Magnetic fields – a window into the deep interiors of planets

# Iron snow dynamos in Ganymede and Mercury

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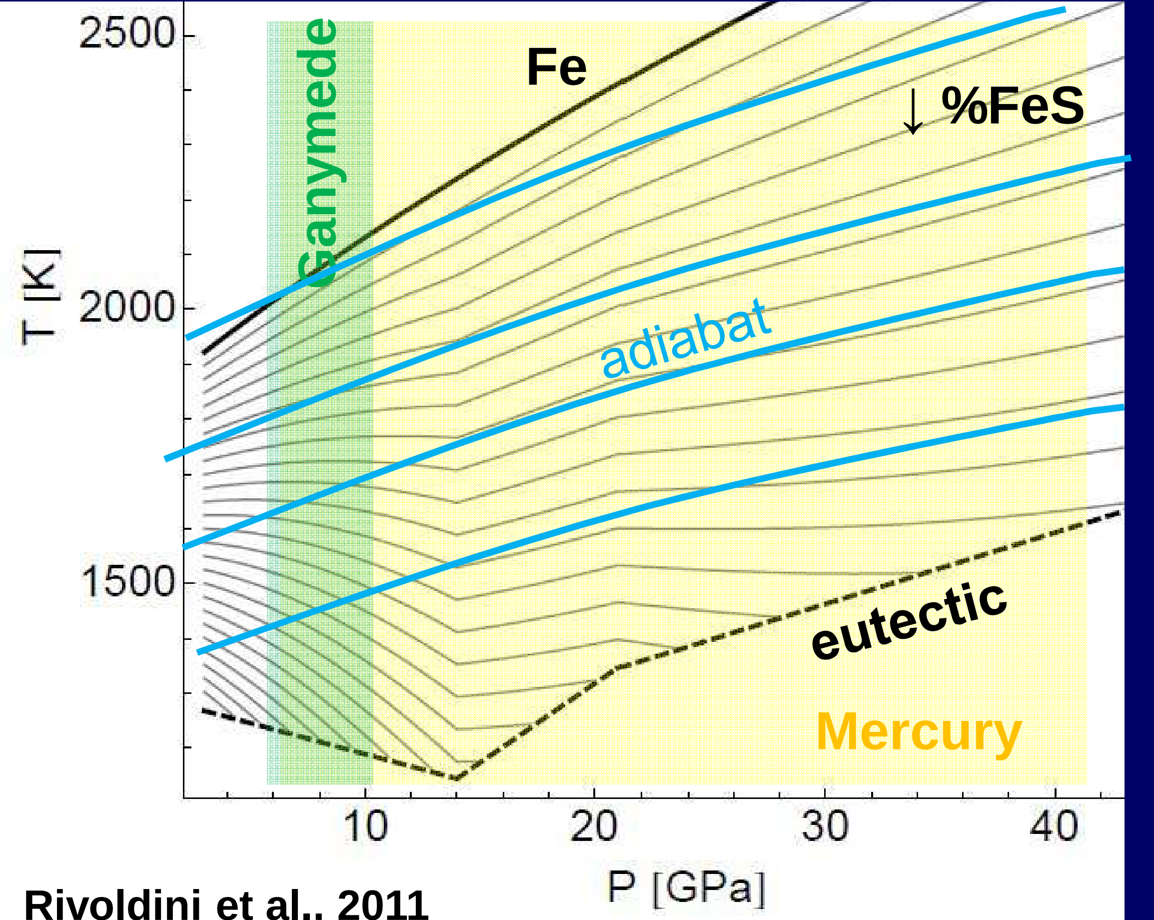
# Convection in cores of rocky planets

- A large heat flux can be conducted along adiabatic gradient in iron core of rocky planet
- For all rocky planets, the CMB heat flux (controlled by the mantle) is probably less than the conductive heat flux along adiabat
- Under this condition, solification of Fe (FeS) needed to drive thermochemical convection
- Is inner core growth like in the Earth the prototype for other rocky planets ?

# Fe – FeS melting curve

- Sulfur reduces melting temperature $T_M$ and gradient $dT_M/dP$
- For more than few percent sulphur, in small planets $dT_M/dP < (dT/dP)_S$ in part or all of core
- ➢ Crystallization of iron proceeds top-down




Rivoldini et al., 2011

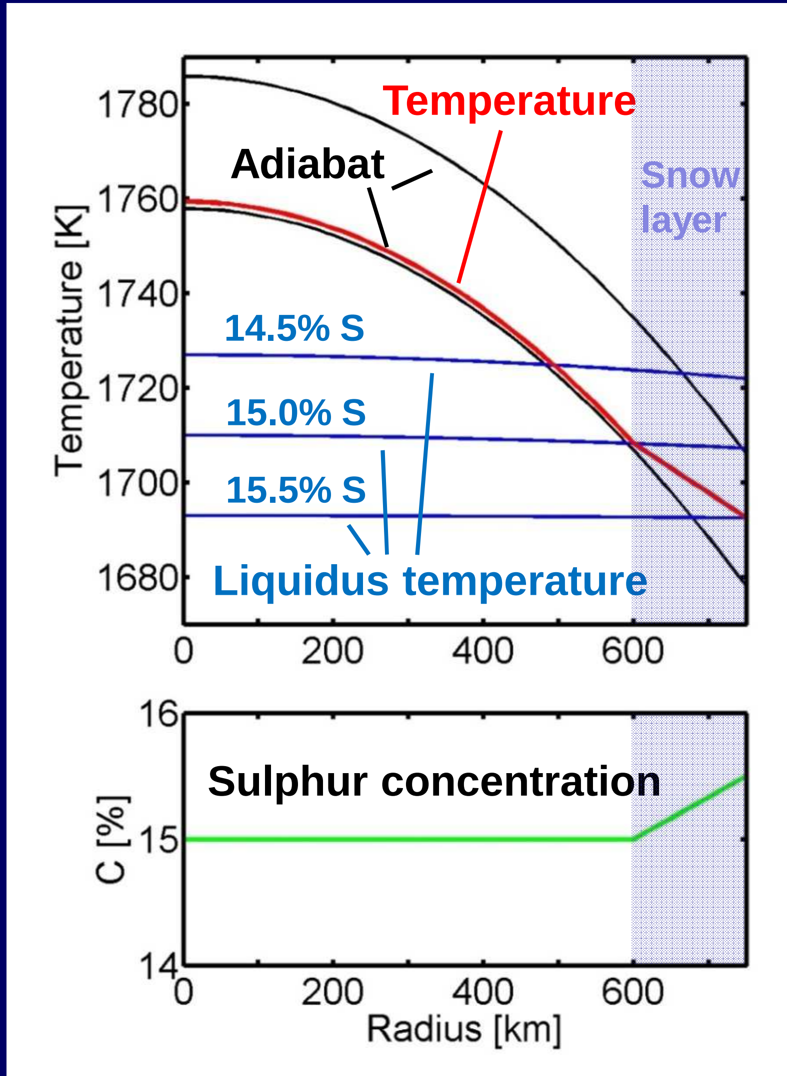
(Hauck et al., 2006; Chen et al., 2008; Williams, 2009; Buono & Walker, 2010)

# Top-down crystallization

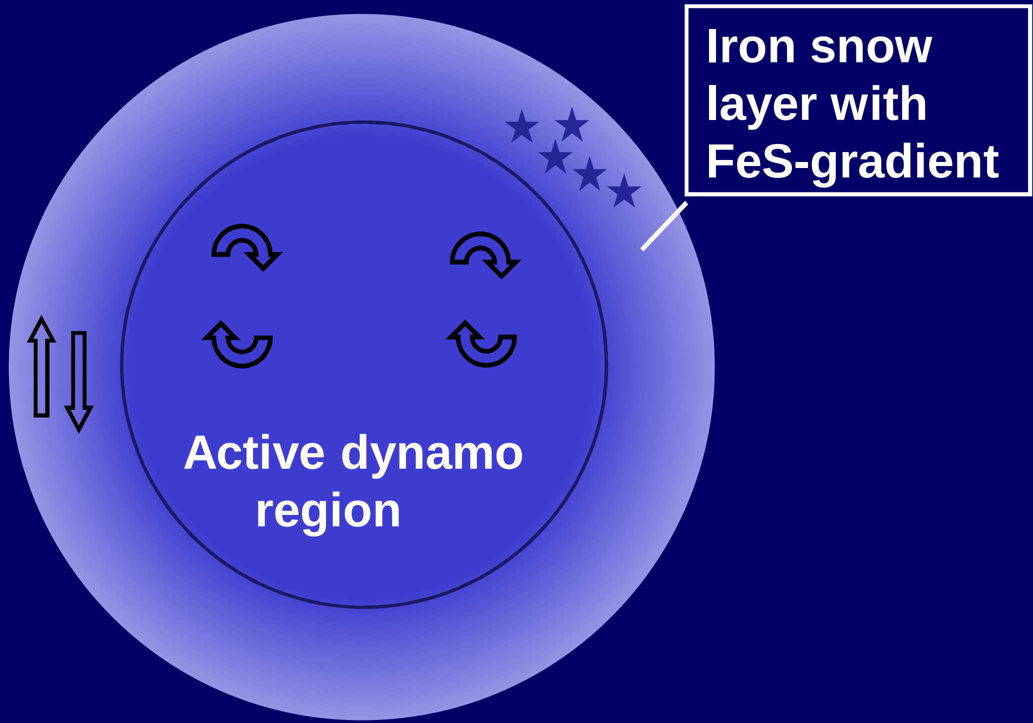
## Ganymede case

- Adiabat steeper than melting point gradient
- Iron snow forms in top layer. Sinks and dissolves at bottom of this layer
- Sulfur-enrichment with stable compositional gradient in snow-forming layer. Here temperature everywhere at liquidus

(Hauck et al., 2006)



# Dynamo below a snow layer



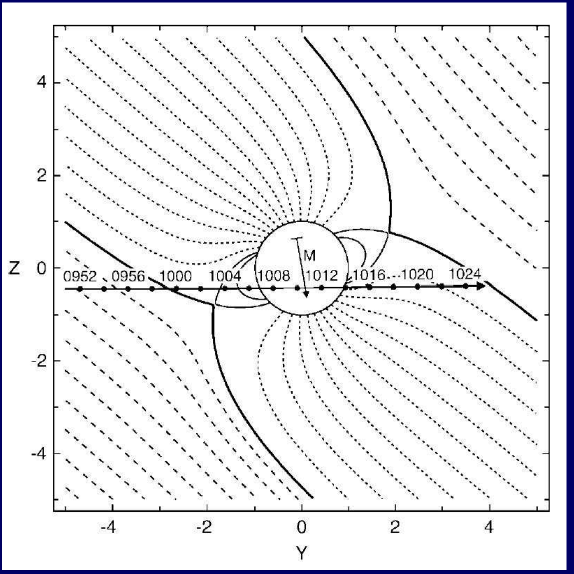

- Fe-enrichment by melting of snow at top of interior region drives compositional convection
- Stable $\Delta\rho$ in snow layer > $10^5$ times larger than typical $\Delta\rho$ of convection $\Rightarrow$ horizontal flow but no radial overturn

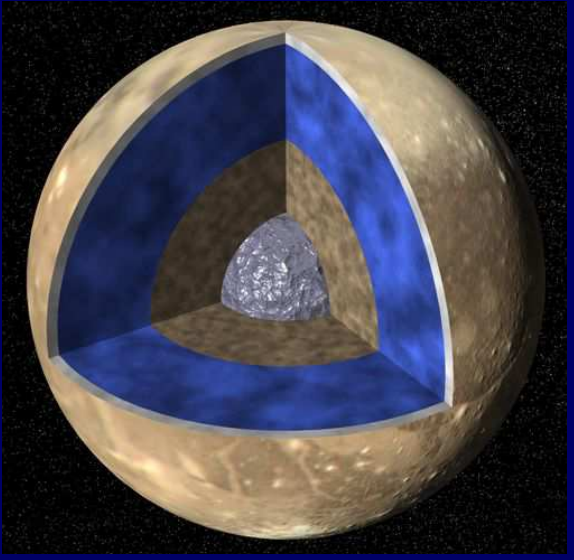
# Ganymede's magnetic field

- Galileo detected global magnetic field: $g_{10}$=711 nT Dipole tilt 4°
- Two models can explain data:
  (1) Dipole + (weak) quadrupole
  (2) Dipole + induced field
  (Kivelson et al., 2002)
- Core radius $r_c \approx$ (1/4 – 1/3) $r_G$
- Even at $r_c$ = 0.25 $r_G$, quadrupole is untypically small

Power ratio $R_2 / R_1 < 0.04$

(Earth CMB 2010: $R_2/R_1 = 0.14$)

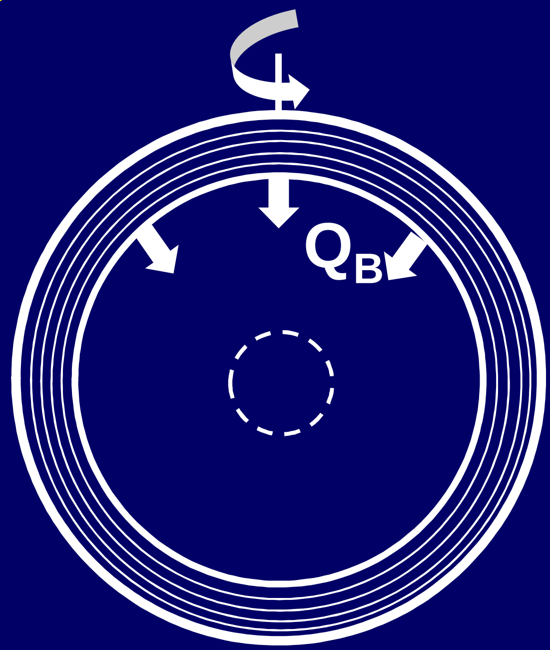


# Numerical dynamo models

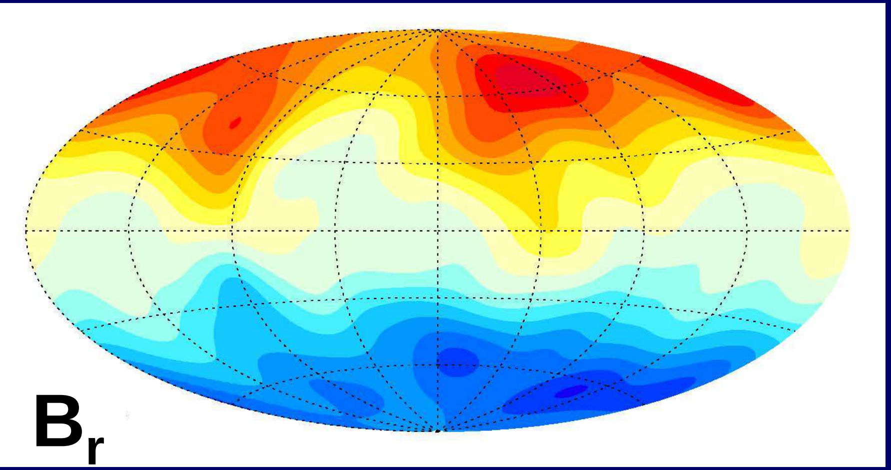
- MHD dynamo model in rotating sphere, fixed buoyancy flux $Q_B$ at top of dynamo region
- Reference model: No extra outer layer
- Snow layer model: Conducting and strongly stable fluid layer above dynamo region; only horizontal flow.
- Parameter range:

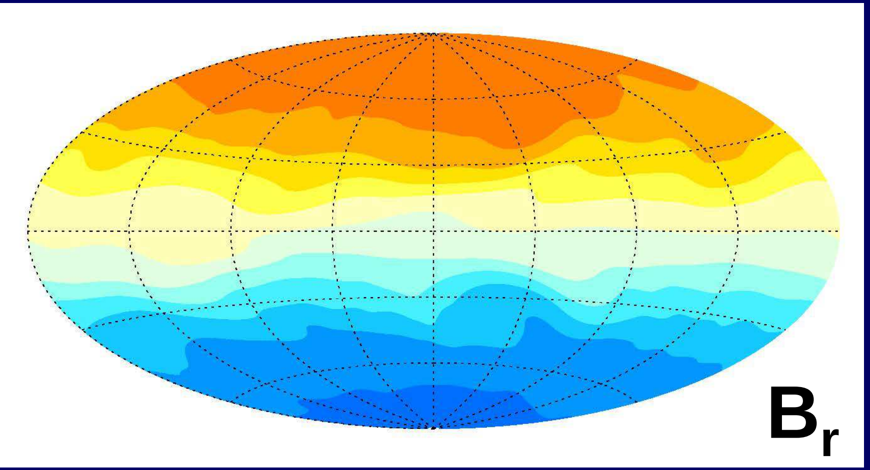
$Ra = (3 – 98) \times Ra_{crit}$
$3\times10^{-4} < E < 3\times10^{-5}$
$Pr = 1 \quad 1 < Pm < 5$
$d_{stable}/r_c = 0.07 – 0.39$ (50 – 300 km)
$80 < Rm < 500$



# Field morphology

$E = 3 \times 10^{-5}$ $Pm = 3$ $Ra=28xRa_{crit}$




**Reference model**

no stable layer

$B_r$ at $r = 1.32\ r_c$

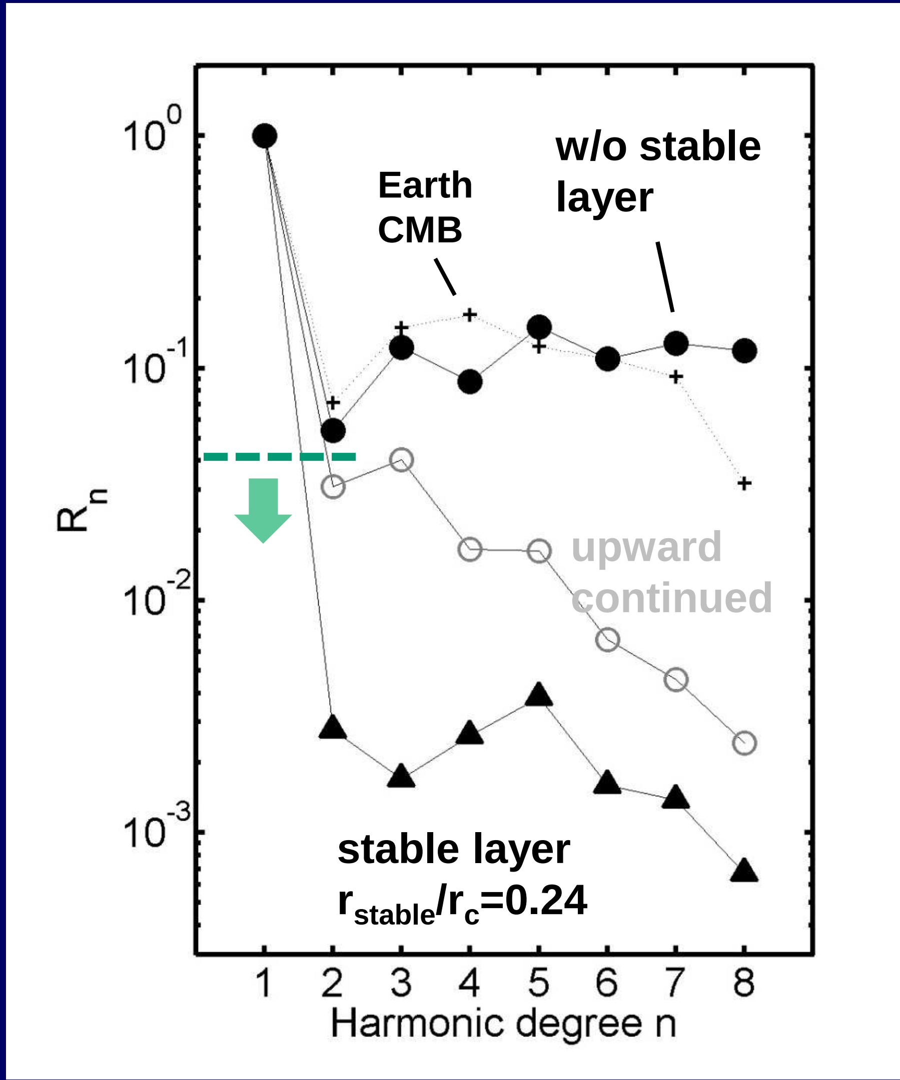
**Stable fluid layer**

$d_{stable}/r_c = 0.24$

$B_r$ at $r = r_c$

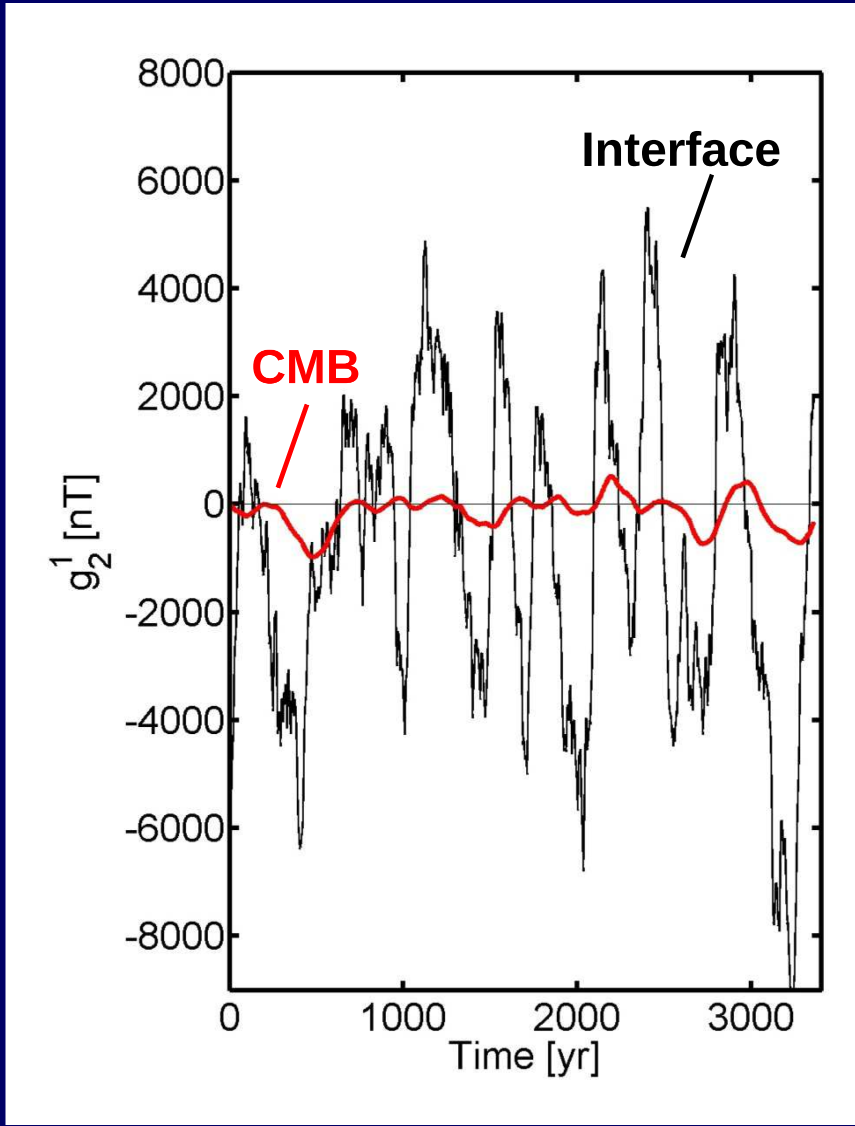
# Magnetic power spectra

- At top of the core, time-averaged, normalized with dipole
- $E=3\times10^{-5}$ $Pm=3$ $28Ra_c$
- Reference model w/o stable layer similar to geodynamo spectrum
- With snow layer drop in multipoles
- $R_2 / R_1 \sim 0.003$



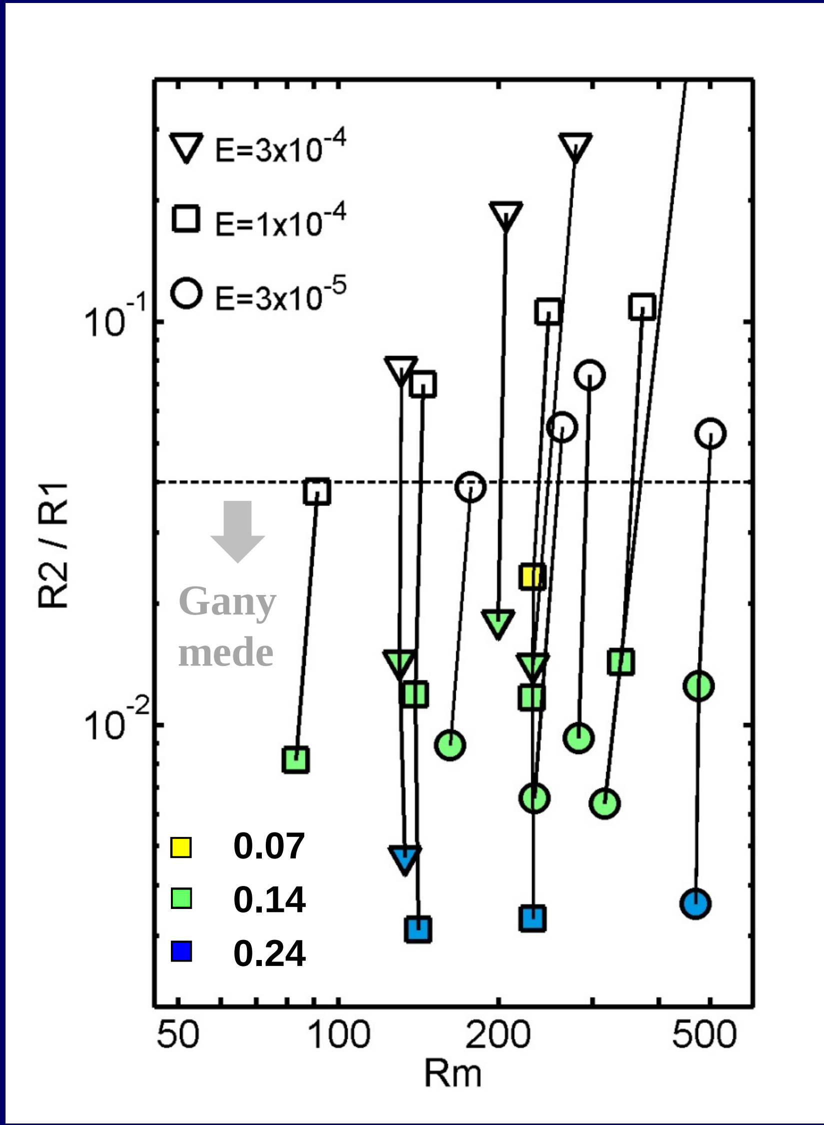
# Skin effect

- Periods of 100-200 yr eliminated
- Dominant period 500 yr attenuated by factor 3 in addition to geometric decrease
- Zonal flow in stable layer additionally damps non-axisymmetric field



# Quadrupole – dipole ratio

- $R_2$ / $R_1$ drops by factor >4 with stable layer
- Without snow layer $R_2$ / $R_1$ too large for Ganymede or marginally compatible
- With snow layer $R_2$ / $R_1$ compatible with observational constraints



# Field strength

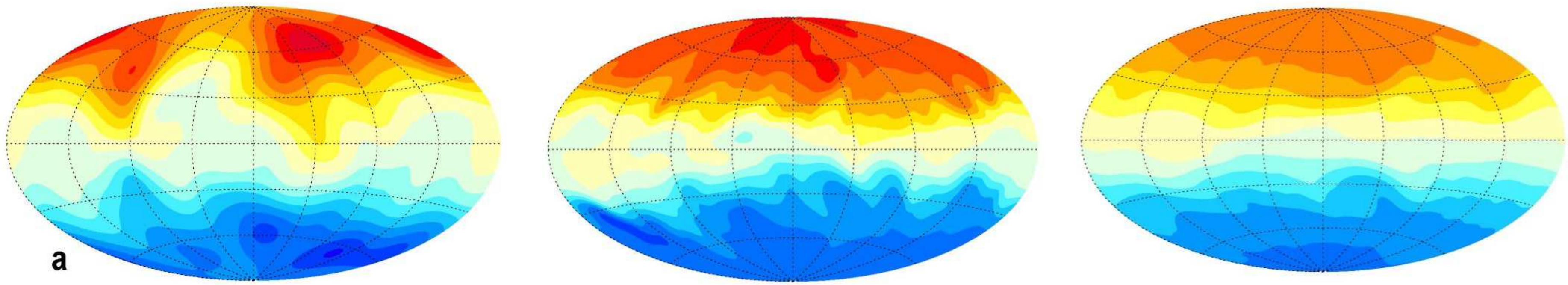
**$E = 3 \times 10^{-5}$ Pm = 3 Pr=1 Ra=$2.5\text{x}10^{8}$**

**Fix D, ρ, g to Ganymede values, $Q_B$ = 10,000 kg/s**

**(Rückriemen et al. 2014)**

- **$\nu = \kappa$ = 4.2 m²/s  λ =1.4 m²/s  $2\pi/\Omega$ = 112 d**

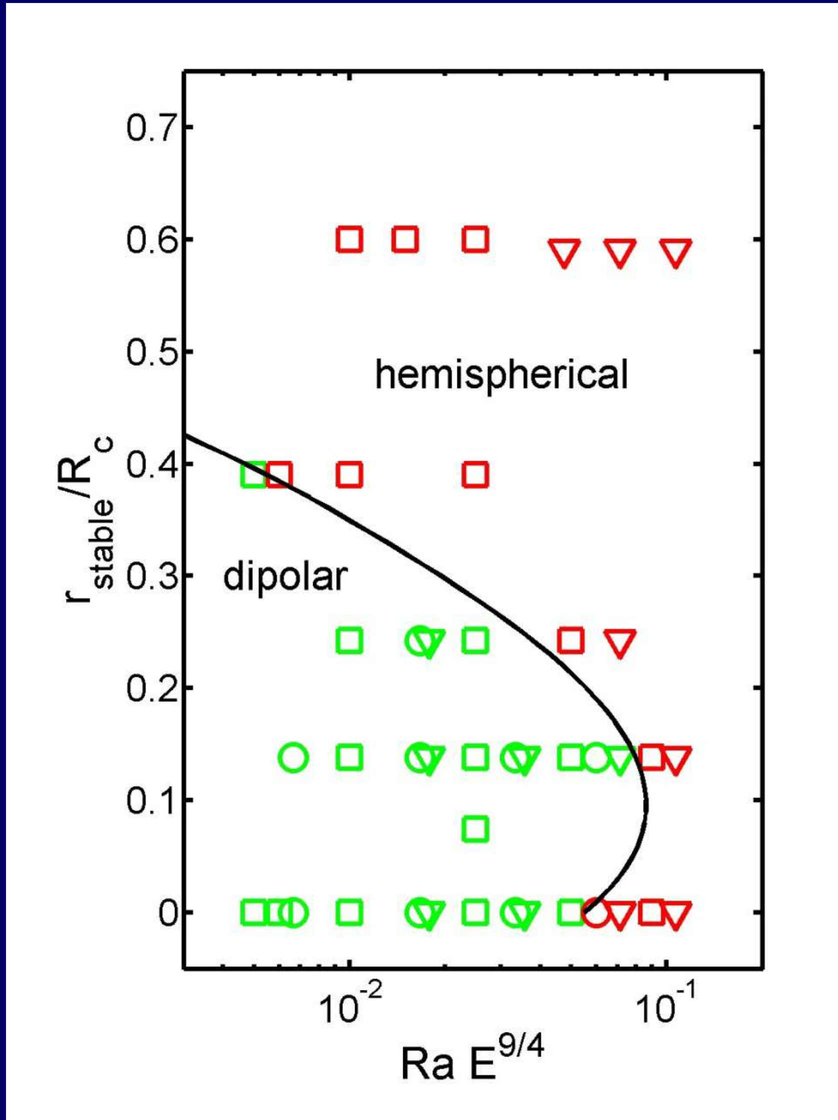
**$g_{10}$ = 1200 nT  $g_{10}$ = 680 nT  $g_{10}$ = 460 nT**



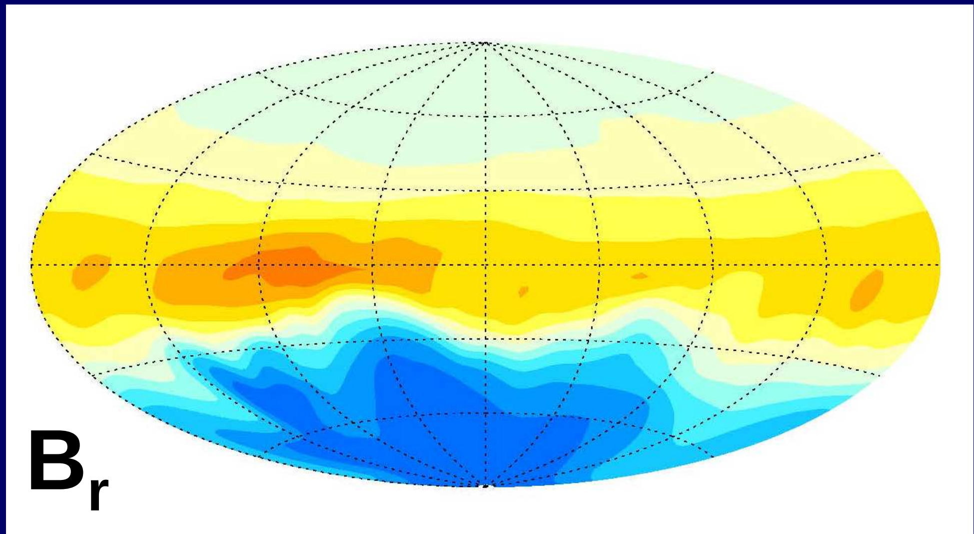

**$d_{stable}/r_c$= 0  0.14  0.24**

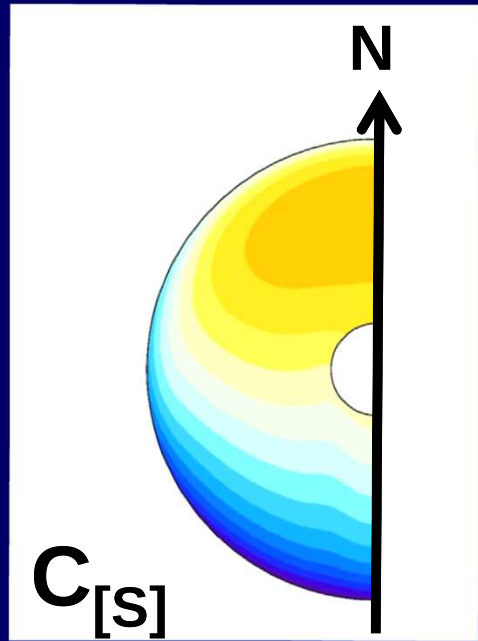
# Stability of dipolar mode

- **Empirical ordering parameter Ra $E^{9/4}$**
- **Stable layer of moderate thickness favors dipolar field**
- **Large stable layer thick-ness (> 0.25 $r_c$) favors hemispherical mode**



# Hemispherical dynamo

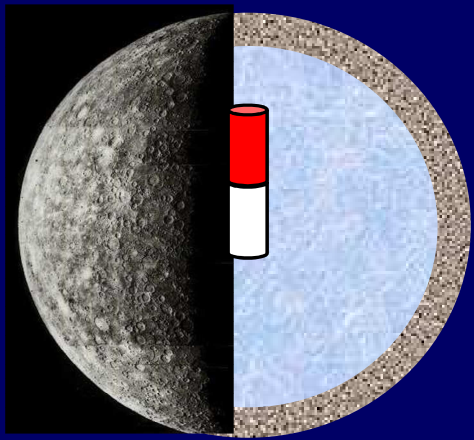


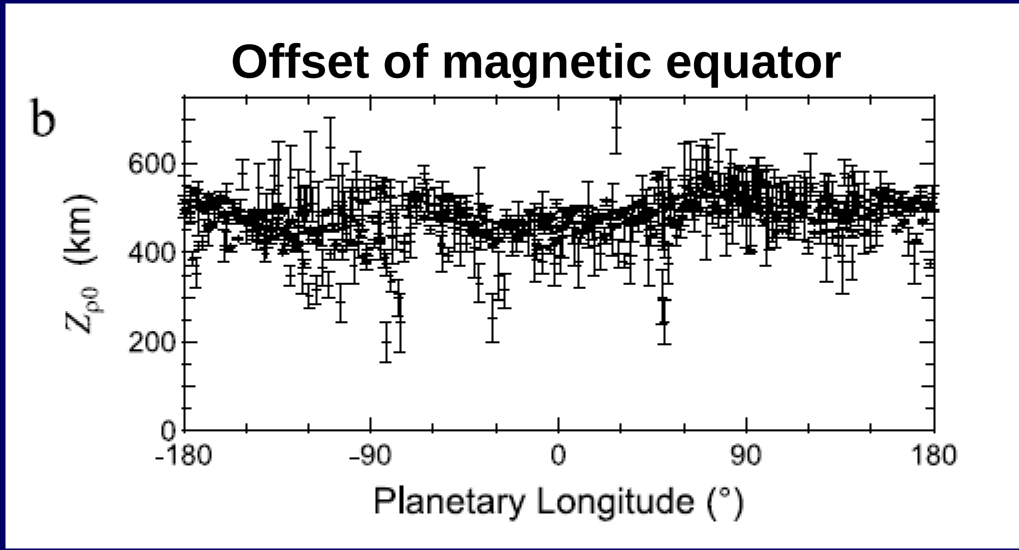




- Hemispherical dichotomy in codensity. Differential rotation.
- Dynamo active in one hemi-sphere.
  $g_{20} >\approx g_{10}$ at top of dynamo

(Grote & Busse, 2000; Landeau & Aubert, 2011)

# Mercury's internal field






**Messenger magnetometer :**

**Dipole offset to the North by 0.2 $R_M$**

**$g_{10}$ = 190 nT　　$g_{20}/g_{10}$ = 0.39　　Dipole tilt < 0.8°**

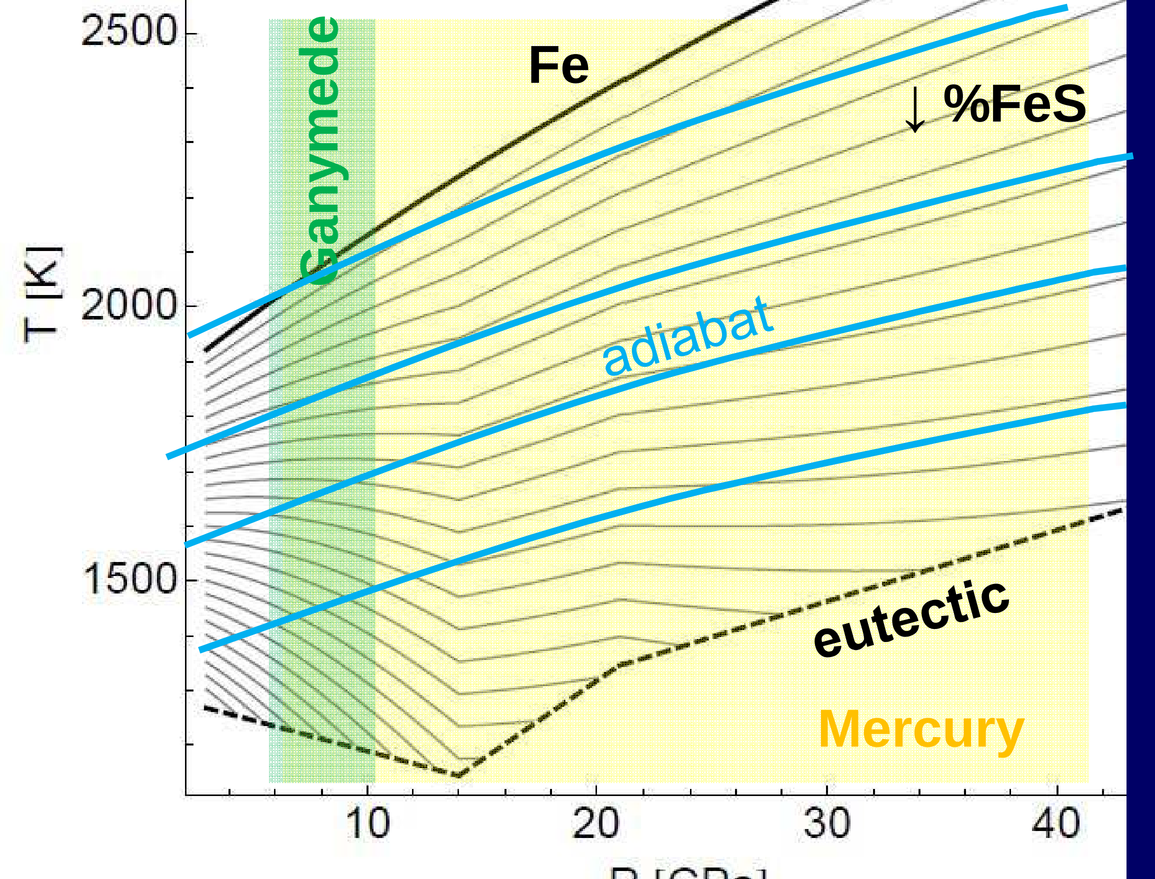
**(Anderson et al., 2011, 2012)**

# Iron snow in Mercury‘s core ?

**For moderate S-content complex with possibility of a double snow layer**

**Dynamo model by Vilim & Stanley (2010) with double snow layer can explain weak field**

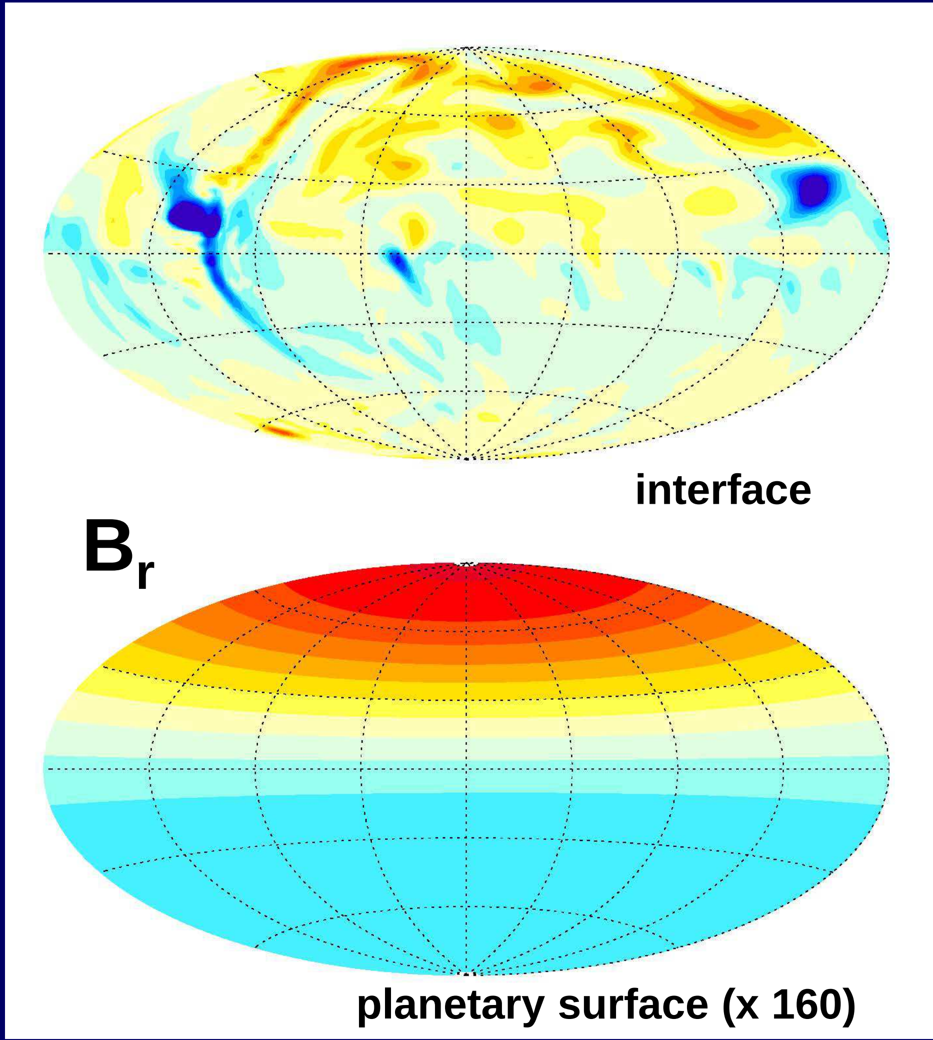
**For high sulfur content, a single deep snow layer possible**

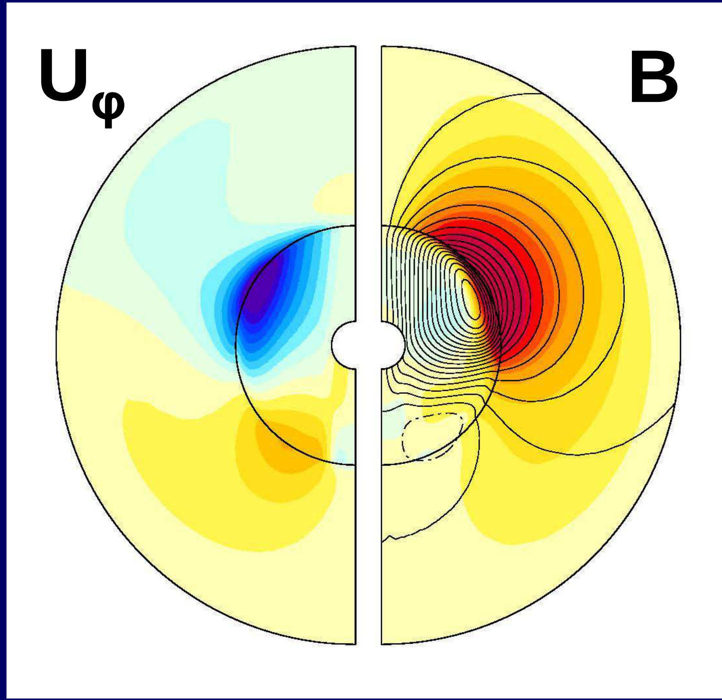



Rivoldini et al., 2011

# Dynamo below thick stable layer

$E = 10^{-4}$ $Pm = 3$ $Ra=1.5x10^{7}$ $d_{stable}/r_{core}=0.6$




**$M_{dip}$ = 410 nT x $R^3$**

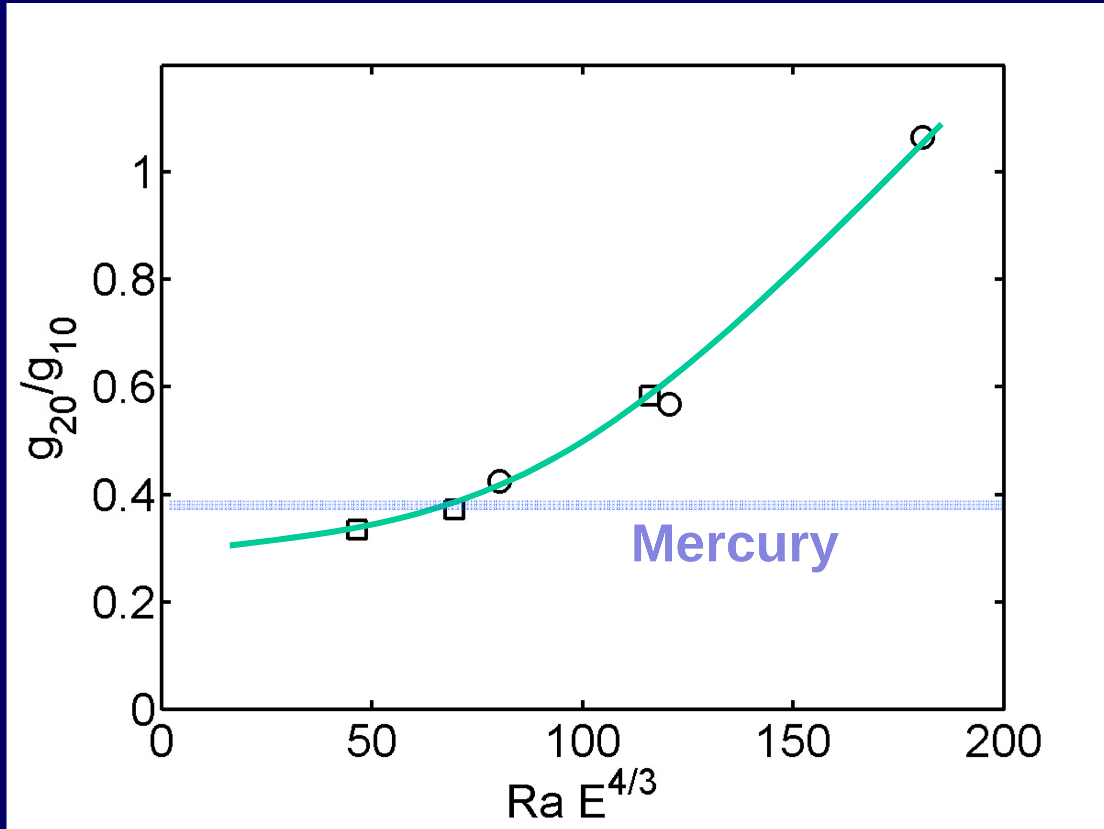
**$g_{20}/g_{10}$ = 0.38**

**Dipole tilt = 0.2°**

# Quadrupole / dipole ratio

Vary Rayleigh# and Ekman# in models with $d_{stable}/r_c = 0.6$

$g_{20}/g_{10}$ increases proportional to $Ra/Ra_{crit} \sim RaE^{4/3}$

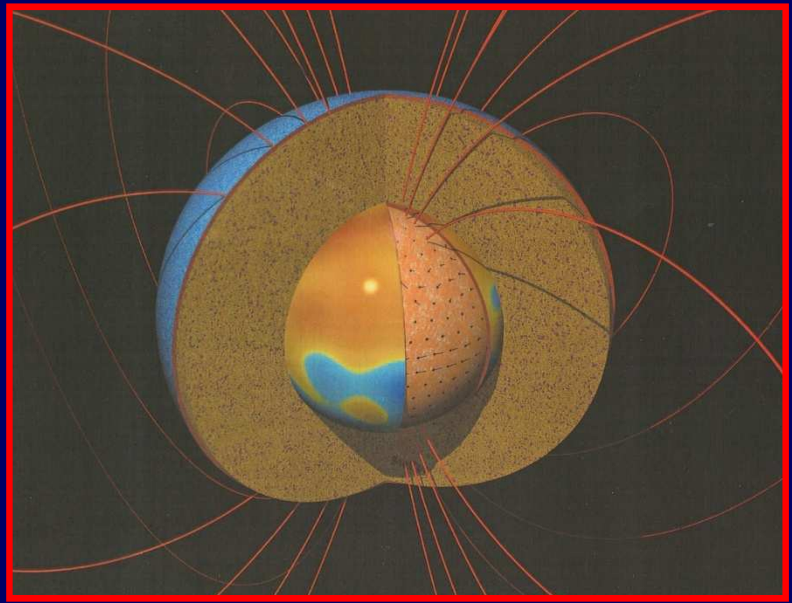


# Summary

- Cores of smaller rocky planets composed of Fe-FeS alloy may start solidifying top-down
- Iron snow forming in top layer may remelt at depth and drive compositional convection
- Thin snow layer in Ganymede allows dipolar dynamo and damps quadrupole above the CMB
- Thick snow layer in Mercury favors hemi-spherical dynamo and may explain Mercury's high axial quadrupole

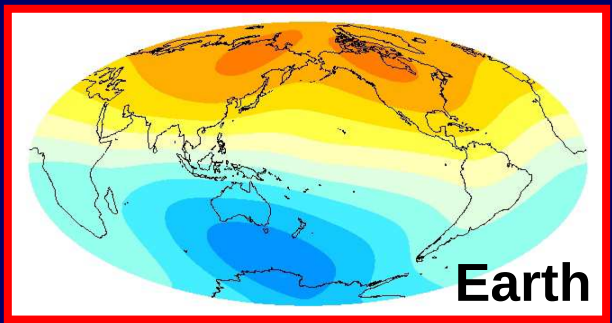
# Magnetic fields: Probes into the deep interiors of planets

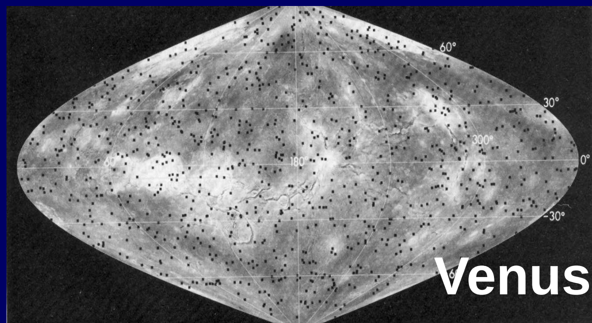
- Information pertaining to the deep interior of other planets scarce
- Magnetic fields easy to measure from orbit
- Information on interior structure, dynamics and energy budget
- Understanding dynamo needed for interpretation

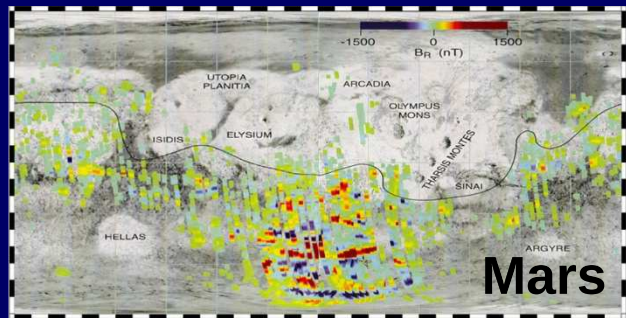


# Magnetic fields of solid planets

| Planet | Dynamo Present | Dynamo Past | $R_c/R_P$ | $B_s$ [nT] | Dipole tilt | Quad / Dipole | Rotation period |
|---|---|---|---|---|---|---|---|
| **Mercury** | Yes | ? | 0.75 | 300 | $< 0.8^{o}$ | 0.48 | 59 d |
| Venus | No | ? | 0.55 | | | | 243 d |
| Earth | Yes | Yes | 0.55 | 44,000 | $10.4^{o}$ | 0.20 | 23h 56m |
| Moon | No | Yes? | 0.2 ? | [>13,000] | | | 27 d |
| Mars | No | Yes | 0.5 | | | | 24h 37m |
| **Ganymede** | Yes | ? | 0.30? | 1000 | $4^{o}$ | < 0.05 | 7d 4h |



# Fundamental requirements for dynamo

- Electrically conducting fluid layer

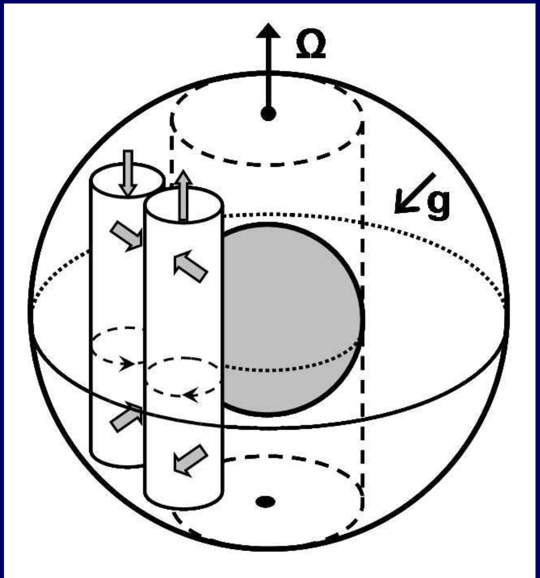
  ⇒ liquid iron cores in rocky planets

- Motion in this layer with a sufficient velocity U (magnetic Reynolds number $Rm = UR/\lambda > 50$)

  ⇒ convection likely fast enough (if it occurs)

- Motions must have suitable geometry (e.g. helical flow)

  ⇒ convection influenced by Coriolis force



# Mars & Venus: which condition fails ?

Core entirely frozen ? Very unlikely

Thermal evolution modeling; Mars: tidal Love number $k_2$

Rotation too slow (Venus) ? Unlikely

Coriolis force still plays significant role in force balance

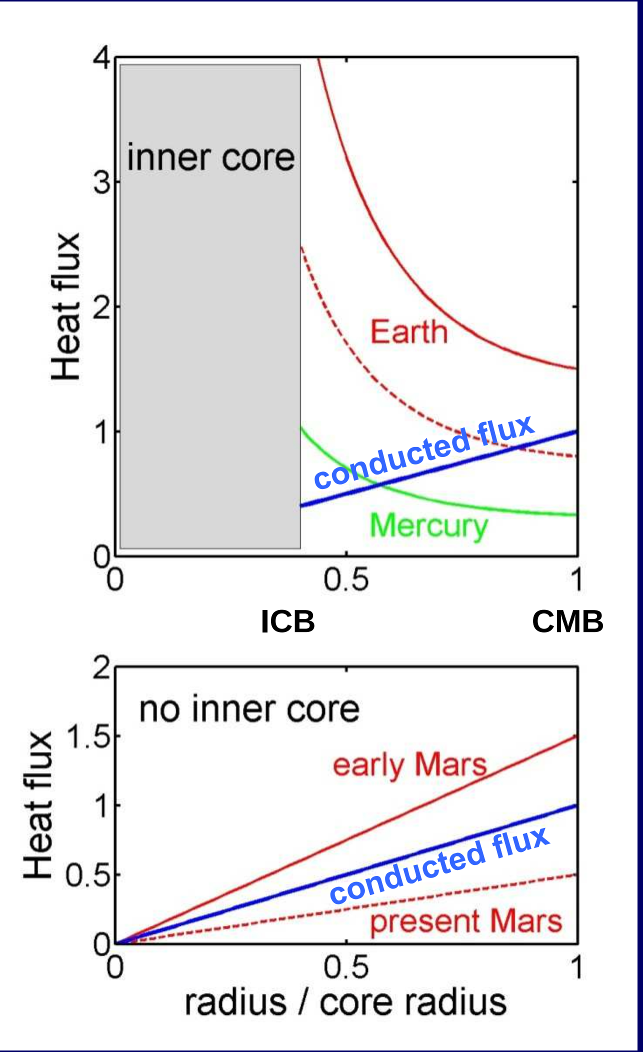
Core not convecting ? Most likely explanation!

Mantle convection controls heat flow from core.

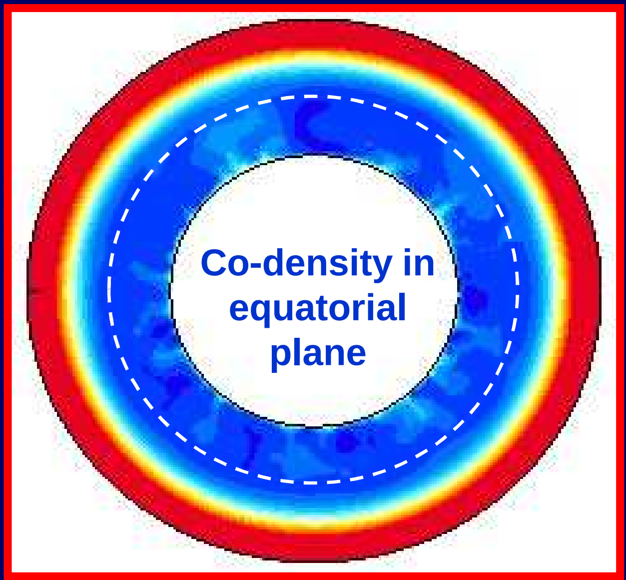
Lack of plate tectonics implies less efficient cooling of the interior and lower heat flux from the core

# Thermal & compositional convection in the cores of terrestrial planets

- Large heat flux $q_{cond}$ conducted along adiabatic gradient (blue line)
- In most (all?) solid planets the CMB heat flux is likely $< q_{cond}$
- If iron solidification has not started (Mars, Venus?) the core is stably stratified $\Rightarrow$ no dynamo
- Latent heat and compositional flux of growing inner core makes fluid core unstable (Earth, Mercury?)
- Top-down freezing (iron snow) can drive compositional convection (Ganymede, Mercury?)



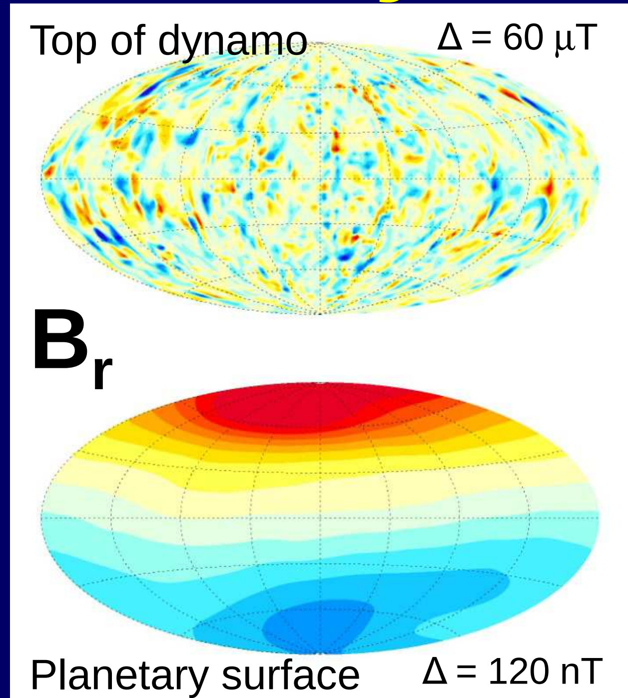
# Dynamo below stable fluid layer

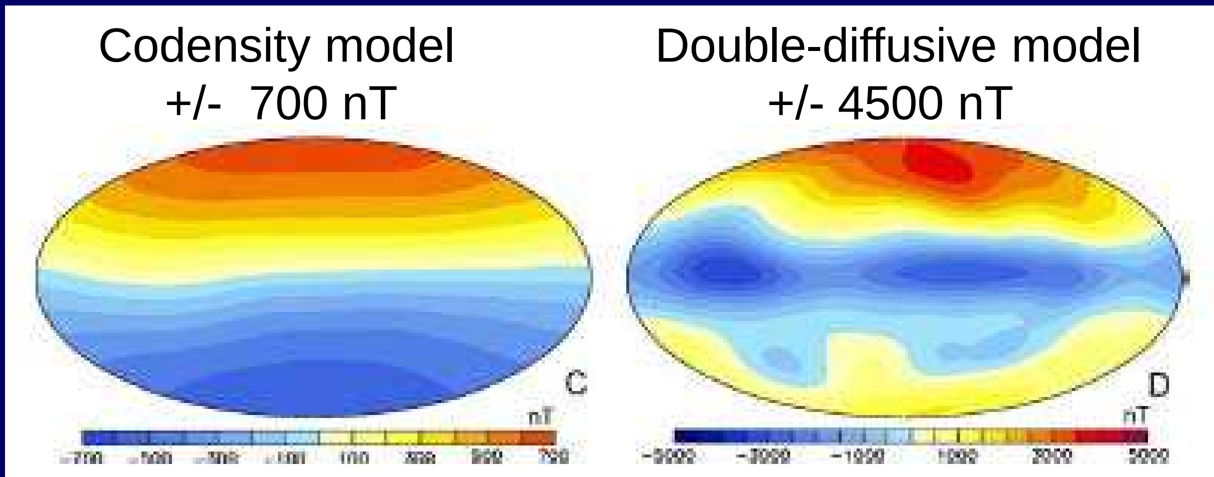



**Co-density model**

Internal field strong and small-scale

Surface field weak and large-scale




**Double diffusive model**

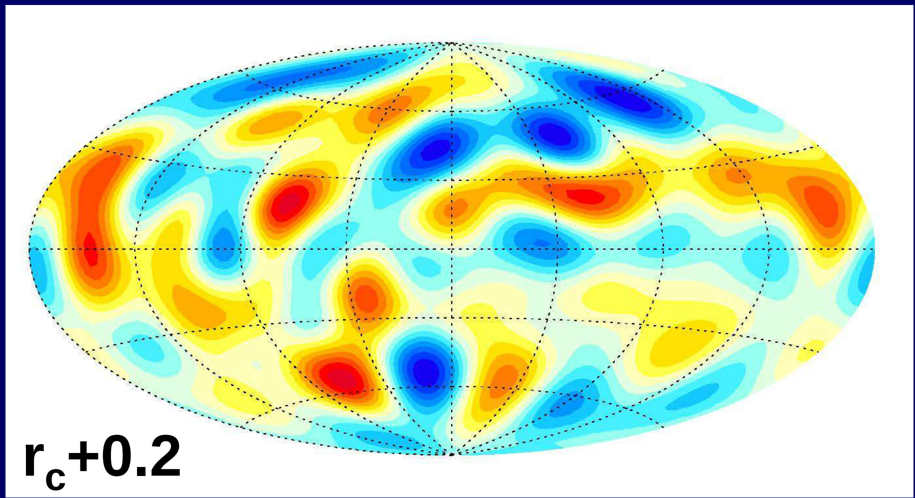
Surface field more structured and stronger

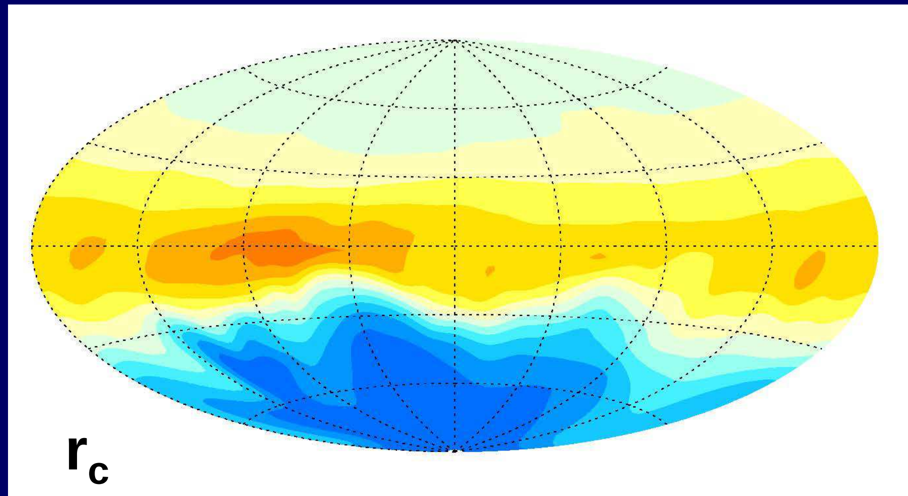
Field strength as observed only for low sulphur content in core (~0.2 %)

Christensen, 2006; Christensen & Wicht, 2008; Manglik et al., 2010

# Nondipolar models

$E = 1 \times 10^{-4}$  $Pm = 3$  $Ra = 46\ Ra_{crit}$  $d_o = 0.0 / 0.2$




## Reference model

**Multipolar**

**(Hemispherical at other times)**

## Stable fluid layer

**Hemispherical**

**$g_{20} \approx g_{10}$ at CMB**