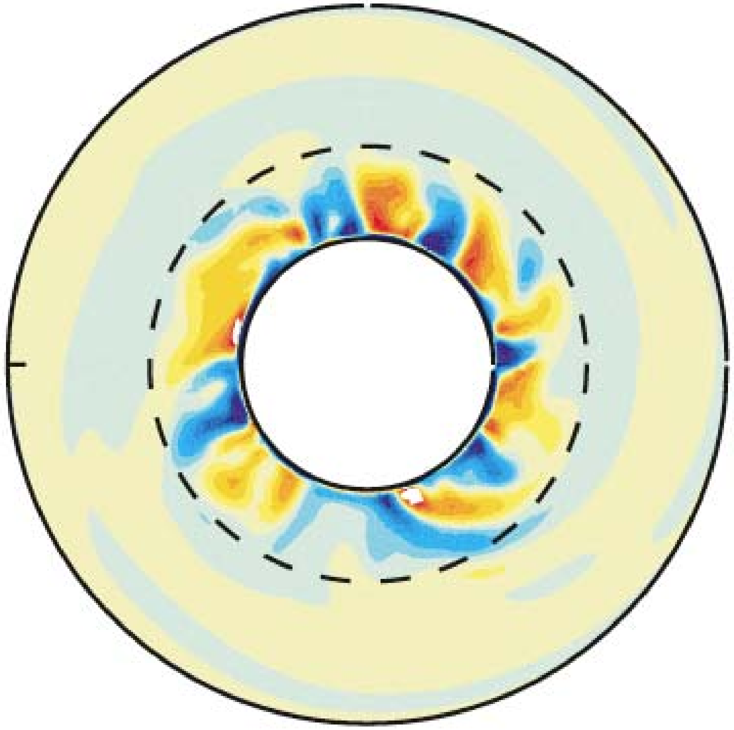


Stanley et al. EPSL, 2005

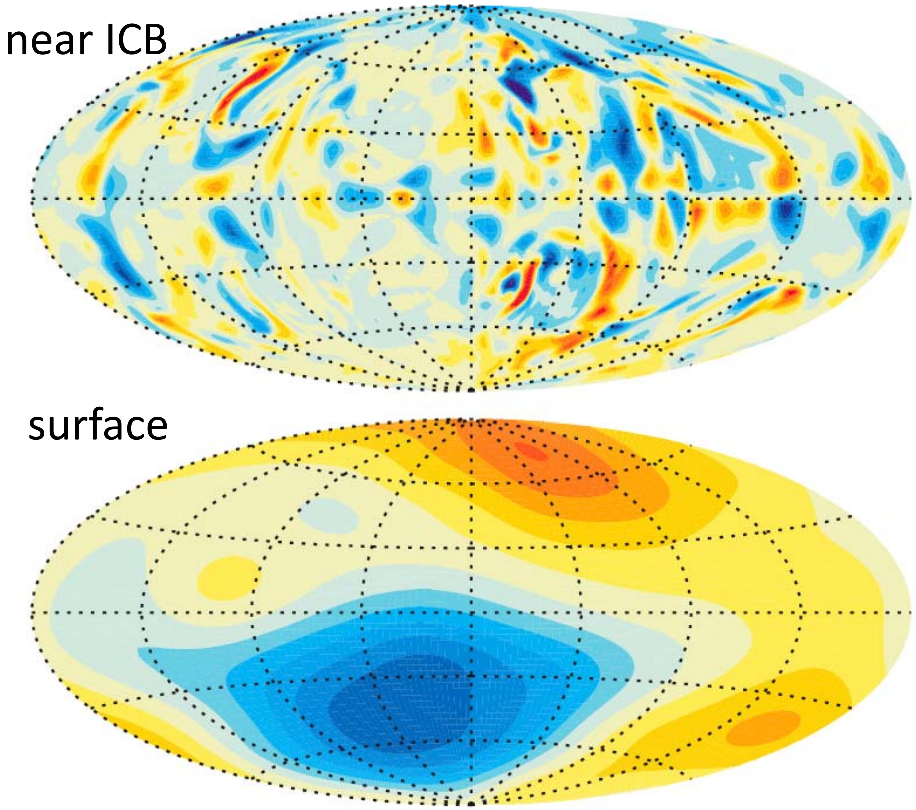
Magnetic field of Mercury

2) Thermally stratified layer

vorticity, top view



radial magnetic field



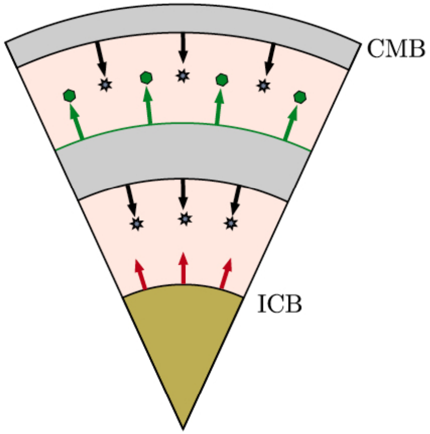
near ICB

surface

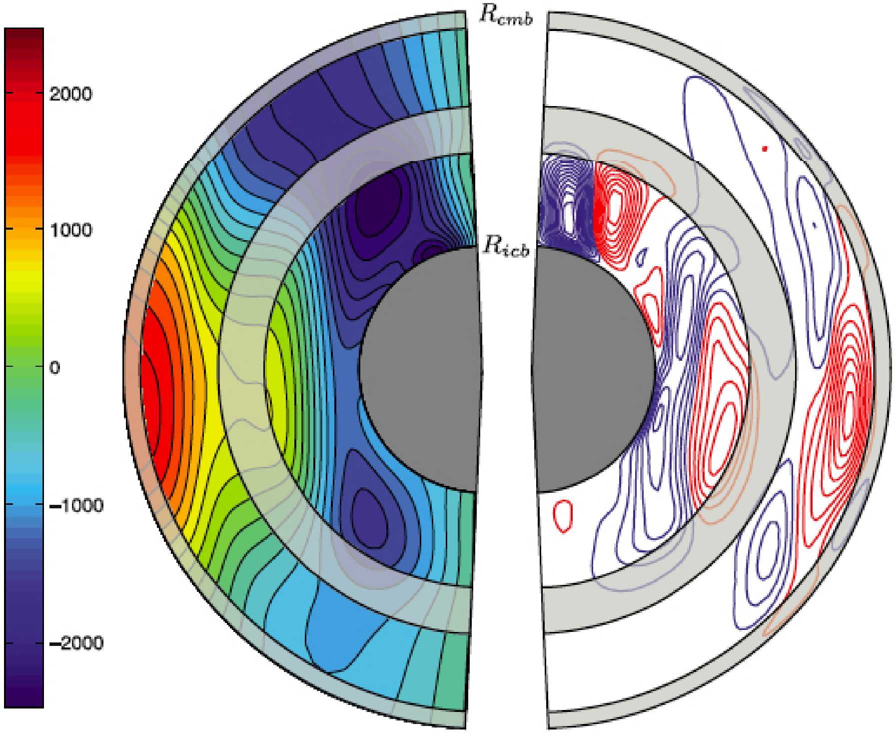
Christensen, Nature, 2006

Magnetic field of Mercury

3) Snow zones

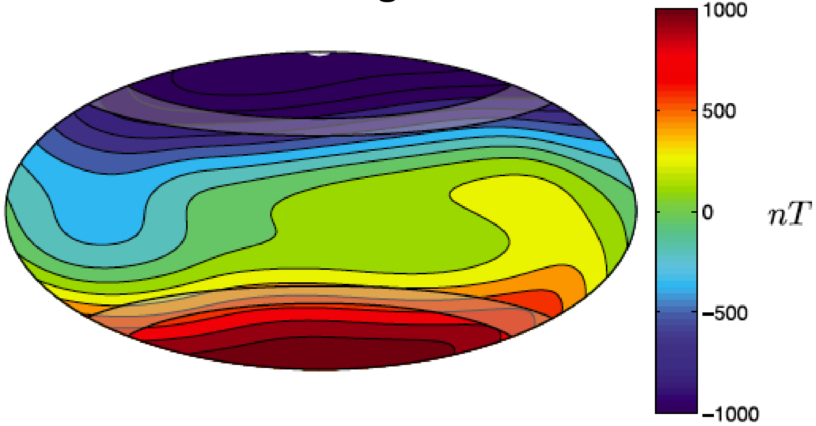


magnetic field, meridional cut



toroidal poloidal

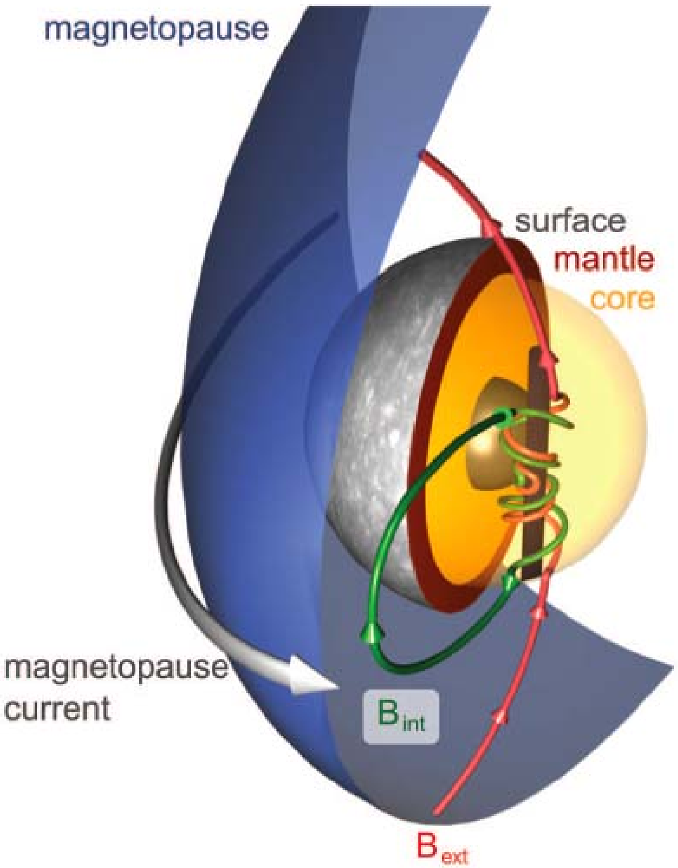
surface radial magnetic field

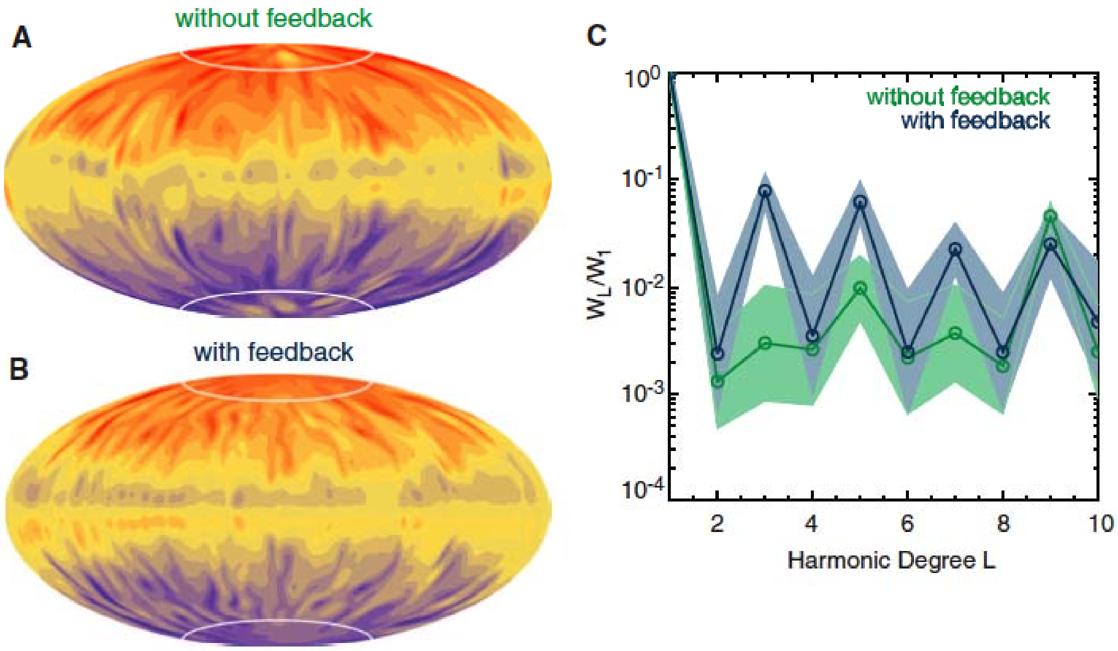


Vilim et al, JGR, 2011

Magnetic field of Mercury

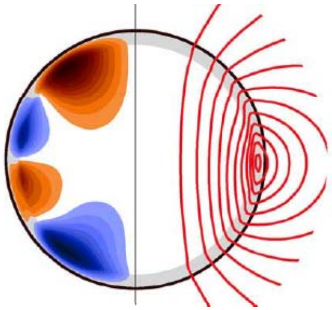
4) Magnetosphere feedback

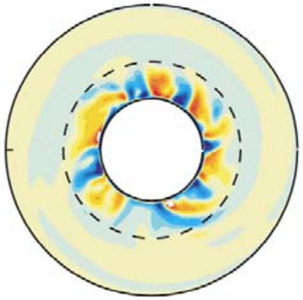


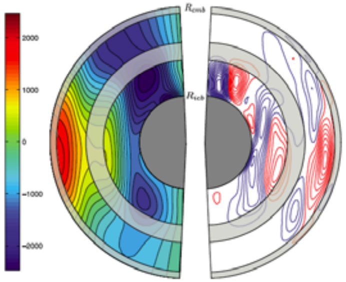


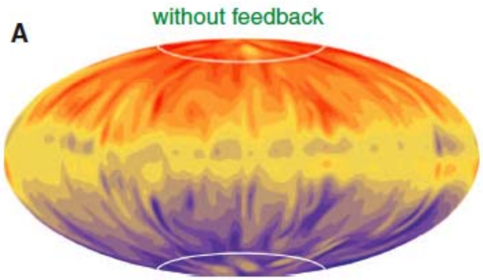
Heyner et al, Science, 2011

Structure & Dynamics of Mercury’s core


thin shell


thermal layer at CMB

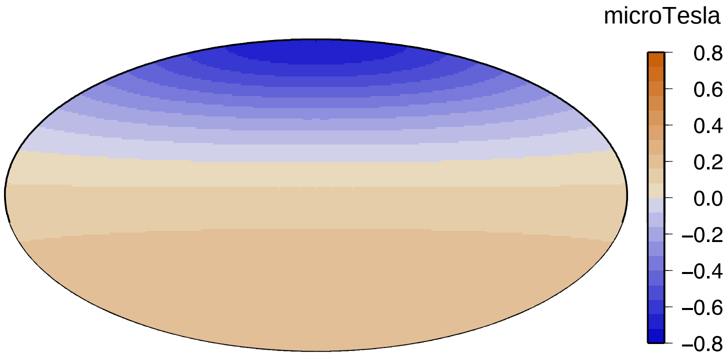

snow zone


magnetosphere feedback

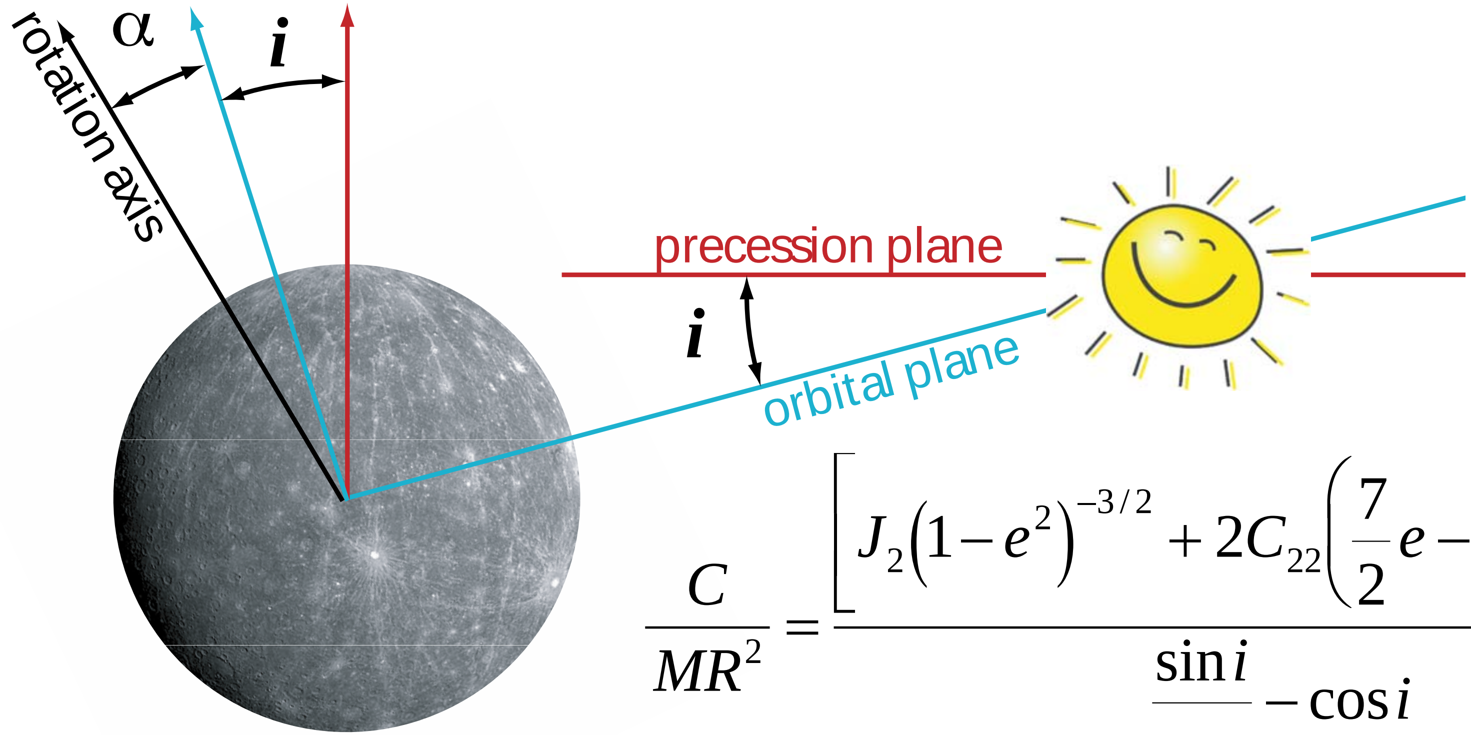
- Which of these models (or combination, or other) can best reproduce observed Mercury field?

- Many models depend on structure of the core

- Can we constrain the interior structure?
    - inner core size?
    - thermal stratification at CMB?
    - Fe snow zone? Fe snow in whole core?



Mercury’s orbital dynamics: Cassini 1 state



$$\frac{C}{MR^2} = \frac{\left[J_2\left(1-e^2\right)^{-3/2} + 2C_{22}\left(\frac{7}{2}e - \frac{123}{16}e^3\right)\right]\frac{n}{\mu}}{\frac{\sin i}{\alpha} - \cos i}$$

$n =$ mean orbital frequency $(= 2\pi / 87.969 \text{ days}^{-1})$

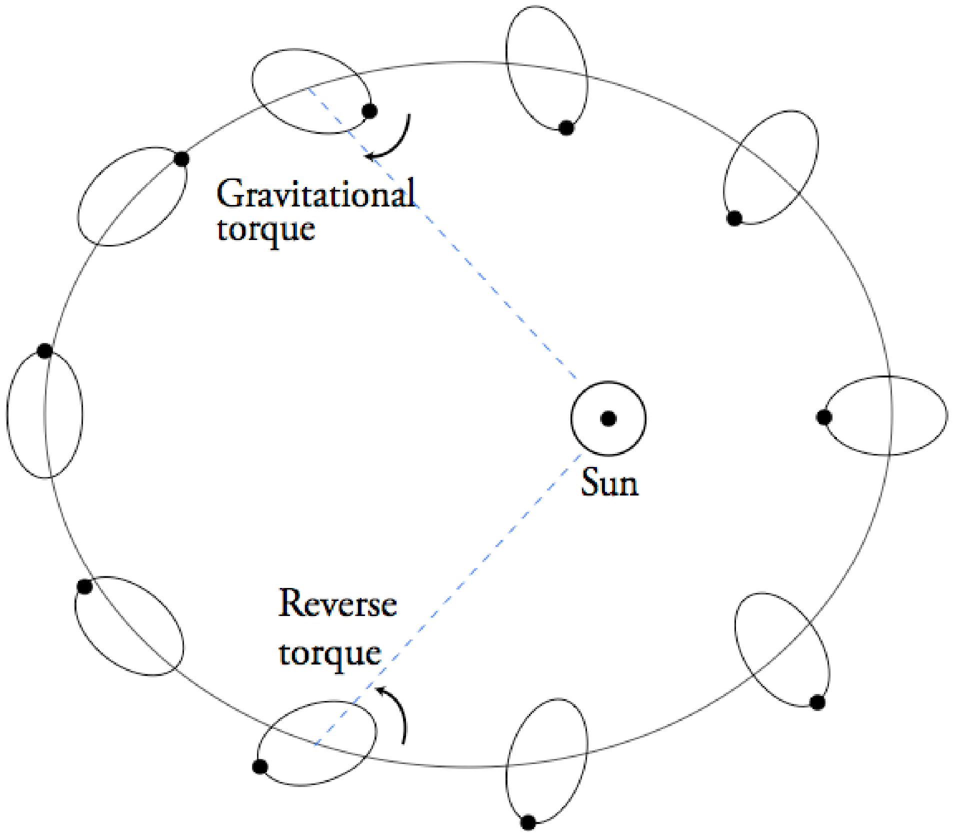
$\mu =$ precession rate $(2\pi / 0.328 \text{ Gyr}^{-1})$

$i =$ orbital inclination (8.6^{o})

$e =$ orbital eccentricity $(= 0.2056)$

$\alpha =$ obliquity

Mercury’s orbital dynamics: 3:2 spin-orbit resonance



- Mercury’s orbital period
  = 87.969 days
- Mercury’s mean rotation period
  = 58.646 days
- Ratio between the two
  = 1.5

- librations:
  small periodic variations
  about mean rotation

Adapted from *Zuber et al., Space Sci. Rev., 2007*

Mercury's longitudinal librations

- If Mercury is a rigid planet, amplitude of libration:

$$\phi = \frac{3}{2}\left(1 - 11e^2 + \frac{959}{48}e^4 \ldots\right)\left(\frac{B-A}{C}\right)$$

$$= \frac{3}{2} f(e)\left(\frac{B-A}{C}\right)$$

- If Mercury has fluid core, only the shell librates

$$\phi_m = \frac{3}{2} f(e)\left(\frac{B-A}{C_m}\right)$$

$B > A =$ equatorial moments of inertia

$C =$ polar moment of inertia

$C_m =$ polar moment of inertia of mantle

$C_m < C$

Does Mercury have a fluid core?

$$\frac{C_m}{C} = \frac{MR^2}{C}\frac{B-A}{MR^2}\frac{C_m}{B-A}$$

$\frac{C}{MR^2}$ from obliquity (Cassini 1 state)

$\frac{C_m}{B-A} = \frac{3}{2}\frac{f(e)}{\phi_m}$ from amplitude of libration

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$C_{22} = \frac{B-A}{4MR^2} = (0.81 \pm 0.01)\times 10^{-5}$ we know from MESSENGER (Smith et al, Science 2012)

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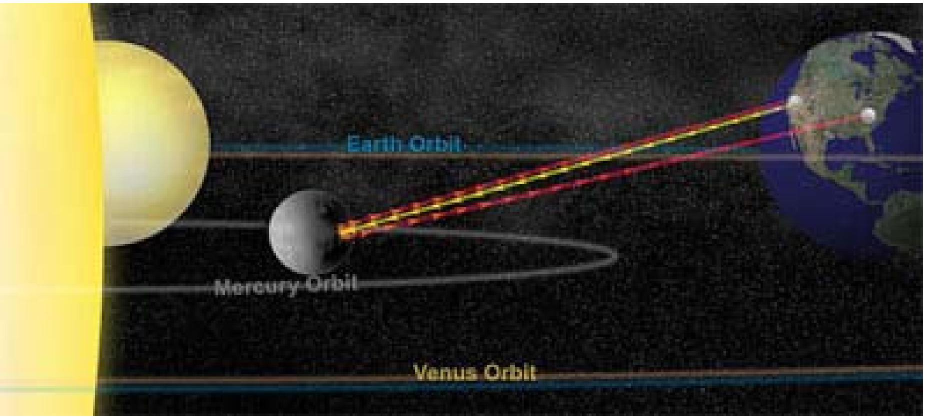
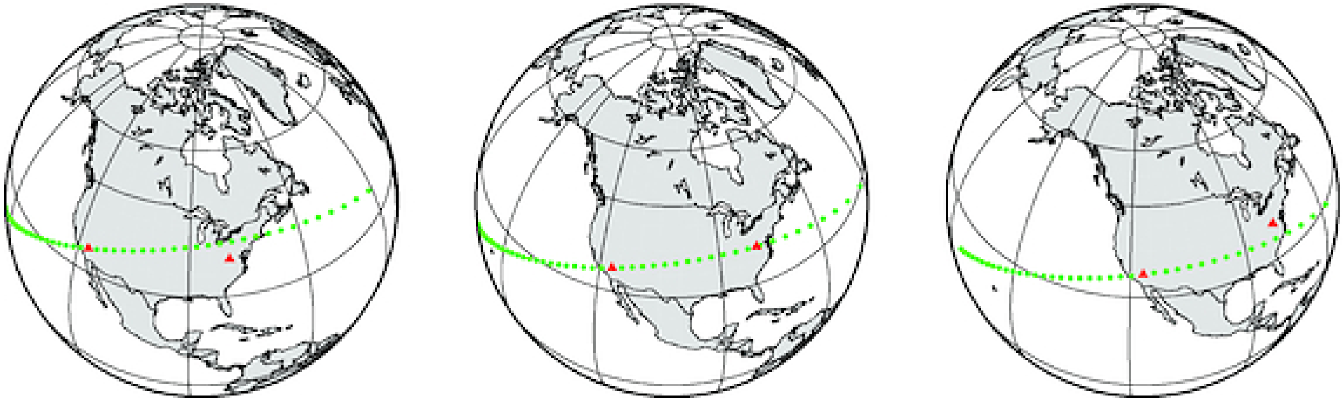
if we get $\frac{C_m}{C} < 1$ Mercury has a fluid core

Peale, Nature, 1976

Radar observations of Mercury's rotation



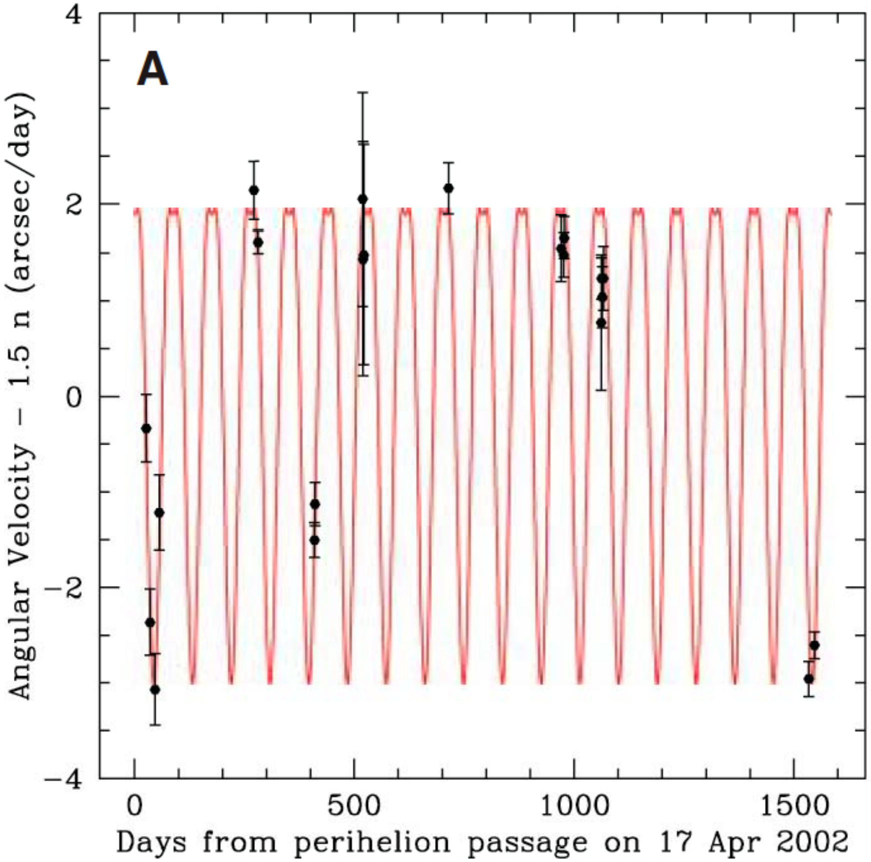
Credit: Bill Saxton, NRAO/AUI/NSF



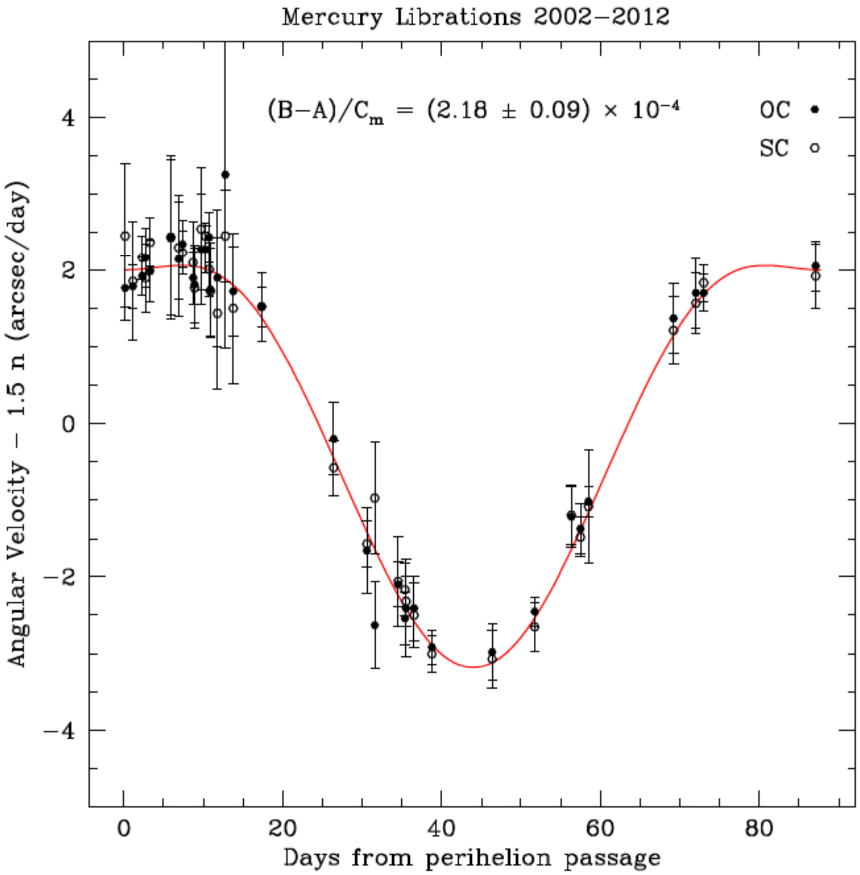
Margot et al., JGR, 2012

- spin-axis orientation (obliquity)
- rotation rate (libration)

Mercury’s longitudinal librations



Margot et al., Science, 2007



Margot et al., JGR, 2012

Amplitude of libration: $\phi_m = (38.5 \pm 1.6)$ arc sec

$$\left(\frac{B-A}{C_m}\right) = (2.18 \pm 0.09) \times 10^{-4}$$

approx 2 times larger than if whole of Mercury librates

Does Mercury have a fluid core?

$$\frac{C_m}{C} = \frac{MR^2}{C}\frac{B-A}{MR^2}\frac{C_m}{B-A}$$

$$\boxed{\mathrm{MoI} = \frac{C}{MR^2} = 0.346 \pm 0.014}$$

from Radar observation
(*Margot et al, JGR, 2012*)

$$\Delta I_m = \frac{B-A}{C_m} = (2.18 \pm 0.09) \times 10^{-4}$$

from Radar observation
(*Margot et al, JGR, 2012*)

$$C_{22} = \frac{B-A}{4MR^2} = (0.81 \pm 0.01) \times 10^{-5}$$

from MESSENGER
(*Smith et al, Science 2012*)

$$\boxed{\frac{C_m}{C} = \frac{4 \cdot C_{22}}{MoI \cdot \Delta I_m} = 0.431 \pm 0.025}$$

YES! Mercury has a fluid core
(solid inner core?)

Two predictions from rotation observations

Building Interior models

- Must match: $M = 3.302 \times 10^{23}$ kg, $R = 2440$ km
- Pressure (P), gravitational acceleration (g), Temperature (T),

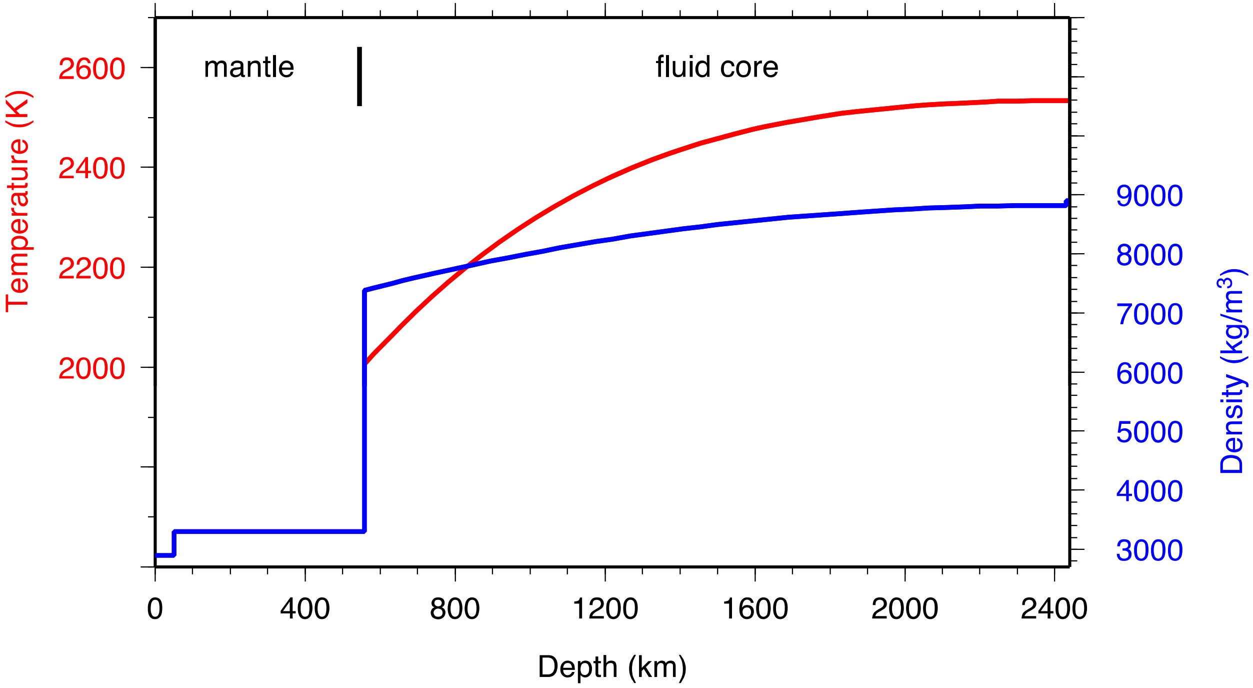
must obey:

$$\frac{\partial P}{\partial r} = -\rho g$$

$$\frac{\partial g}{\partial r} = 4\pi G\rho - \frac{2g}{r}$$

$$\frac{\partial T}{\partial r} = -\frac{\rho g \gamma}{K_s} T$$

$$P = f(\rho, T, \chi)$$

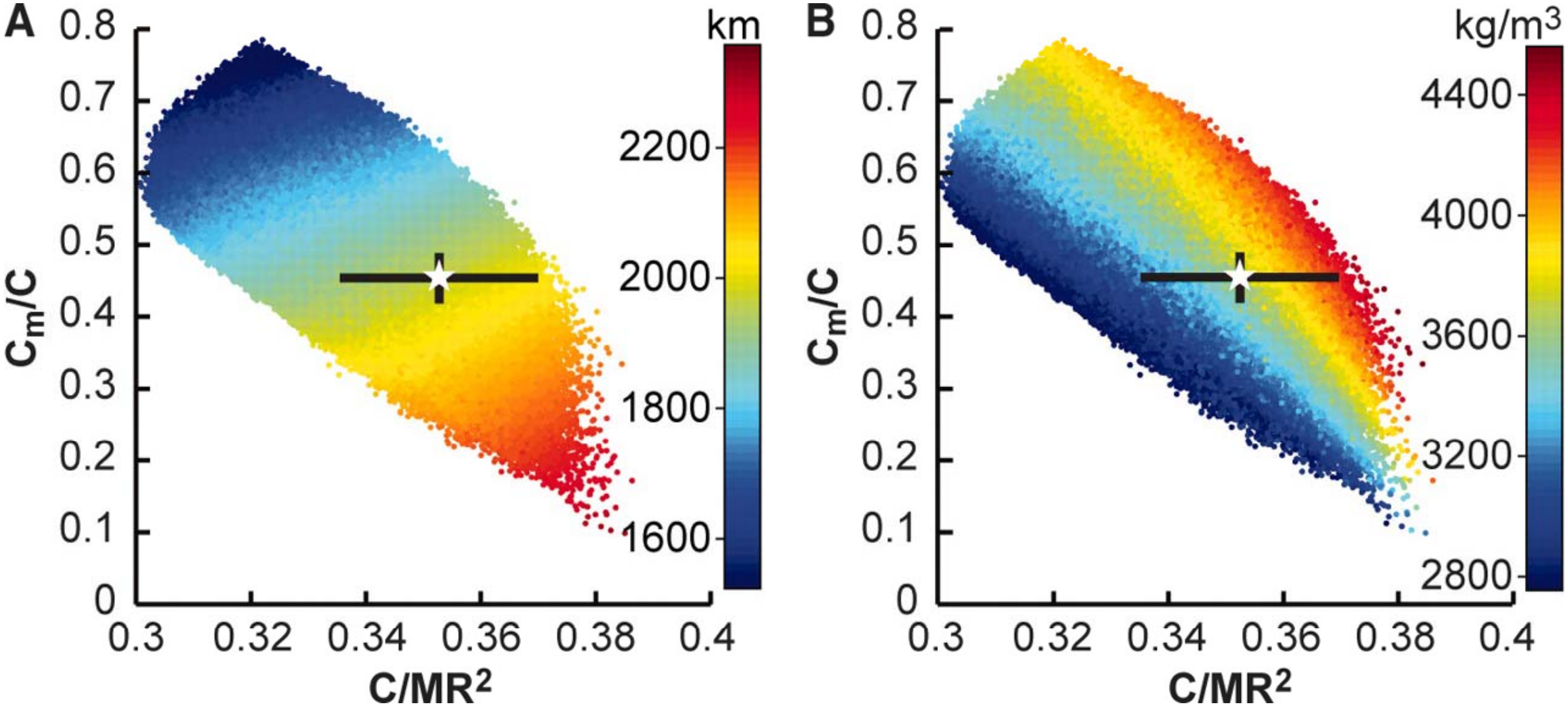


- Calculate $\frac{C_m}{C}, \frac{C}{MR^2}$ Does it match constraints from observations?

Interior structure of Mercury

$$\mathrm{MoI} = \frac{C}{MR^2} = 0.353 \pm 0.017 \qquad \frac{C_m}{C} = \frac{4 \cdot C_{22}}{MoI \cdot \Delta I_m} = 0.452 \pm 0.035$$

Margot et al., Science, 2007



Core-mantle boundary radius

mantle density

Smith et al., Science, 2012

An Iron sulphide layer at base of mantle?

Smith et al., Science, 2012

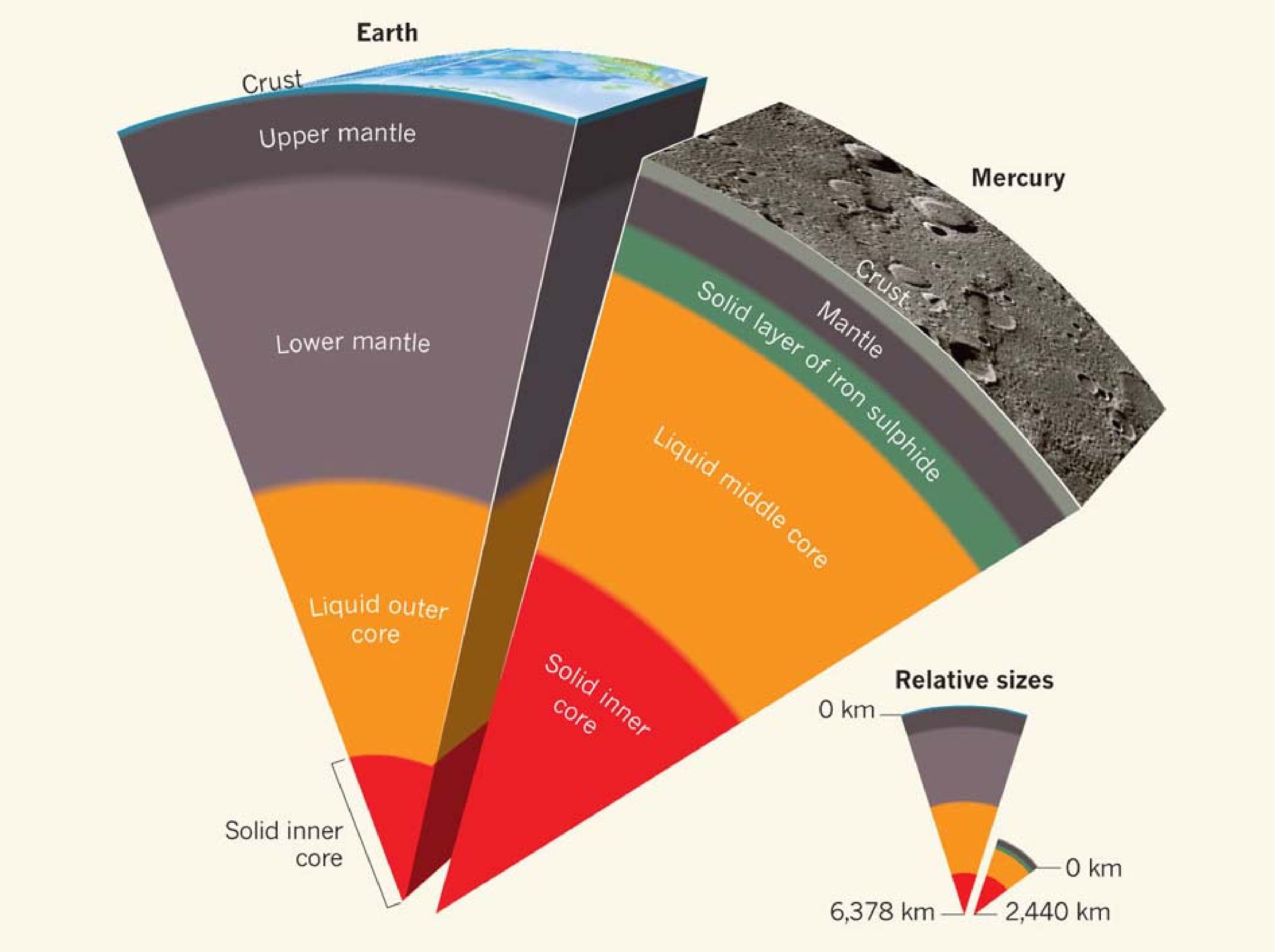


Image from *Stevenson, Nature, 2012*

Moments of Inertia of Mercury from radar data

"Old" values

(Margot et al, 2007; Smith et al, 2012)

$$\mathrm{MoI} = \frac{C}{MR^2} = 0.353 \pm 0.017$$

$$\Delta I_m = \frac{B - A}{C_m} = (2.03 \pm 0.12) \times 10^{-4}$$

$$\frac{C_m}{C} = \frac{4 \cdot C_{22}}{MoI \cdot \Delta I_m} = 0.452 \pm 0.035$$

"New" values

(Margot et al, JGR, 2012)

$$\mathrm{MoI} = \frac{C}{MR^2} = 0.346 \pm 0.014$$

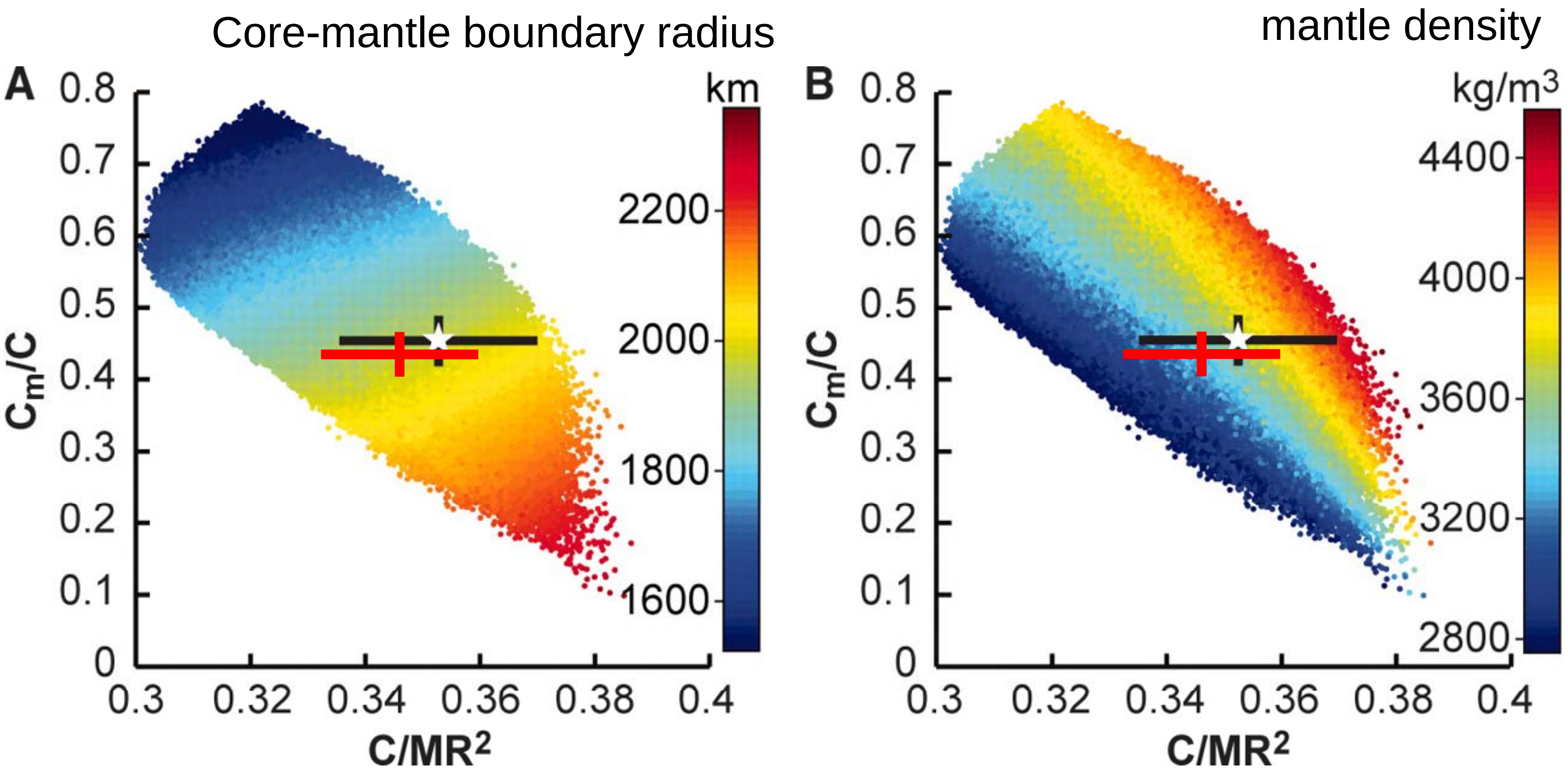
$$\Delta I_m = \frac{B - A}{C_m} = (2.18 \pm 0.09) \times 10^{-4}$$

$$\frac{C_m}{C} = \frac{4 \cdot C_{22}}{MoI \cdot \Delta I_m} = 0.431 \pm 0.025$$

Interior structure of Mercury

$$\mathrm{MoI} = \frac{C}{MR^2} = 0.346 \pm 0.014 \qquad \frac{C_m}{C} = \frac{4 \cdot C_{22}}{MoI \cdot \Delta I_m} = 0.431 \pm 0.025$$

Margot et al., JGR, 2012



Core-mantle boundary radius

mantle density

Smith et al., Science, 2012

Summary so far…

- Rotation + gravity observations, $$MoI = \frac{C}{MR^2} = 0.346 \pm 0.014$$

  Give us constraints on: $$\frac{C_m}{C} = \frac{4 \cdot C_{22}}{MoI \cdot \Delta I_m} = 0.431 \pm 0.025$$

- CMB radius: ≈ 2000±80 km ; mantle density $\rho_m \approx 3300 \pm 300$ kg/m^3
- What is the effect of an inner core?
- What is inner core growth regime? Growth from solidification at ICB?

  Accumulation of "snow"?
- Can we constrain size of inner core & regime of convection from

  C_m / C and C / MR^2?
- Important for:

  Dynamo mechanism

  Thermal history of Mercury

  nature + concentration of light element in fluid core

Building Interior models

- Must match: M = 3.302 x 10^{23} kg, R = 2440 km
- Pressure (P), gravitational acceleration (g), Temperature (T), obey:

$$\frac{\partial P}{\partial r} = -\rho g \qquad \frac{\partial g}{\partial r} = 4\pi G\rho - \frac{2g}{r} \qquad \frac{\partial T}{\partial r} = -\frac{\rho g \gamma}{K_s} T \qquad P = f(\rho, T, \chi)$$

adjustment: sub-adiabatic in top half of fluid core, linearly decreasing to 5% of dT/dr at CMB
Also: allow T of Liquidus to adjust to local adiabat

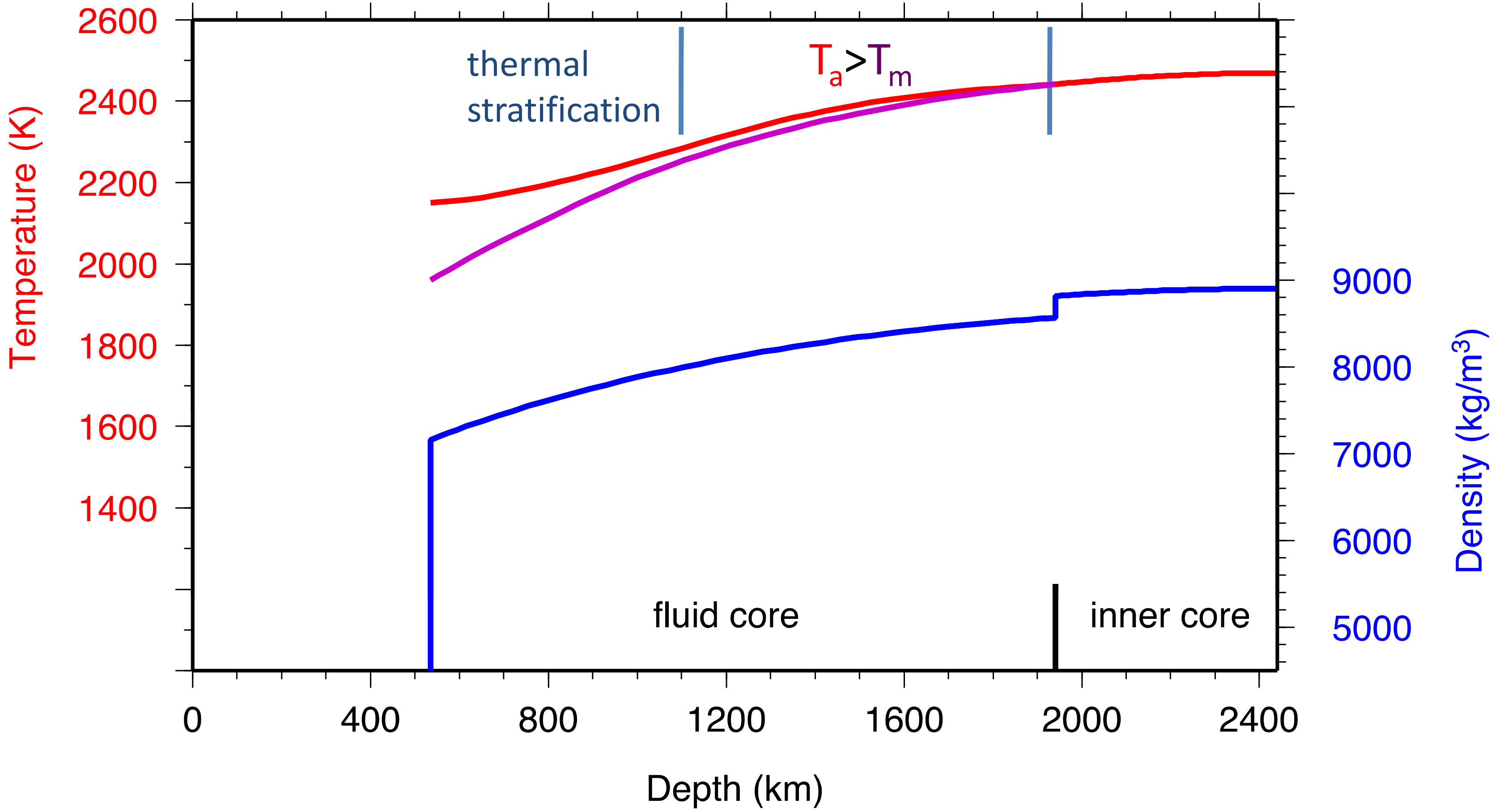
- light element = sulfur : data on liquidus, eutectic, thermoelastic properties for Equation of State
- T at ICB = T of liquidus
- choose mantle density, Sulfur fraction at ICB, ICB radius
- calculate

$$\frac{C_m}{C}, \frac{C}{MR^2}$$

How does it match constraints from observations?

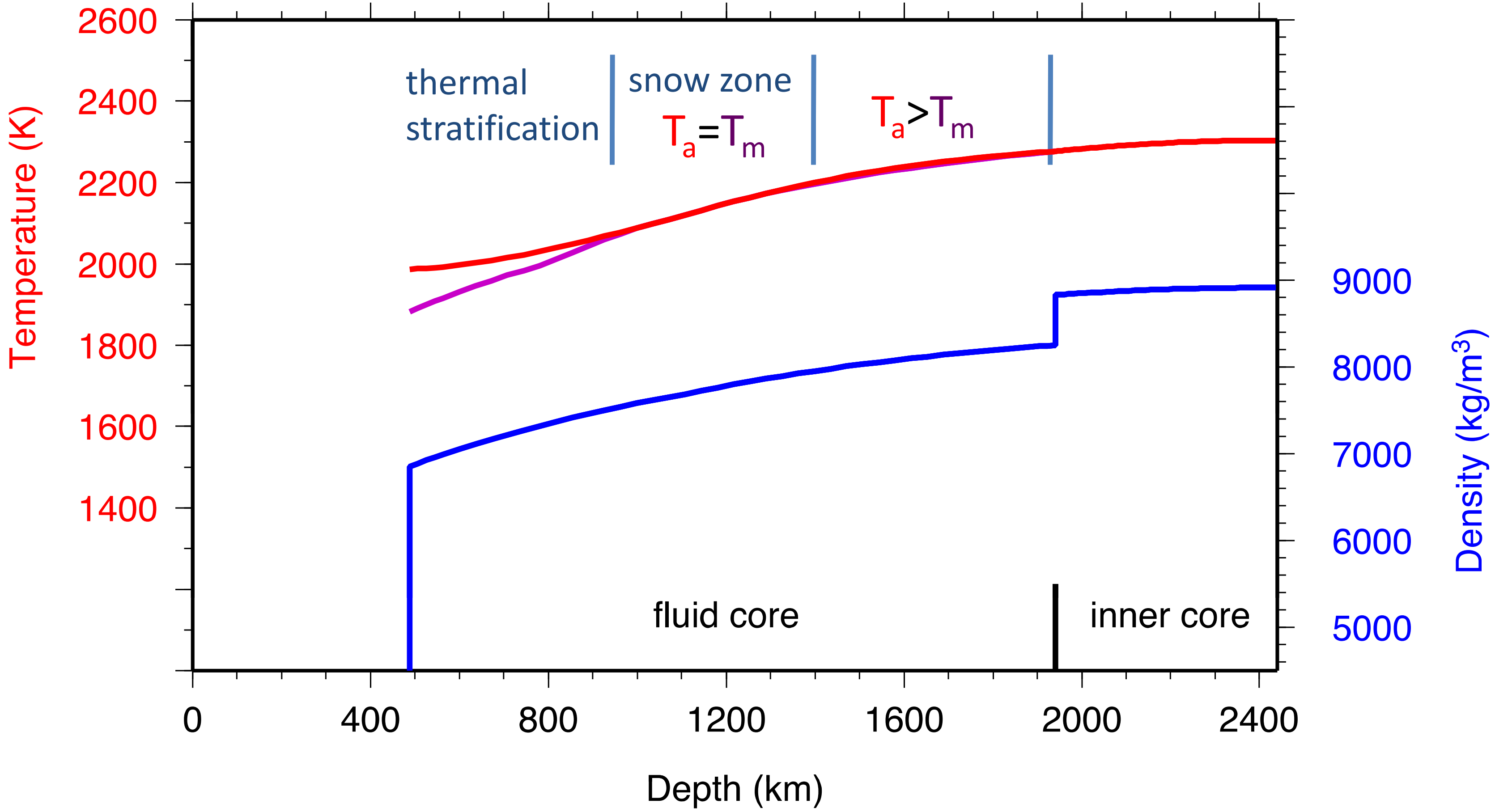
Interior model: no snow

ICB = 500km, ρ_m= 3300 kg/m^3, Sulfur = 1%



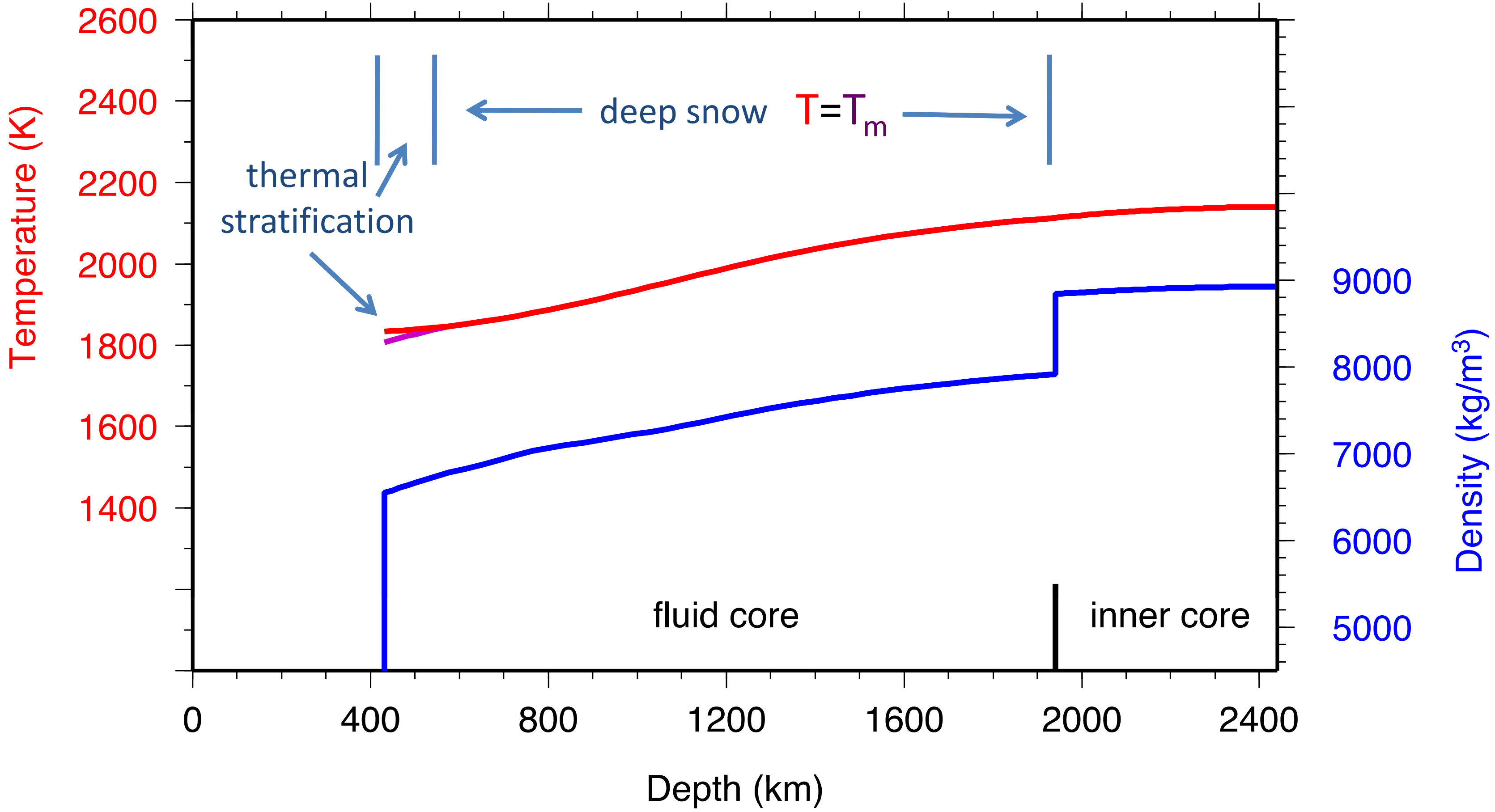
Interior model: snow zone

ICB = 500km, ρ_m= 3300 kg/m^3, Sulfur at ICB = 3%



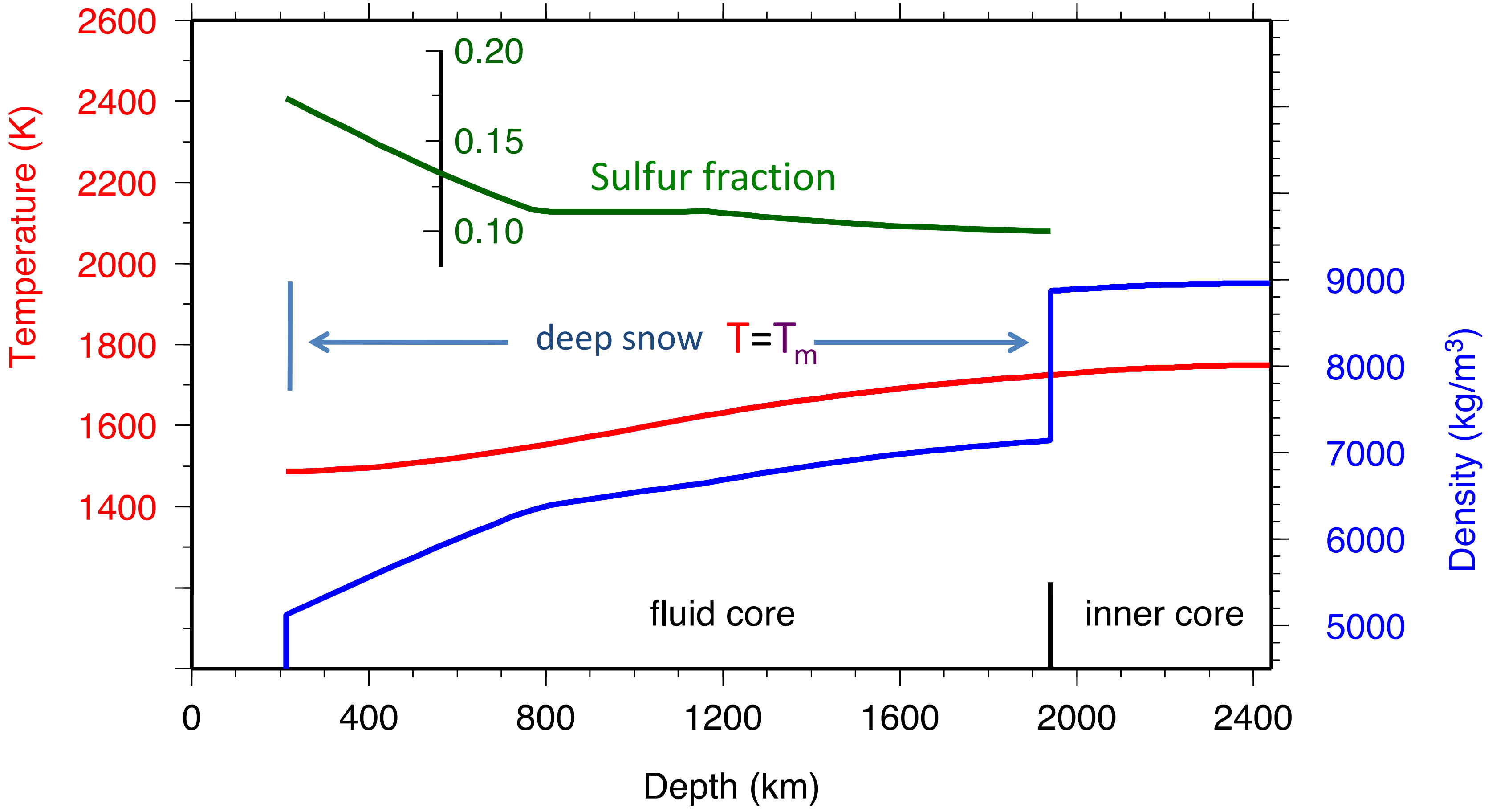
Interior model: deep snow + stratification

ICB = 500km, ρ_m= 3300 kg/m^3, Sulfur at ICB = 5%



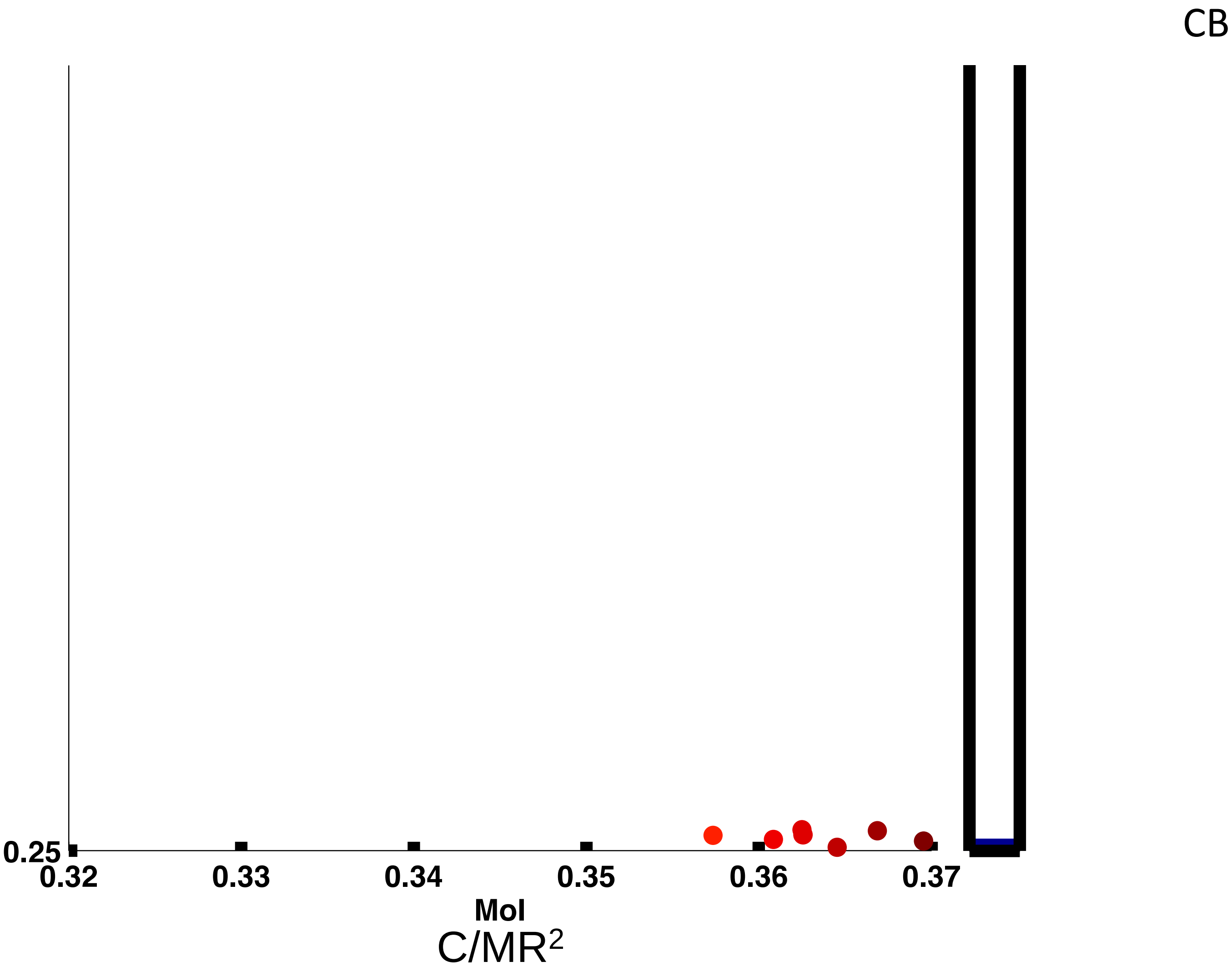
Interior model: deep snow

ICB = 500km, ρ_m= 3300 kg/m^3, Sulfur at ICB= 10%



Interior model: ICB = 50 km

■ no snow
● deep snow + stratification
▲ snow zone
● deep snow, no stratification



Interior model: ICB = 50 km

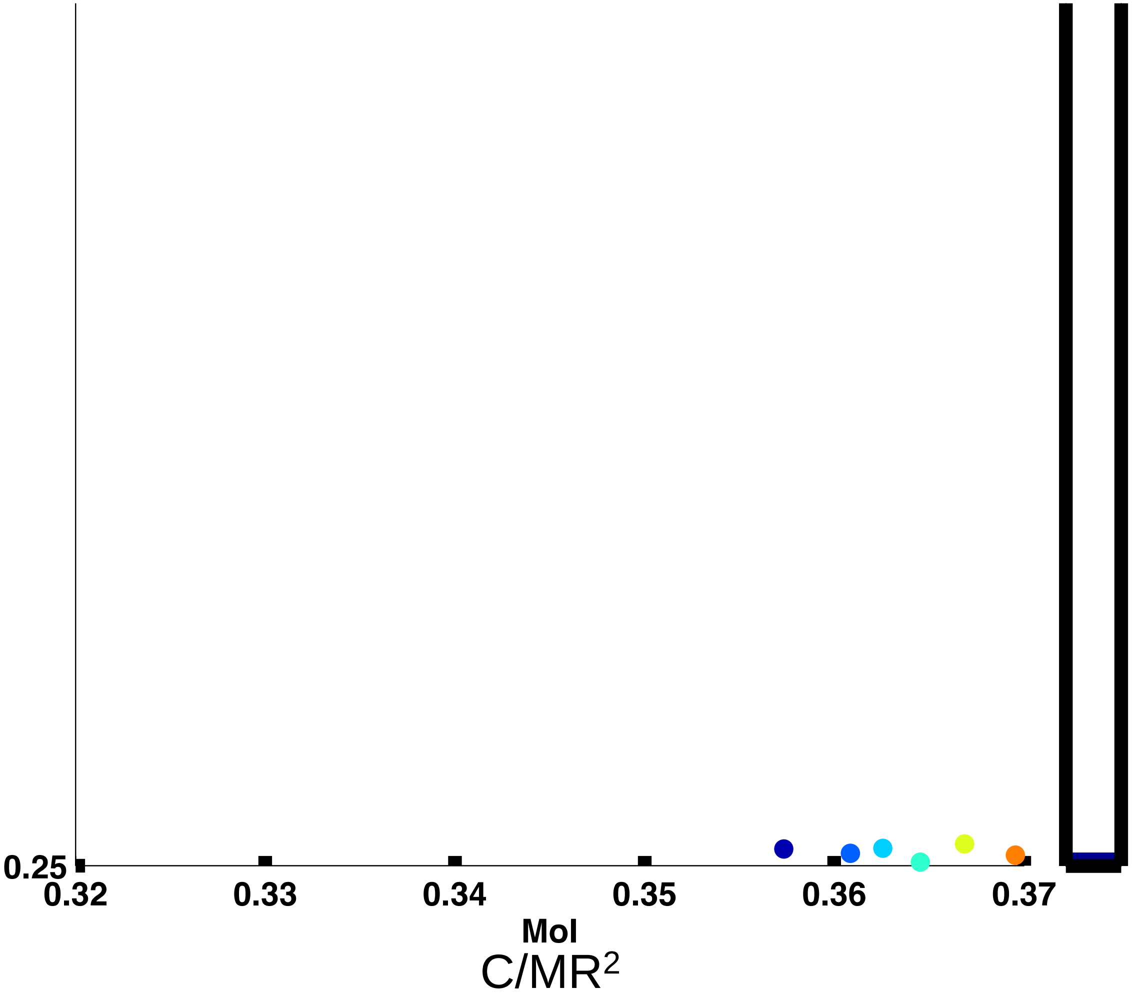
■ no snow

● deep snow + stratification

▲ snow zone

● deep snow, no stratification

/m^3)



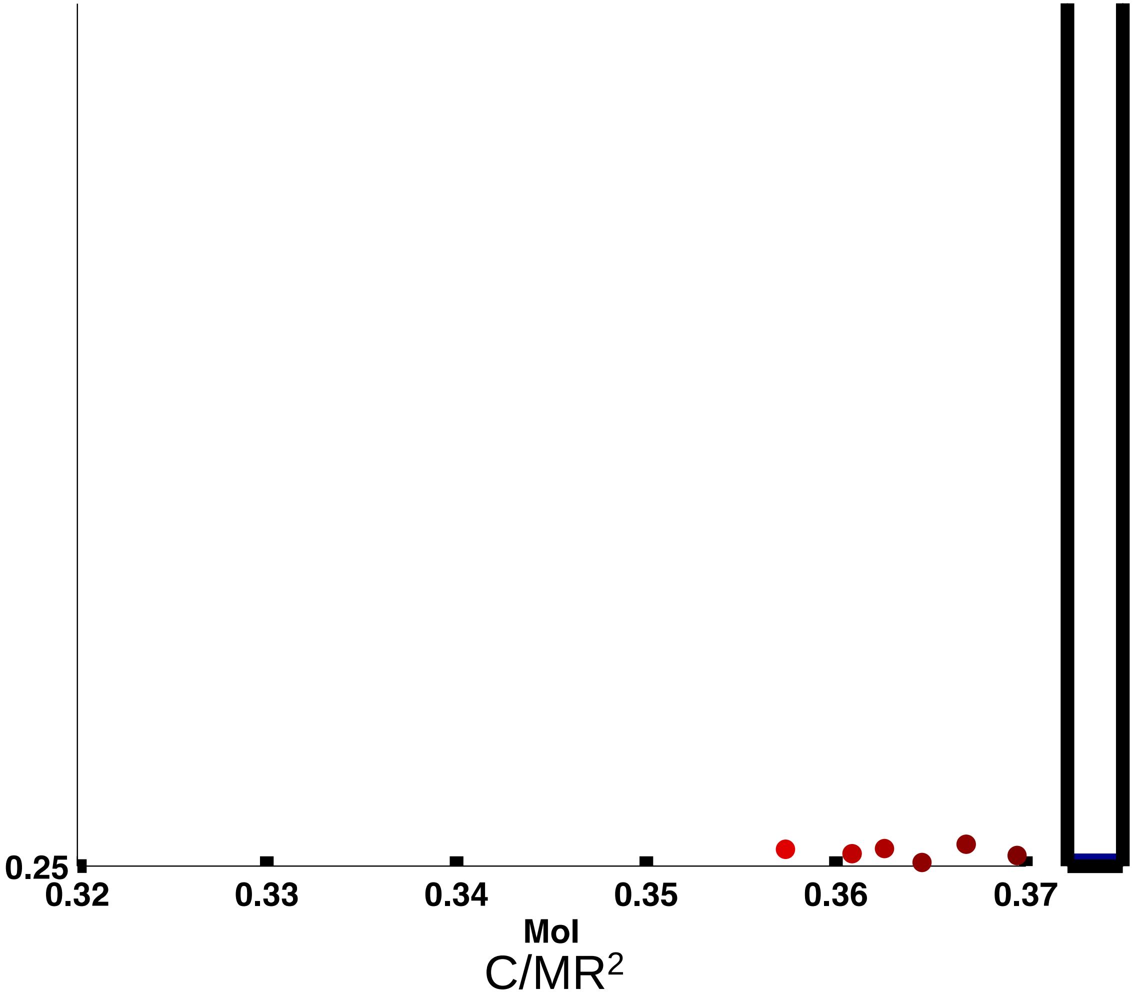
Interior model: ICB = 50 km

■ no snow

● deep snow + stratification

▲ snow zone

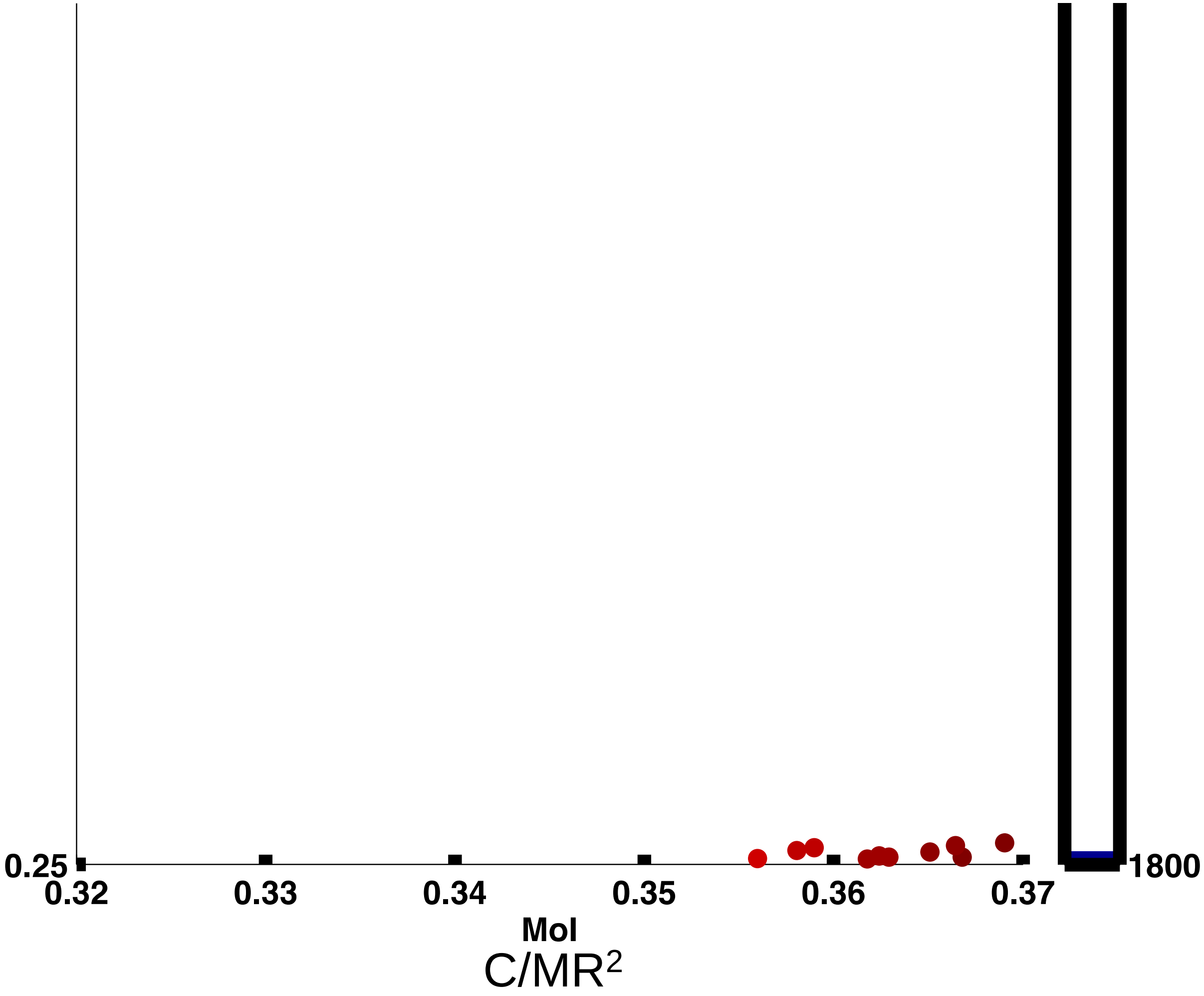
● deep snow, no stratification



Interior model: ICB = 500 km

■ no snow ● deep snow + stratification

▲ snow zone ● deep snow, no stratification



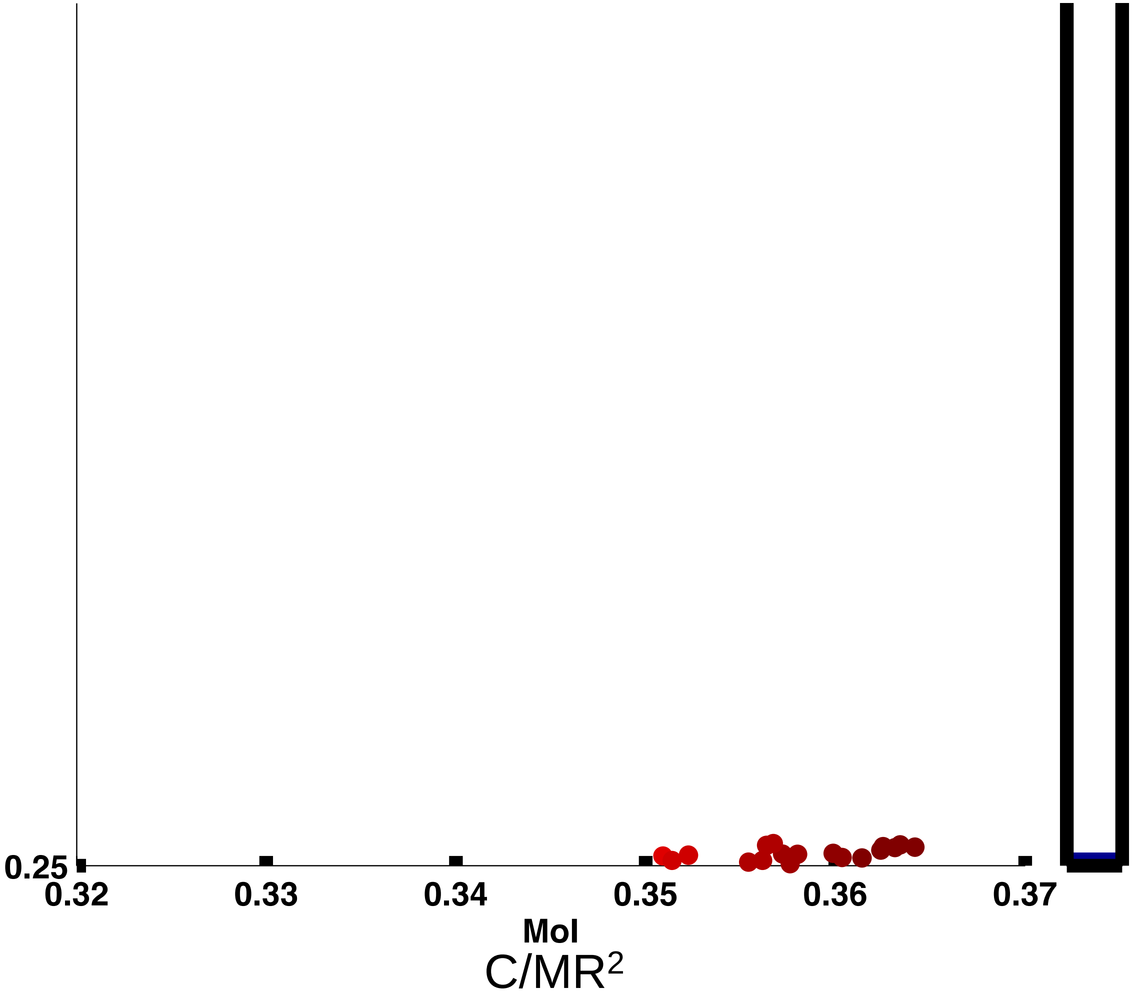
Interior model: ICB = 1000 km

■ no snow

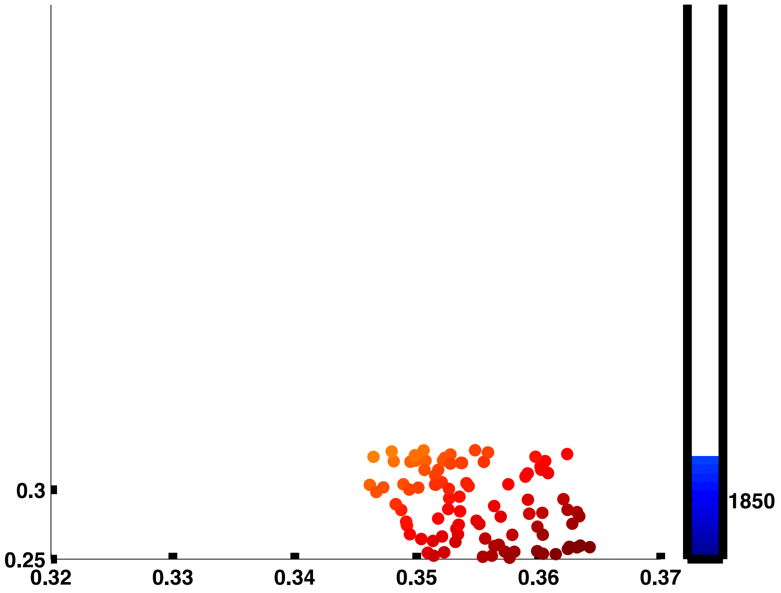
▲ snow zone

● deep snow + stratification

● deep snow, no stratification



Interior model: ICB = 1000 km

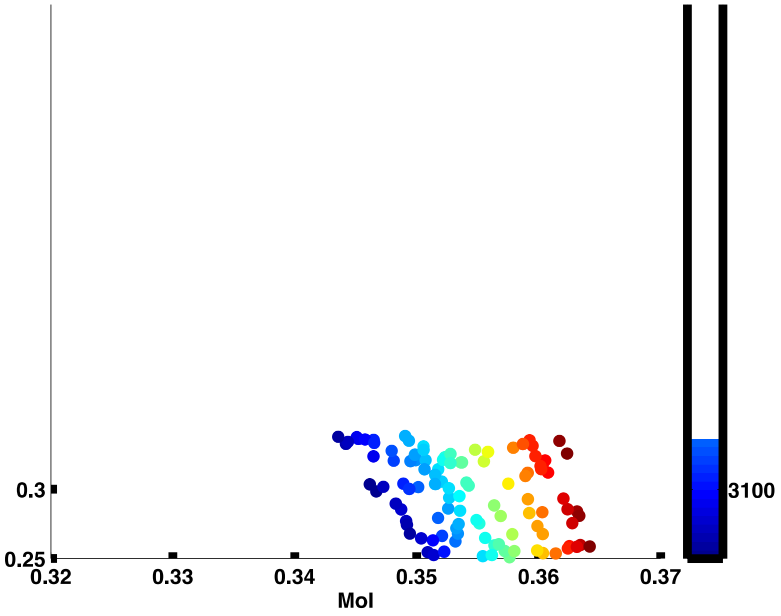


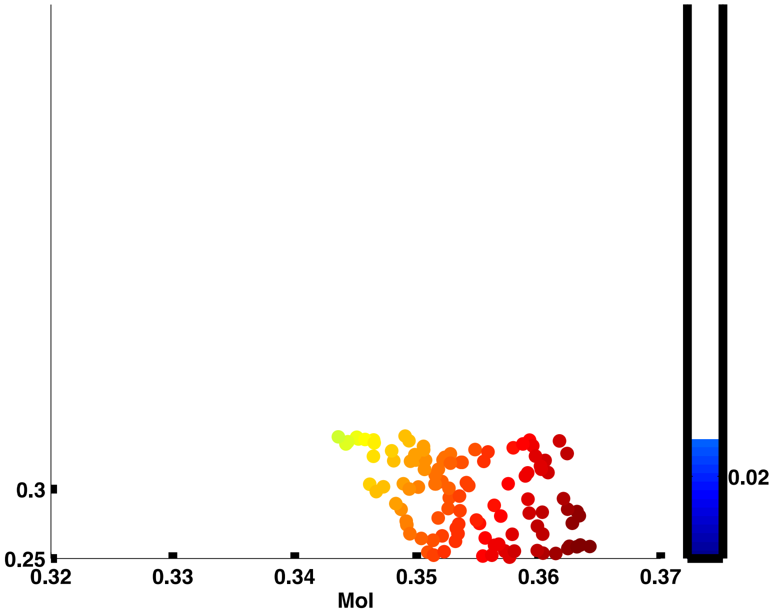
■ no snow

▲ snow zone

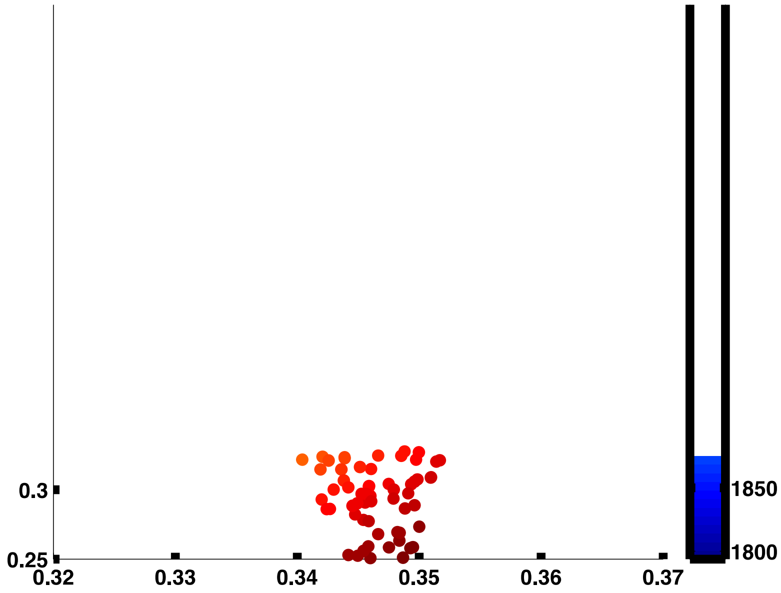
● deep snow + stratification

● deep snow, no stratification





Interior model: ICB = 1250 km

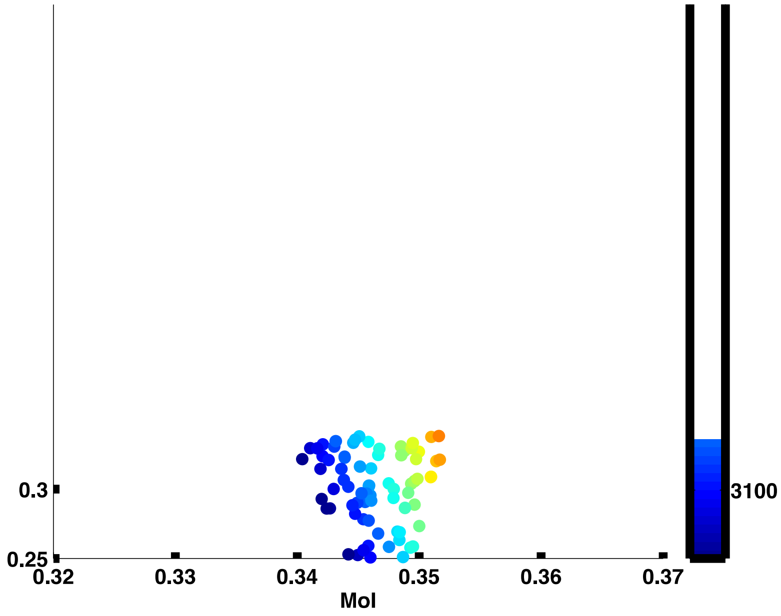


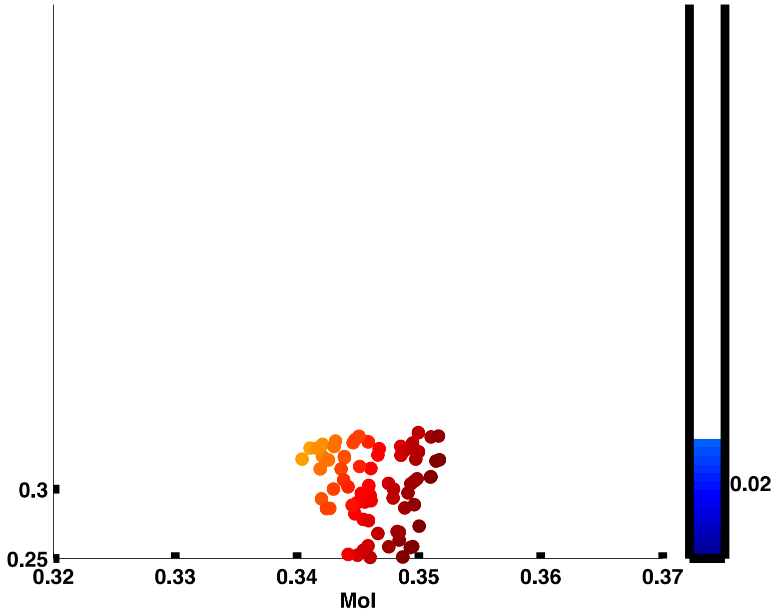
■ no snow

▲ snow zone

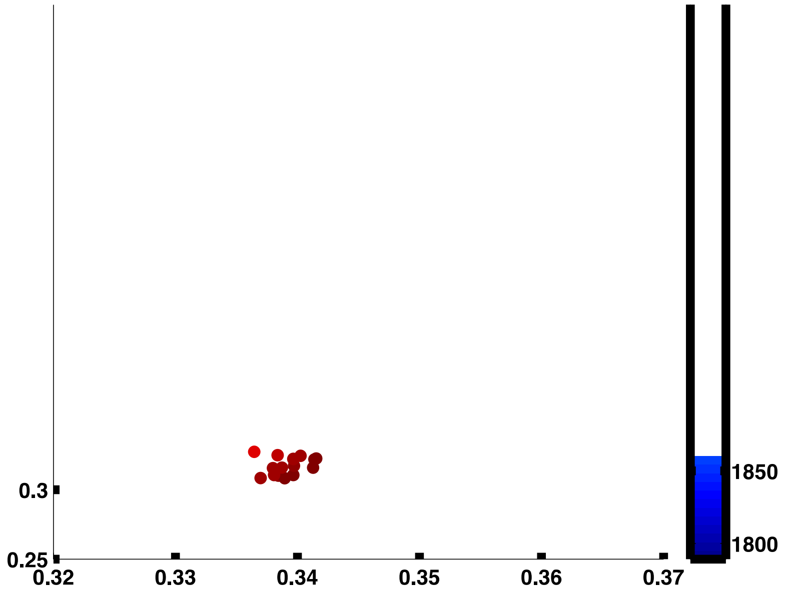
● deep snow + stratification

● deep snow, no stratification





Interior model: ICB = 1400 km

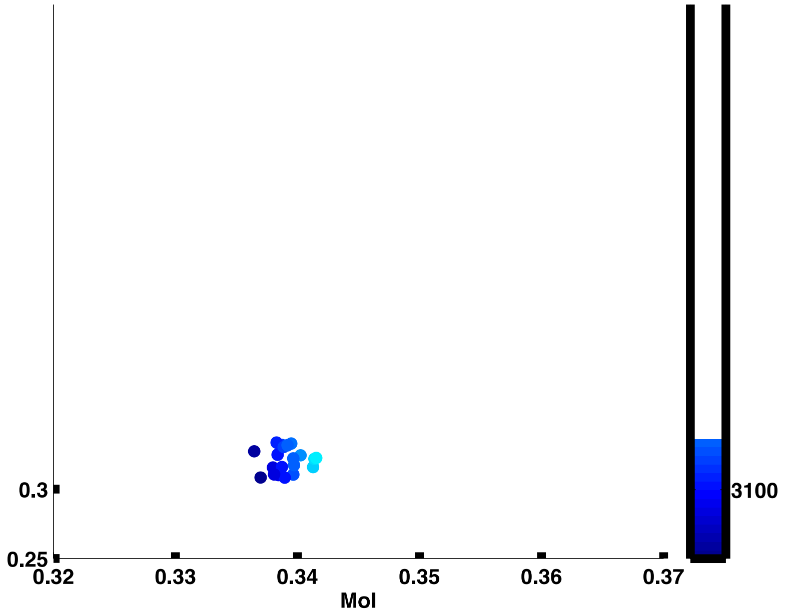


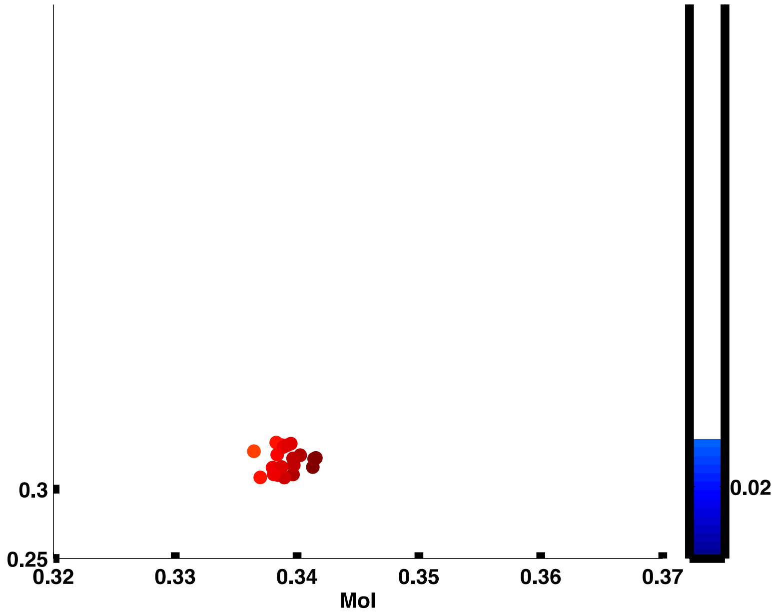
■ no snow

▲ snow zone

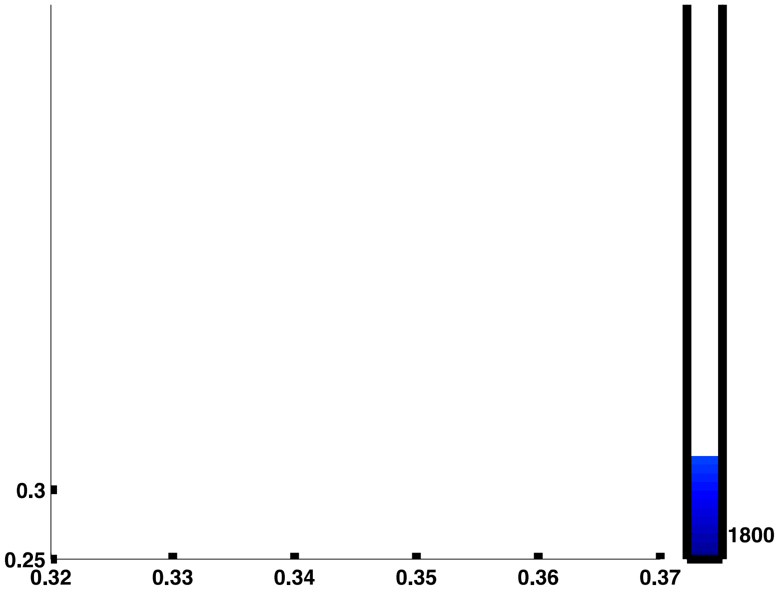
○ deep snow + stratification

● deep snow, no stratification





Interior model: ICB = 1550 km

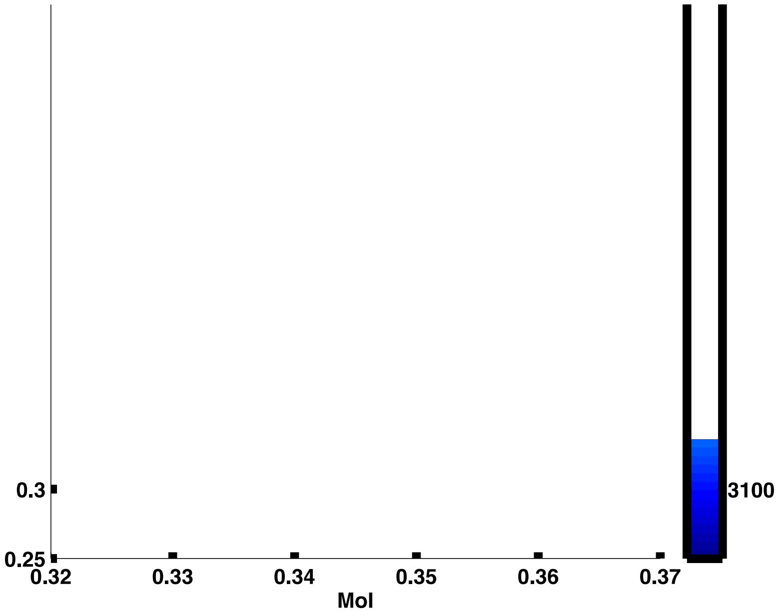


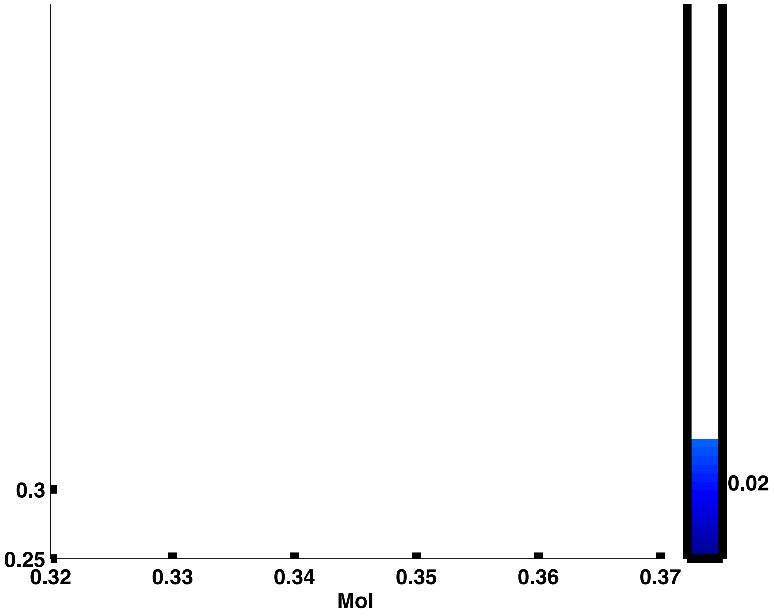
■ no snow

▲ snow zone

○ deep snow + stratification

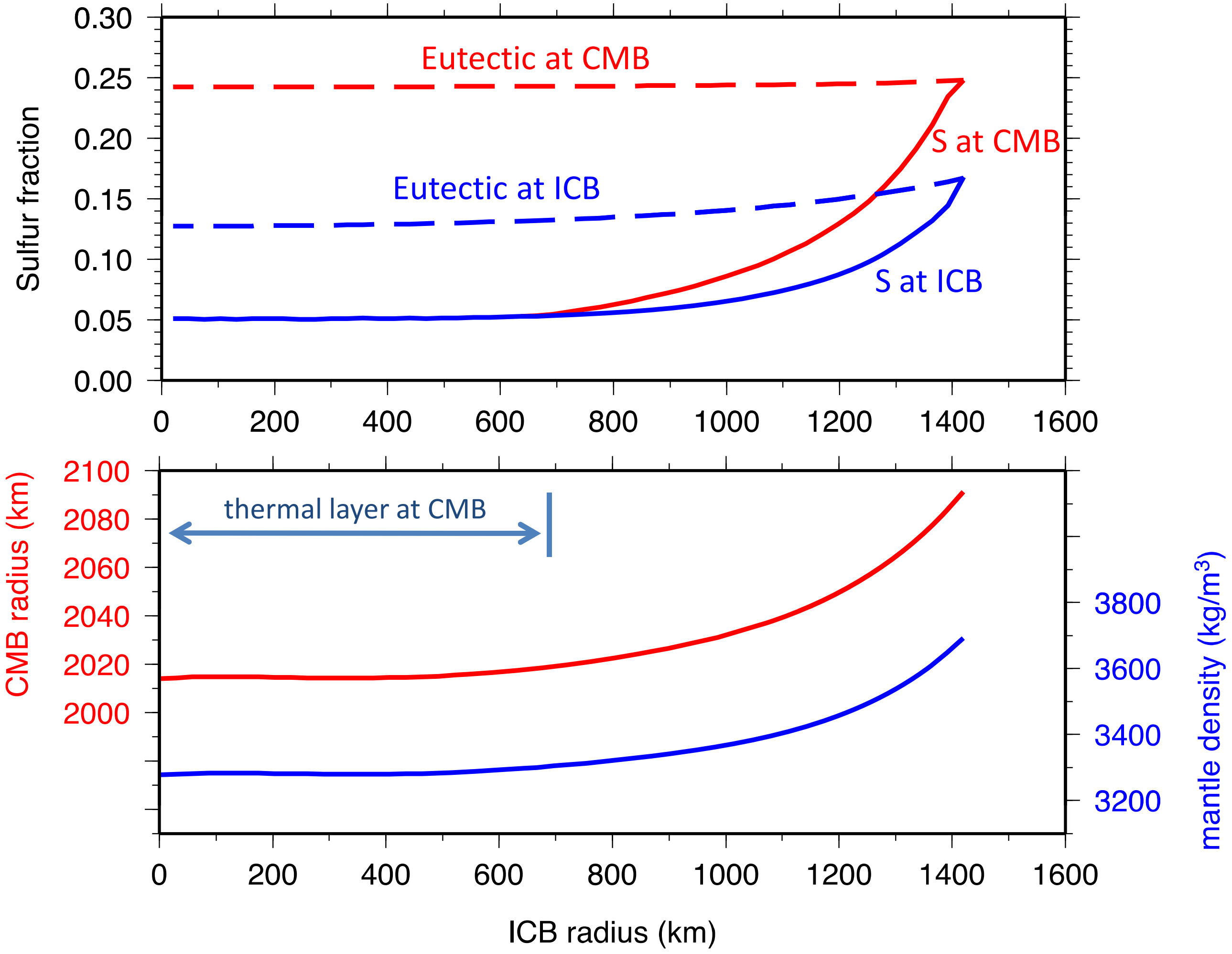
● deep snow, no stratification





Constrained Models

- Find models that match: $M = 3.302 \times 10^{23}$ kg, $R = 2440$ km
- Also match: $C_m/C = 0.431$, $C/MR^2 = 0.346$



- Reduced error bars on C_m/C, C/MR^2

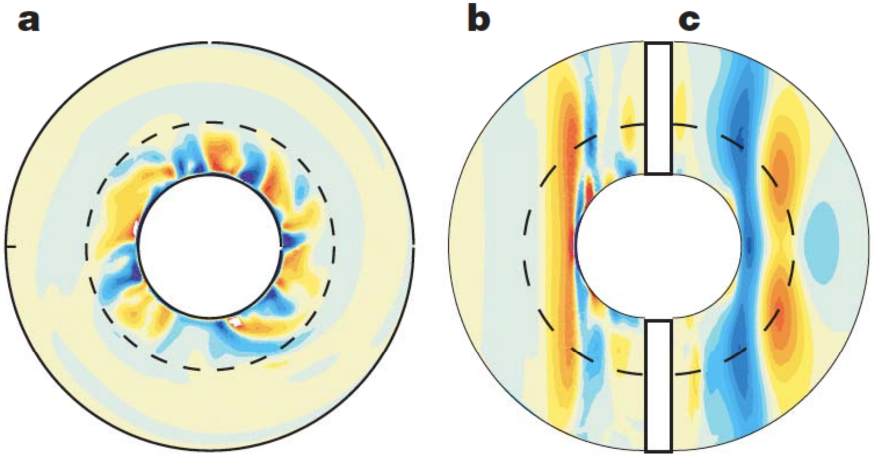
➔ constraint on maximum ICB radius

Conclusions

- If sulfur is the dominant light element in Mercury's core, constraints on C_m/C and C/MR^2 suggest that
  - convection in Mercury's core more likely involves Fe snow zone perhaps extending to ICB
  - thermal stratification only for small inner core
  - Mercury's inner core smaller than 1550 km (1420 km if error bars were much smaller)
  - implications for Mercury's dynamo?

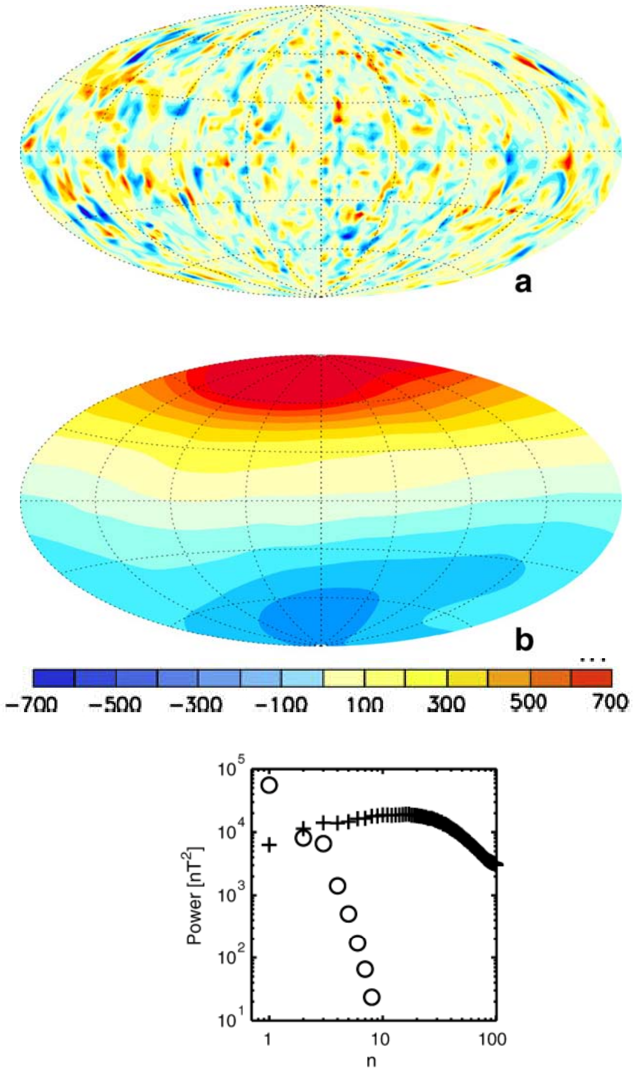
Most promising dynamo model

Thermal layer at CMB + thermal winds



Christensen, Nature, 2006

Can explain axisymmetry, offset &
low field strength of Mercury



Christensen & Wicht, Icarus, 2008

For this to work:
- thick thermal layer
- small inner core
- vigorous deep convection

Consistent with what we find?

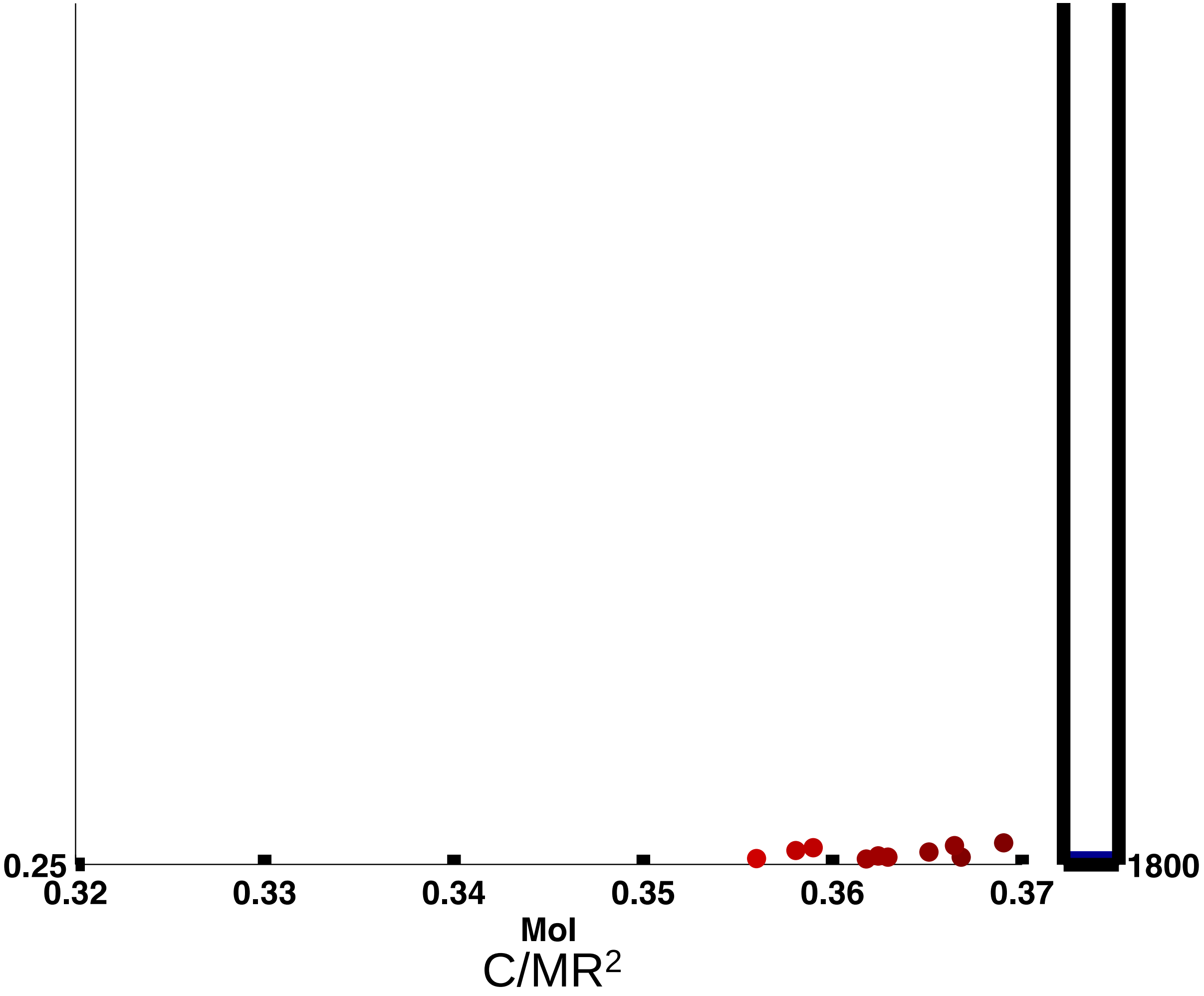
Interior model: ICB = 500 km

■ no snow

● deep snow + stratification

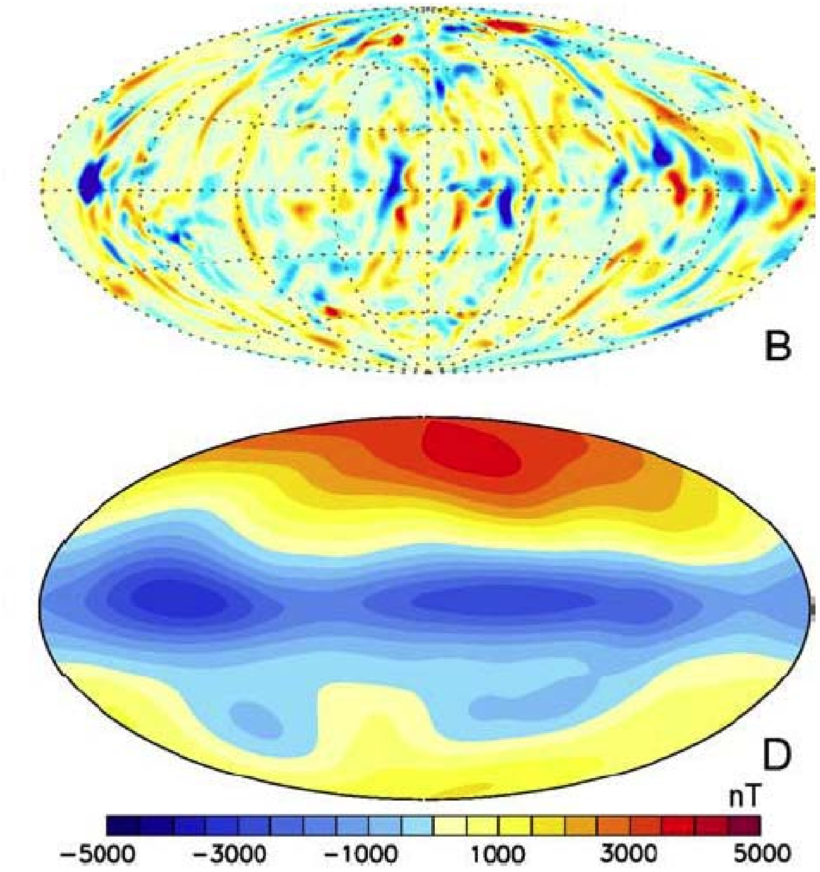
▲ snow zone

● deep snow, no stratification



Last slide …

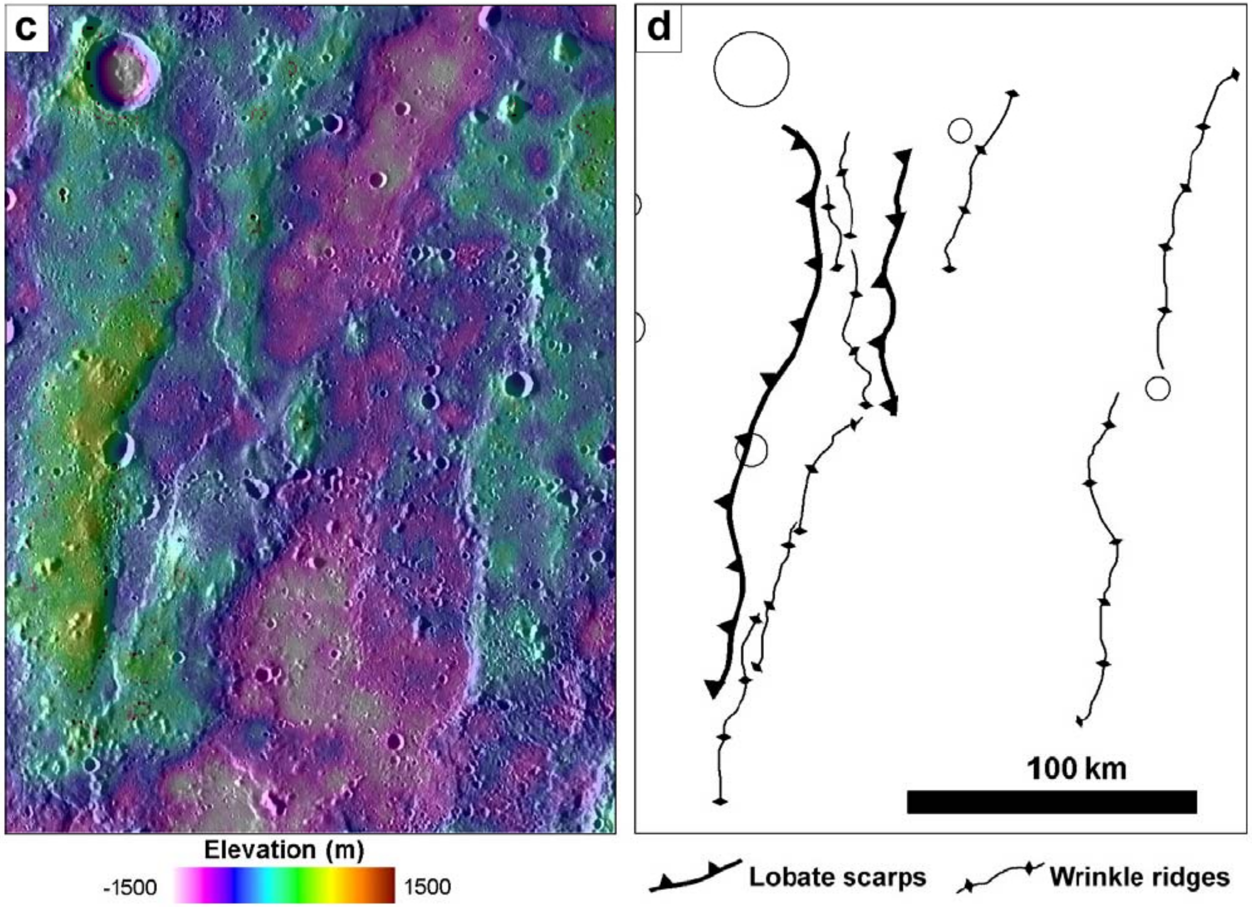
double-diffusive fingering convection
In thermal layer



Manglik et al., EPSL, 2010

How would double-diffusion
Convection affect dynamo
In a deep snow regime?

Lobate scarps



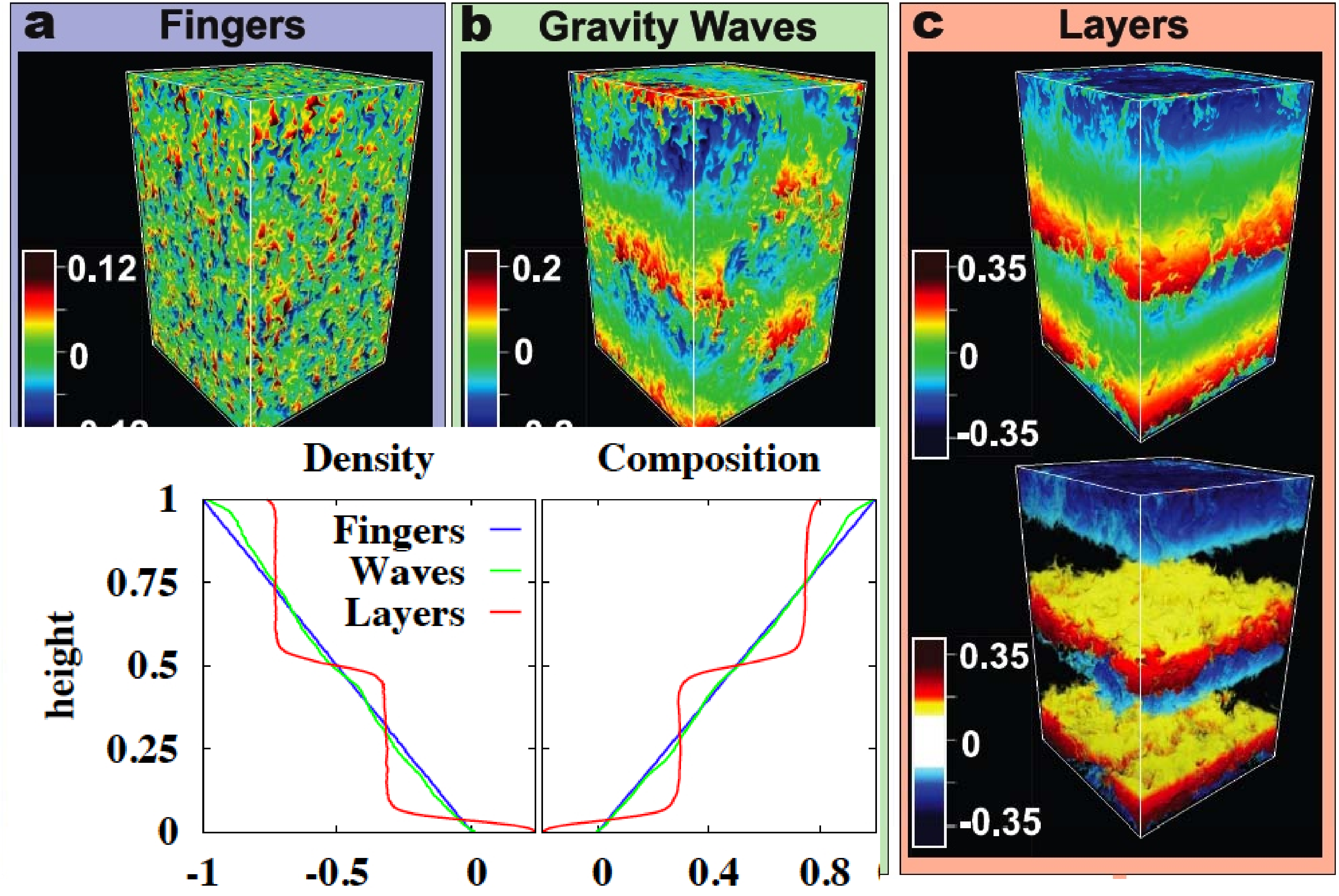
Di Achille et al., Icarus, 2012

Estimated decrease in radius ≈ 2.4-3.6 km

Estimated decrease from solidification of whole core ≈ 17 km

ICB radius:
≈ 1000-1200 km

Double diffusion convection



Stellmach et al, JFM, 2011

Iron sulfide layer? (as extra)

mantle density (kg/m^3)

Sulfur fraction at ICB

0.32 0.33 0.34 0.35 0.36 0.37

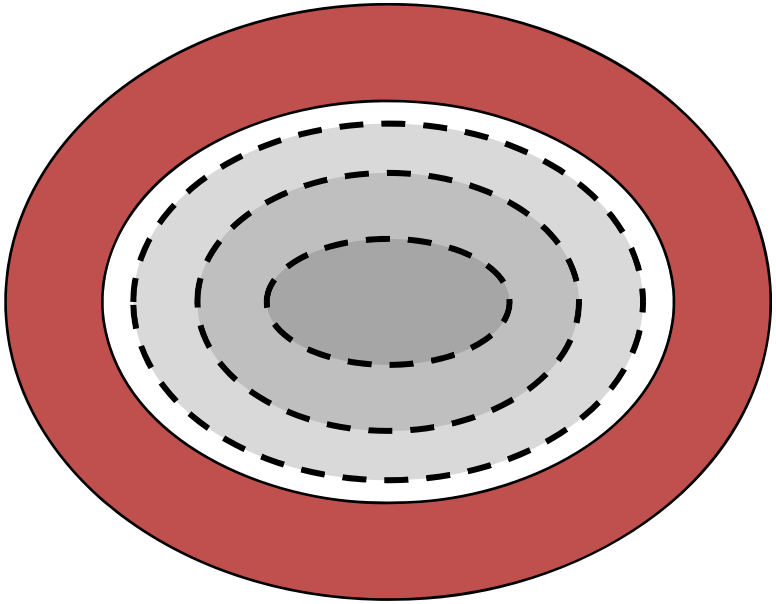
Mol

0.32 0.33 0.34 0.35 0.36 0.37

Mol

Libration amplitude (no inner core)

$$\Delta I_m = \frac{B - A}{C_m} = (2.18 \pm 0.09) \times 10^{-4}$$



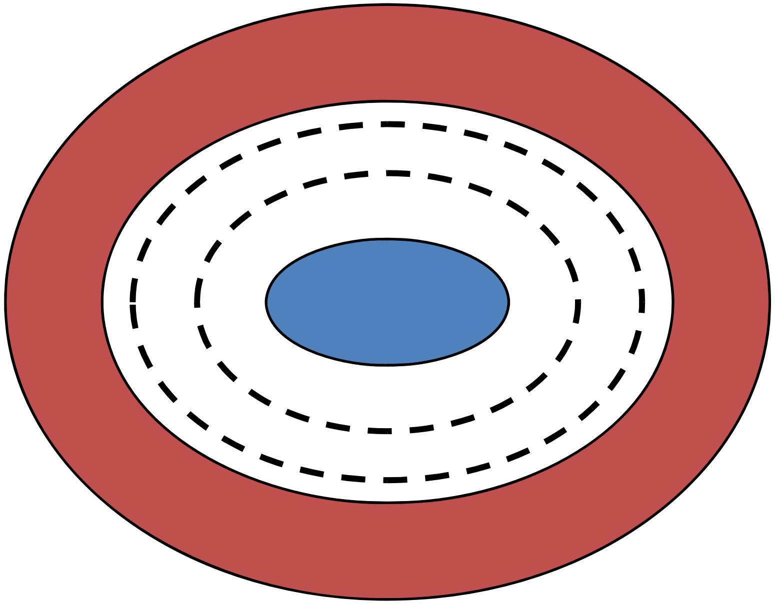
$$\Delta I_m = \cancel{\frac{B_m - A_m}{C_m} = \frac{\rho_m \left(R^5 \beta_m - R_f^5 \beta_f\right)}{\rho_m \left(R^5 - R_f^5\right)}}$$

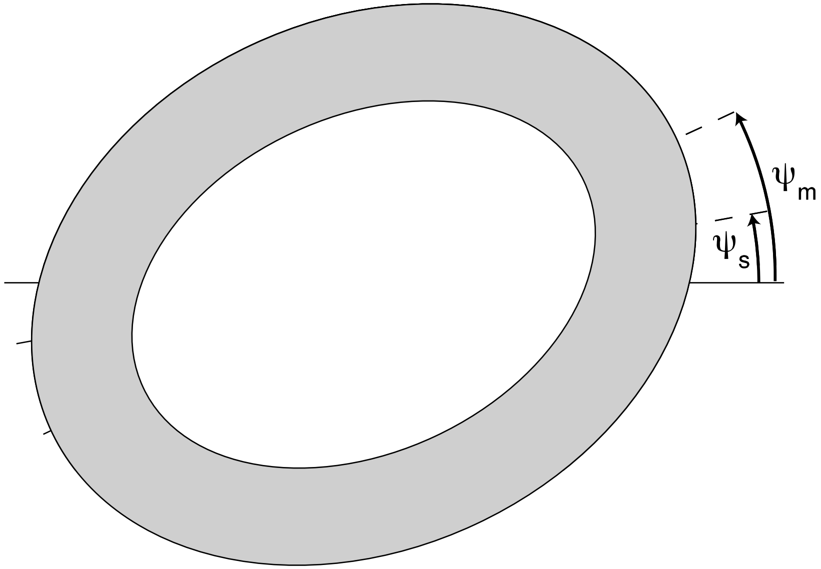
Van Hoolst et al, ESPL, 2012

$$\Delta I_m = \frac{B_m - A_m}{C_m} + \frac{B_f - A_f}{C_m}$$

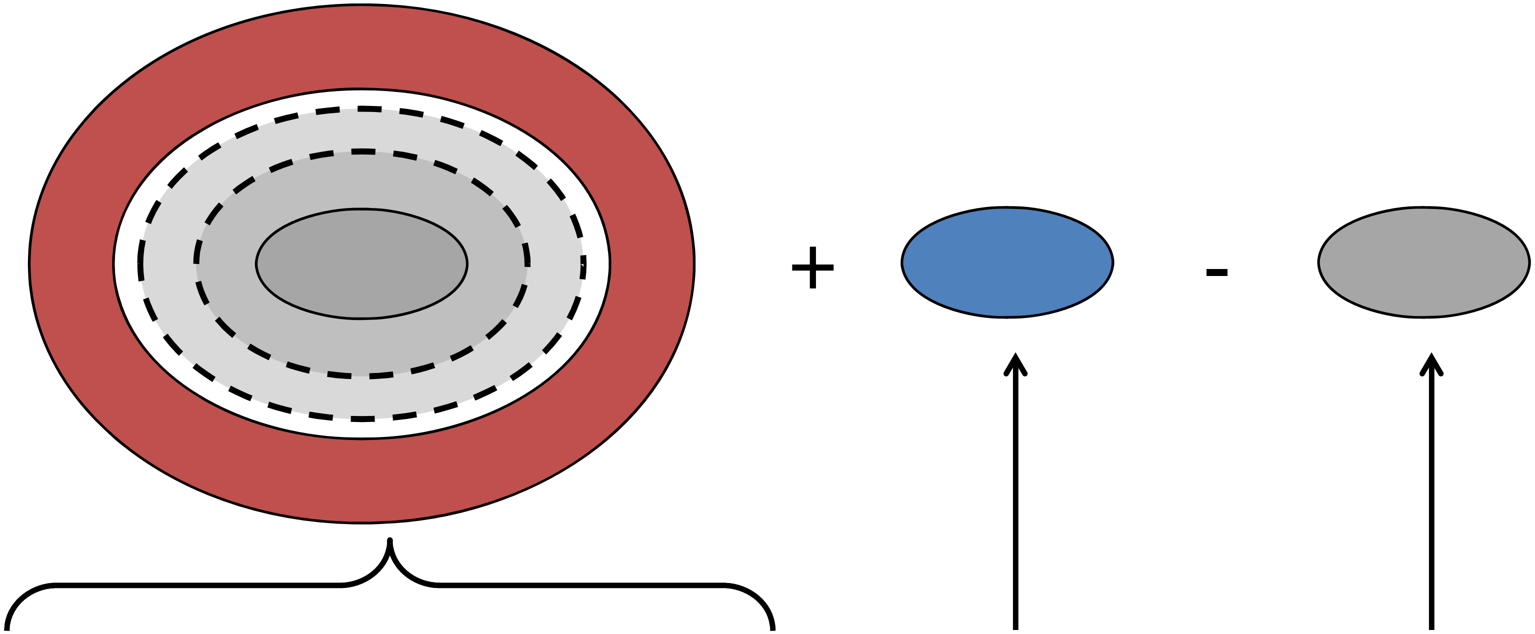
$$= \frac{B - A}{C_m}$$

Libration amplitude (with inner core)





Libration amplitude (with inner core)

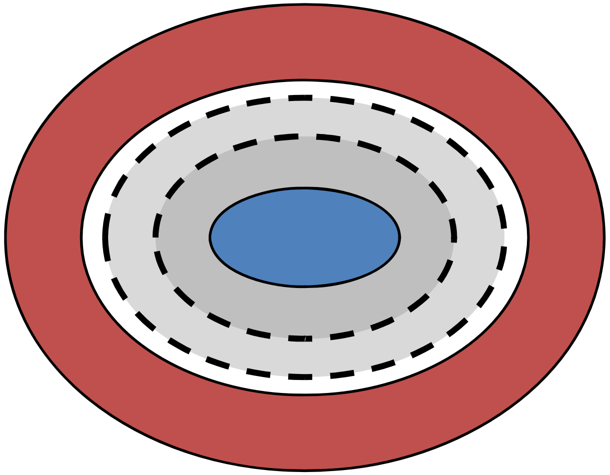


$$B-A=\underbrace{\overbrace{(B_m-A_m)+(B_f-A_f)+(B_s'-A_s')}}_{\text{“mantle libration”}}+\underbrace{(B_s-A_s)-(B_s'-A_s')}_{\text{“Inner core libration”}}$$

$$\Delta I_m=\frac{B-A}{C_m}-\left[\frac{(B_s-A_s)-(B_s'-A_s')}{C_m}\right]$$

For a small inner core,
this is a small correction

Interior models + Equatorial ellipticity



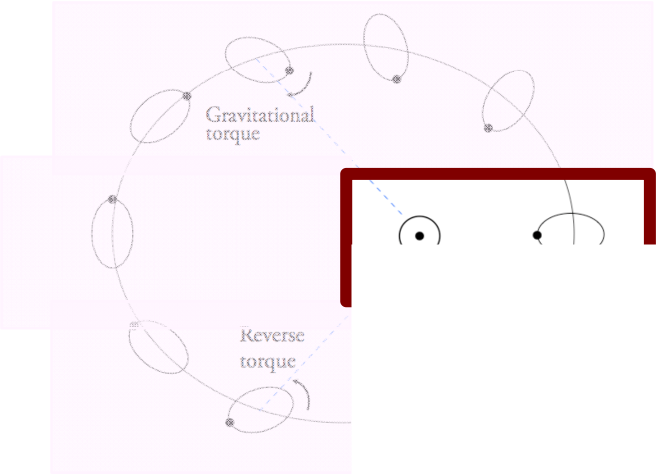
- For given equatorial ellipticity at
  - Surface: β_m
  - CMB: β_c
- Calculate potential of degree 2 at CMB
- Calculate hydrostatic deformation inside core

$$\Phi_{cmb} = \Phi_m + \Phi_c \qquad \Phi_m = f(\beta_m, \beta_c)$$

$$\Phi_c = k \cdot \Phi_m$$

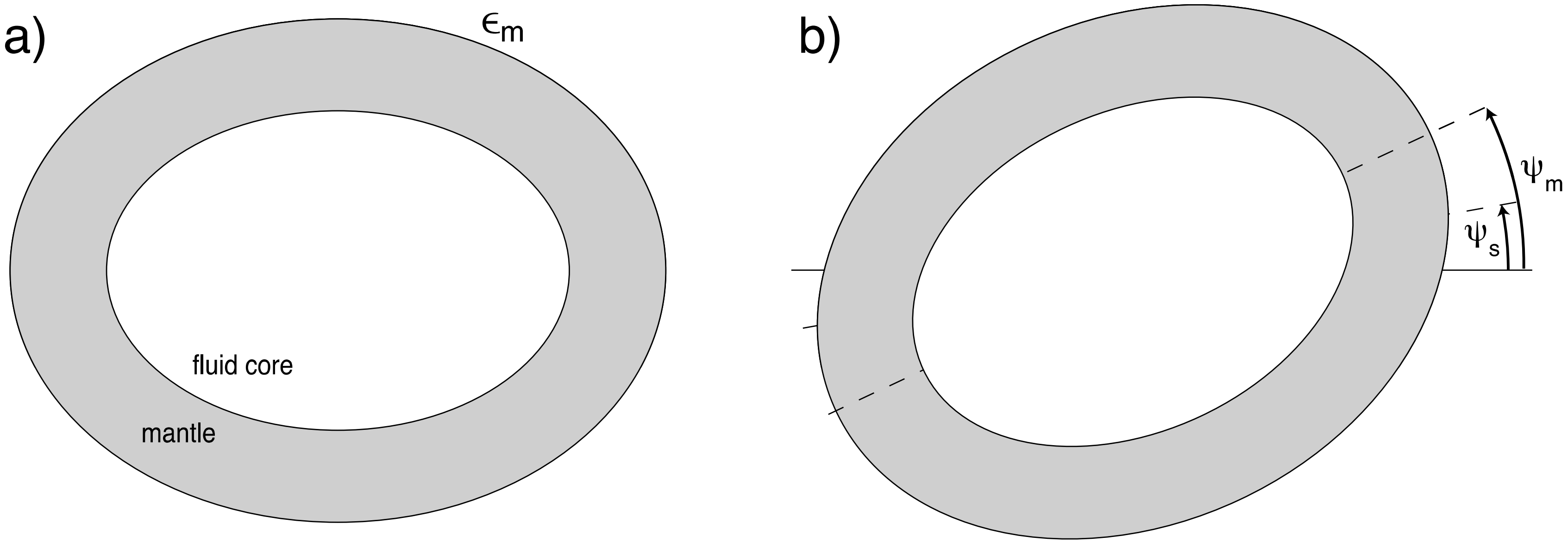
- Gives us $\beta(r)$ in whole core
- Find ellipticity that matches C_{22}: $$C_{22} = \frac{B-A}{4MR^2} = (0.81 \pm 0.01) \times 10^{-5}$$
- Calculate ΔI_m: $$\Delta I_m = \frac{B-A}{C_m} - \left[\frac{(B_s - A_s) - (B_s' - A_s')}{C_m} \right]$$

Free mantle libration



Effect of inner core on libration

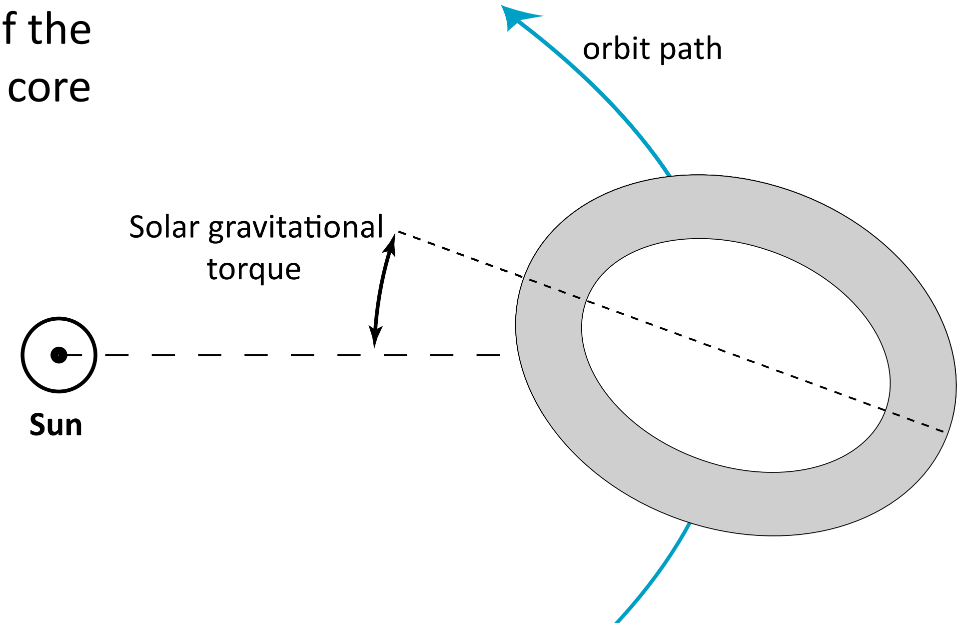
viewed from above rotation axis



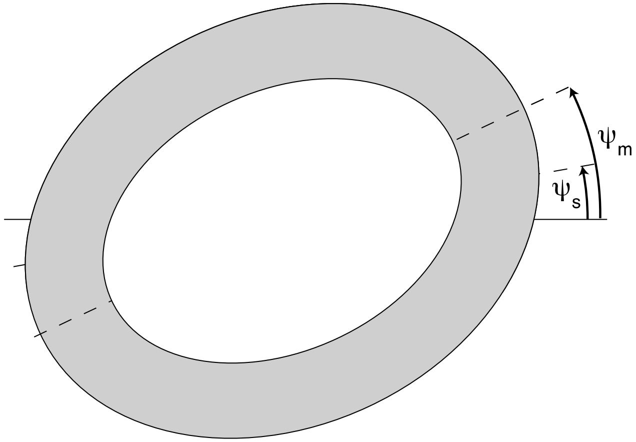
from *Veasey & Dumberry, Icarus, 2011*

Free libration modes

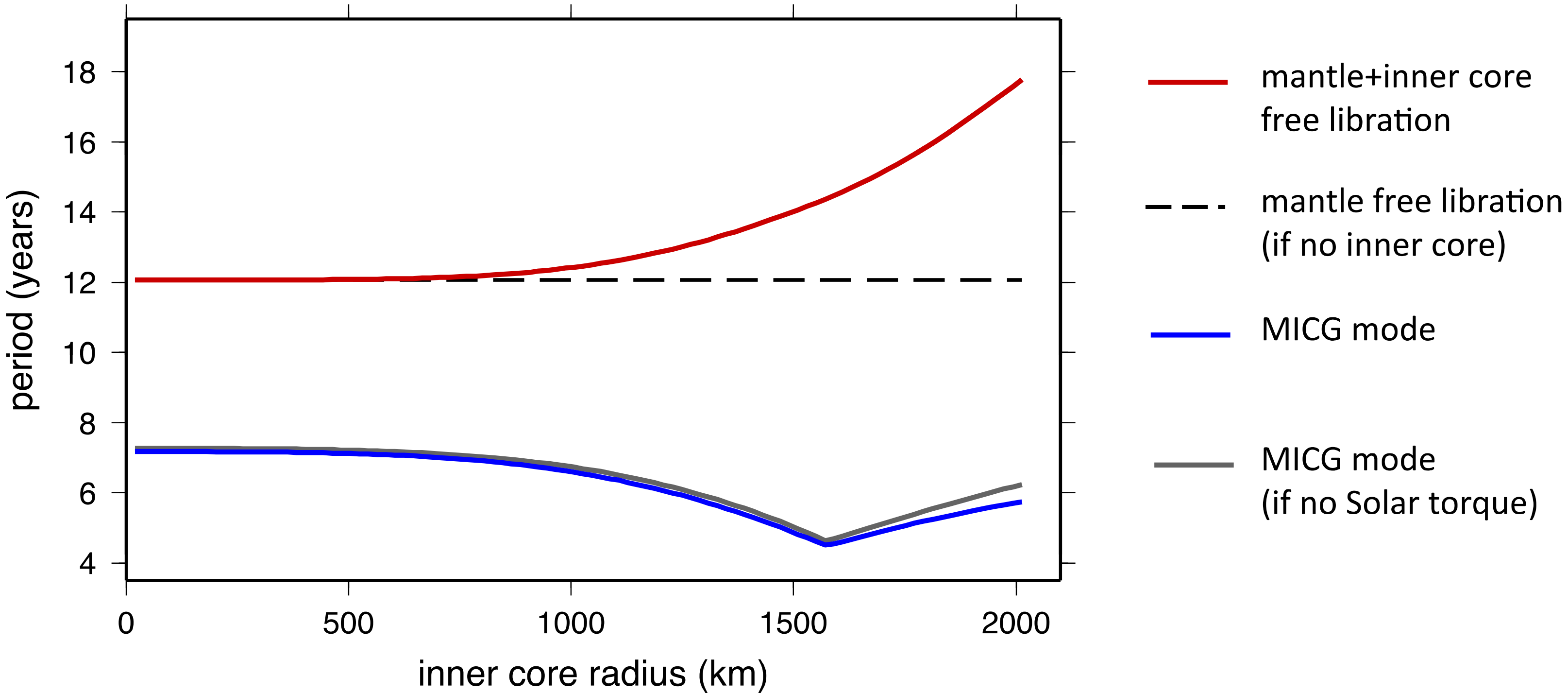
1) Free libration of the mantle + inner core



2) Mantle – inner core gravitational (MICG) mode



Free libration modes

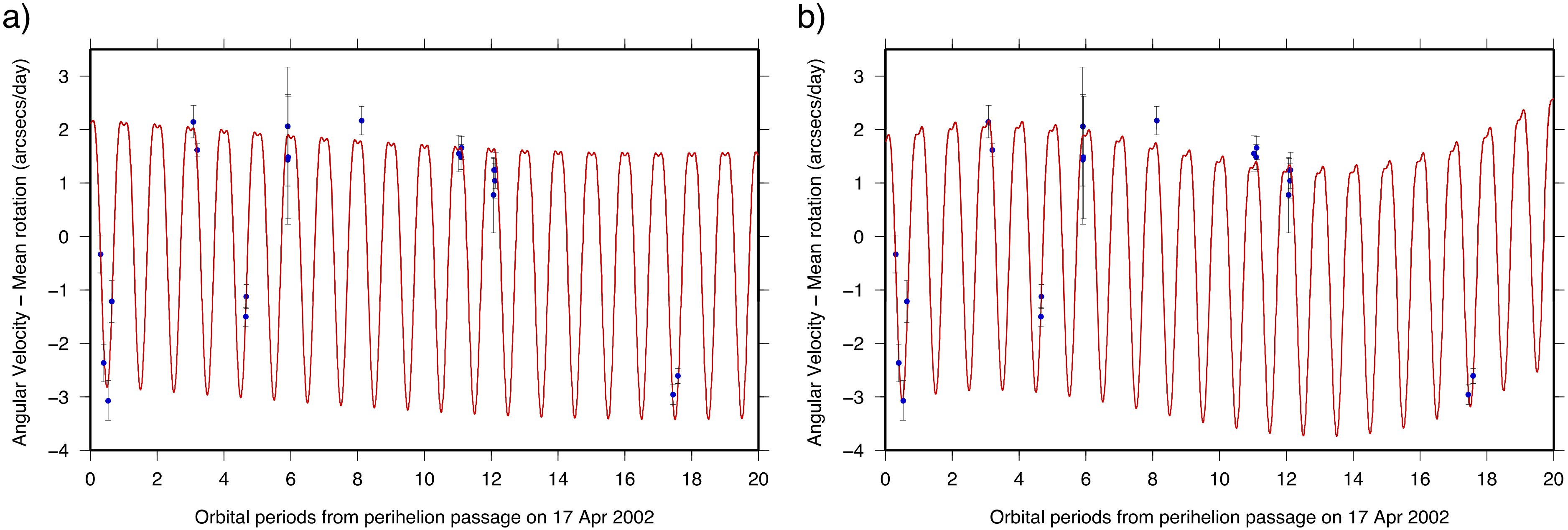


Dumberry, GRL, 2011
Van Hoolst et al, EPSL, 2012

If inner core > 1000 km, Free “mantle” libration very different from 12 yr

MICG mode: period of approximately 4-10 yr

Effect of inner core on libration



without an inner core

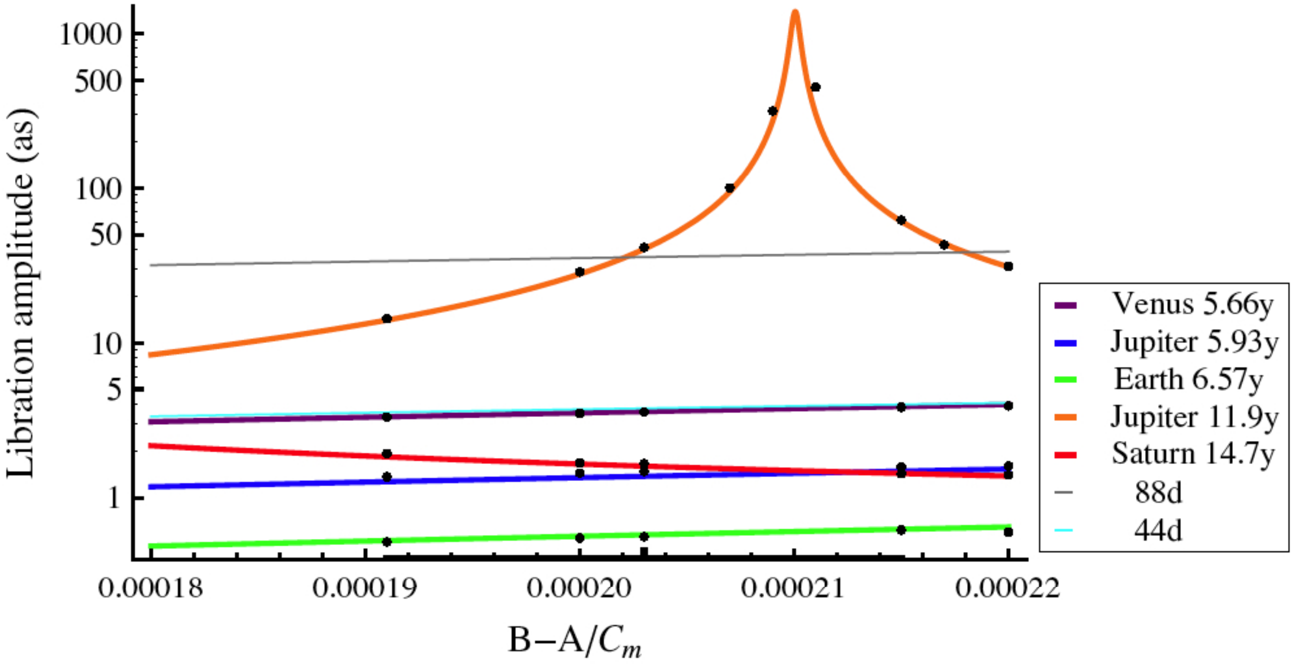
with an inner core

Veasey & Dumberry, Icarus, 2011

- Little change in 88-day forced libration
- Can lead to a change in decadal period libration

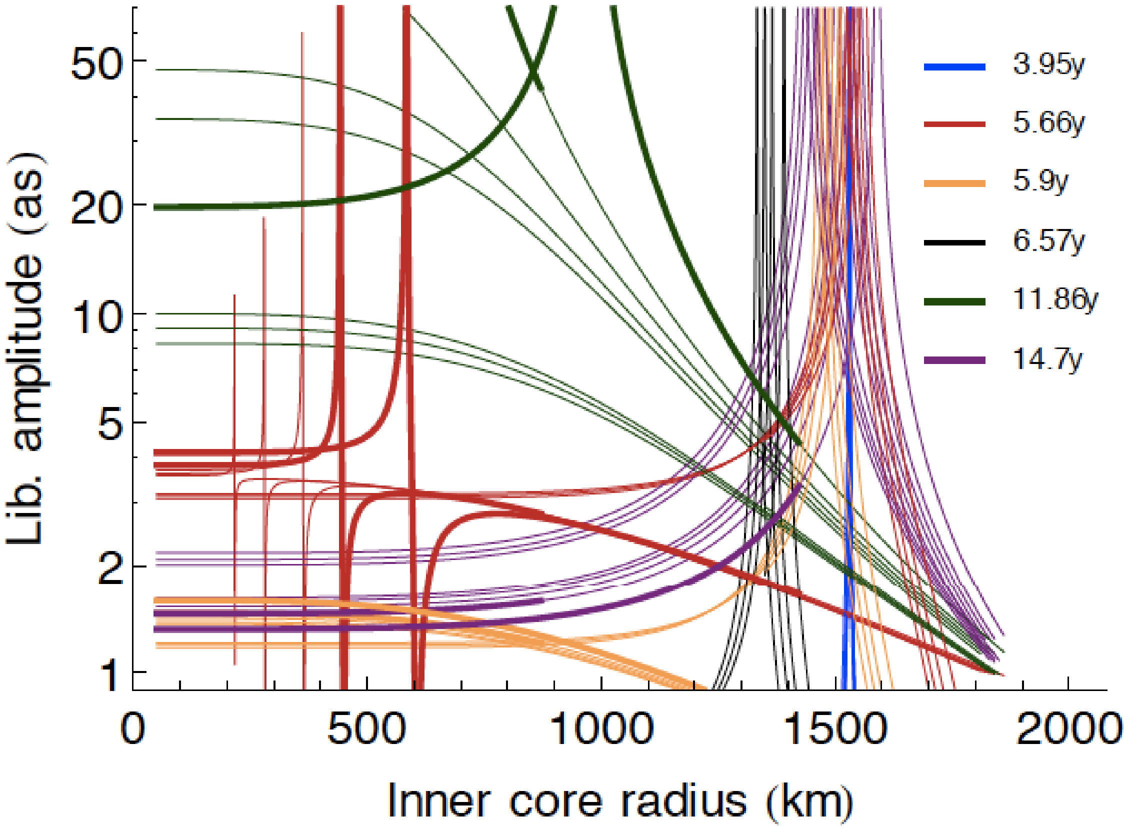
External forcing:

- Periodic changes on Mercury's orbit from planets
- Jupiter, orbital period = 11.86 yr
  - Close to free mantle libration (if inner core < 1000 km)
  - Can produce a large libration



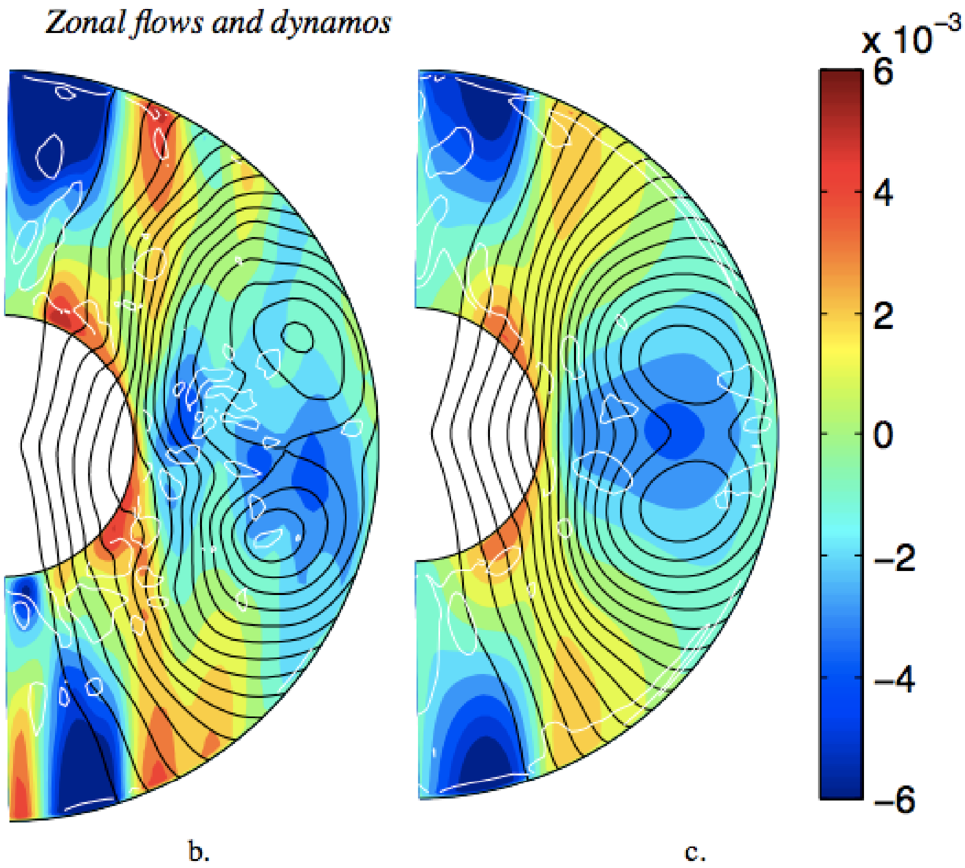
Peale et al, Icarus, 2009; Yseboodt et al, Icarus, 2010

Long period forced librations



mantle libration from internal forcing

- Convection naturally produces zonal flows
- Chaotic forcing: time-dependent zonal flows

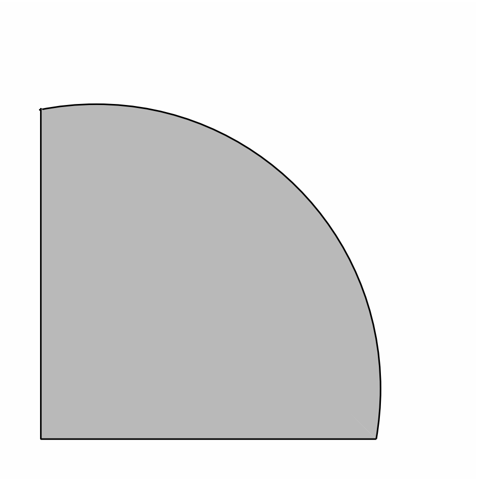


Aubert, JFM, 2005

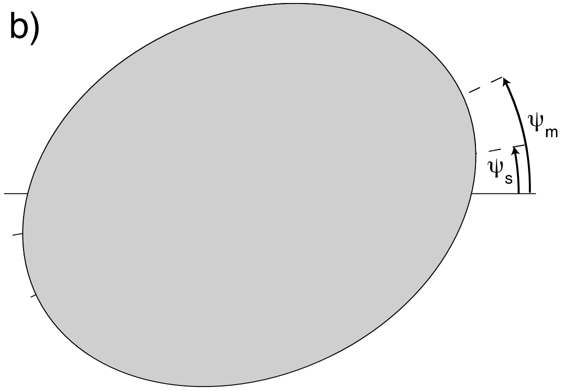
mantle libration from internal forcing

- Scenario: time-dependent zonal flows in Mercury’s core

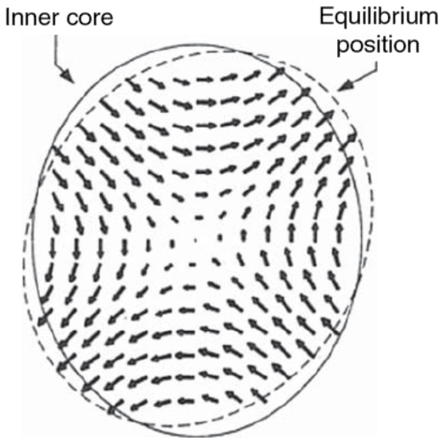
- EM coupling at ICB



- MICG coupling



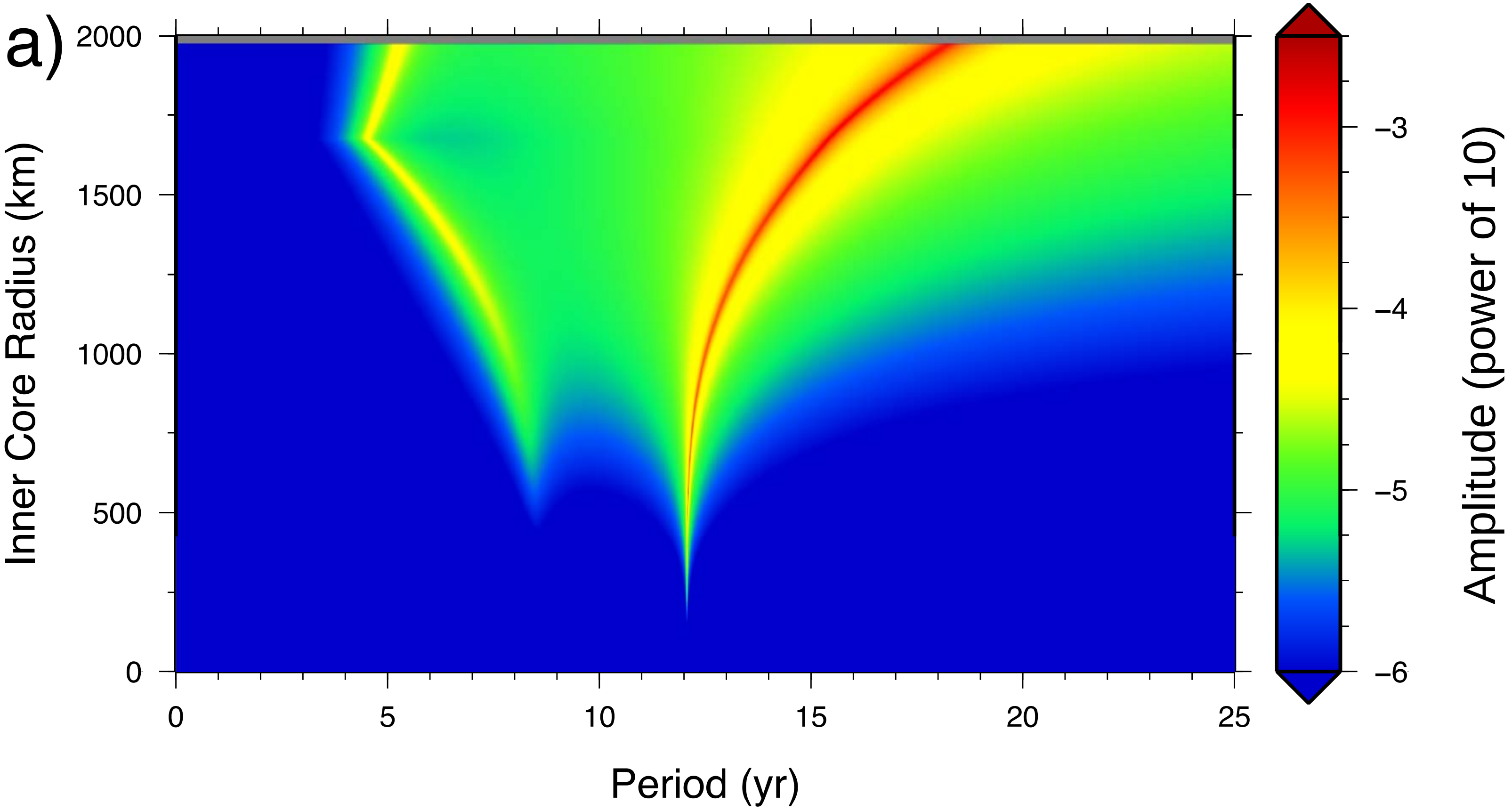
- IC viscous deformation



mantle libration from internal forcing

As a function of frequency

viscous relaxation time = 25 yr

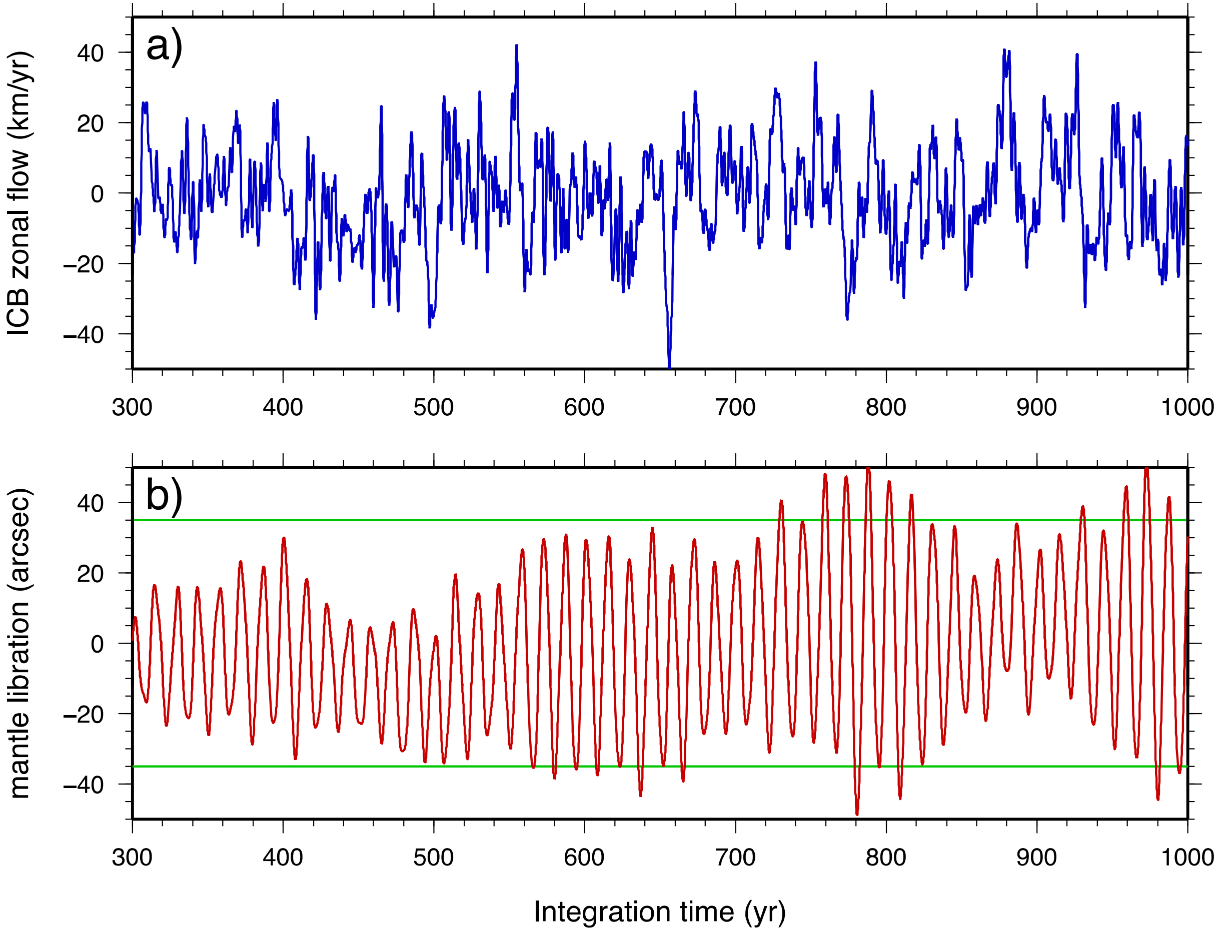


mantle libration from internal forcing

Solution as function of time

Imposed zonal flow at ICB

Mantle response

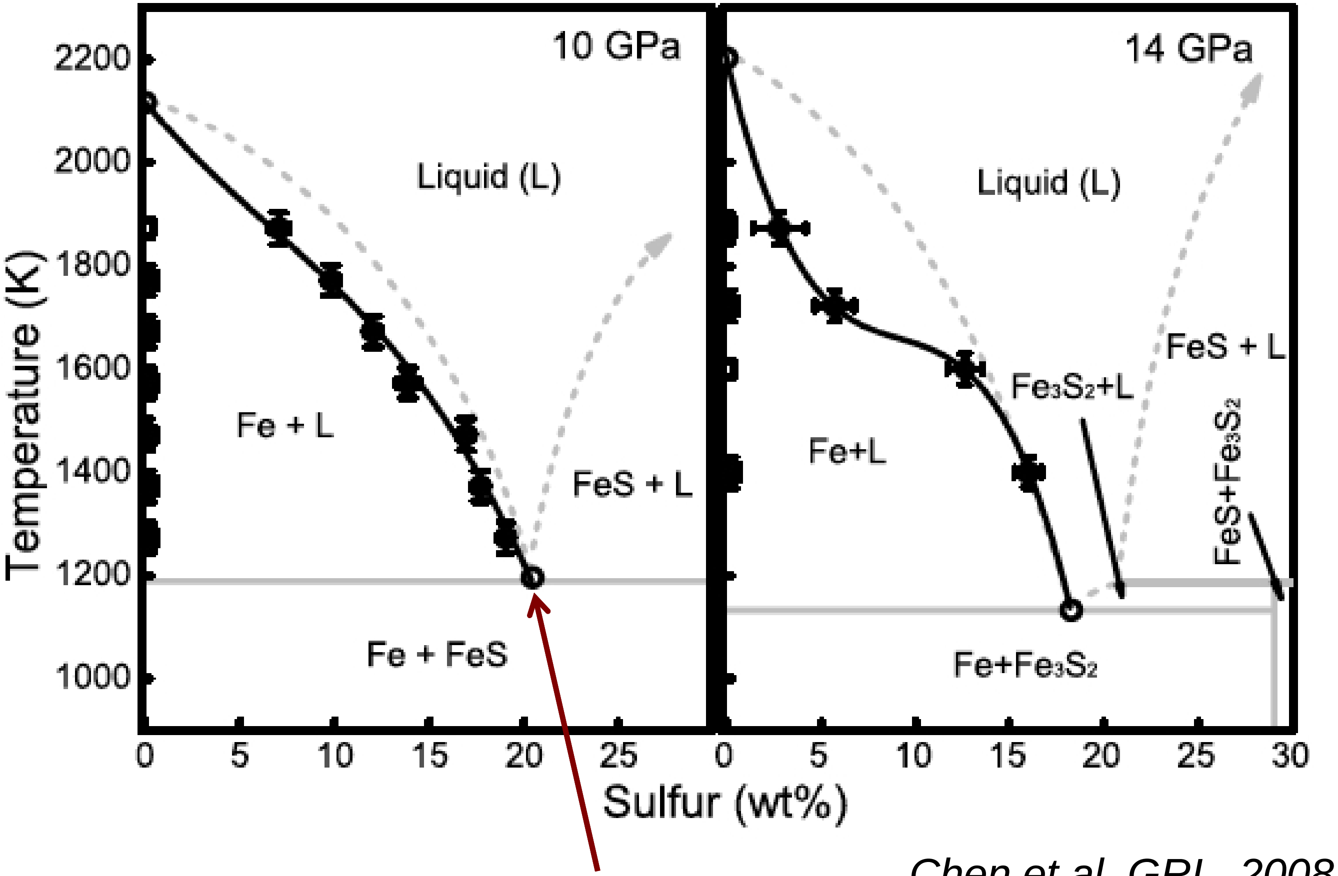


mantle libration from internal forcing

To get a long-period libration of 35 arcsec :

- Need decadal zonal flow changes of ≈ 2000 km/yr
- If B at ICB x 10: need changes of ≈ 20 km/yr

Fe-FeS Liquidus



eutectic

Chen et al, GRL, 2008