1st Neutrino Oscillation Tomography Workshop
Jan. 7, 2016

Recent progress in studies of the geomagnetic field and dynamics of the Earth's core

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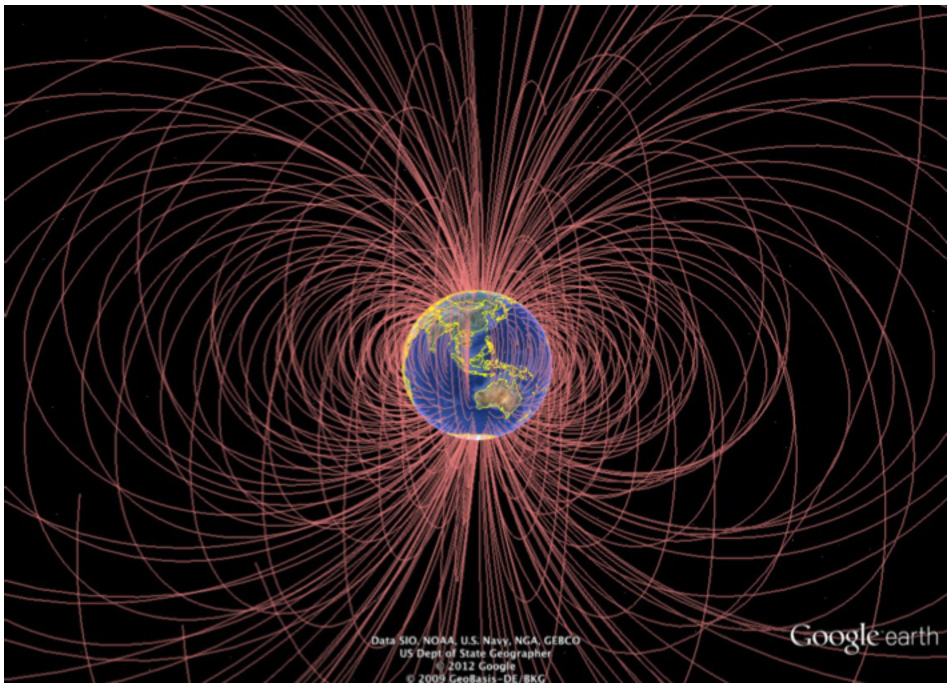
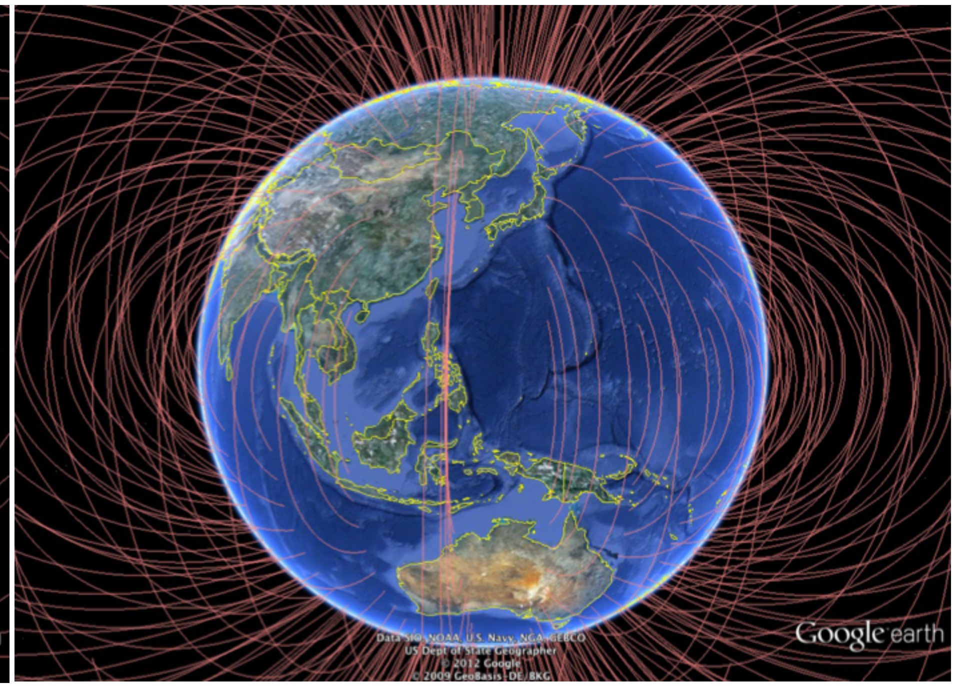
- Geomagnetic field and its variation
  . Present field and secular variation (~ several hundred years)
  . Paleomagnetic field (1 ka ~ 4.3 Ga)

- Geodynamo
  . Cooling of Earth and convection in the core
  . Composition of the core
    - thermal conductivity and convection
    - inner core crystallization and convection
    - stable stratification at the core surface

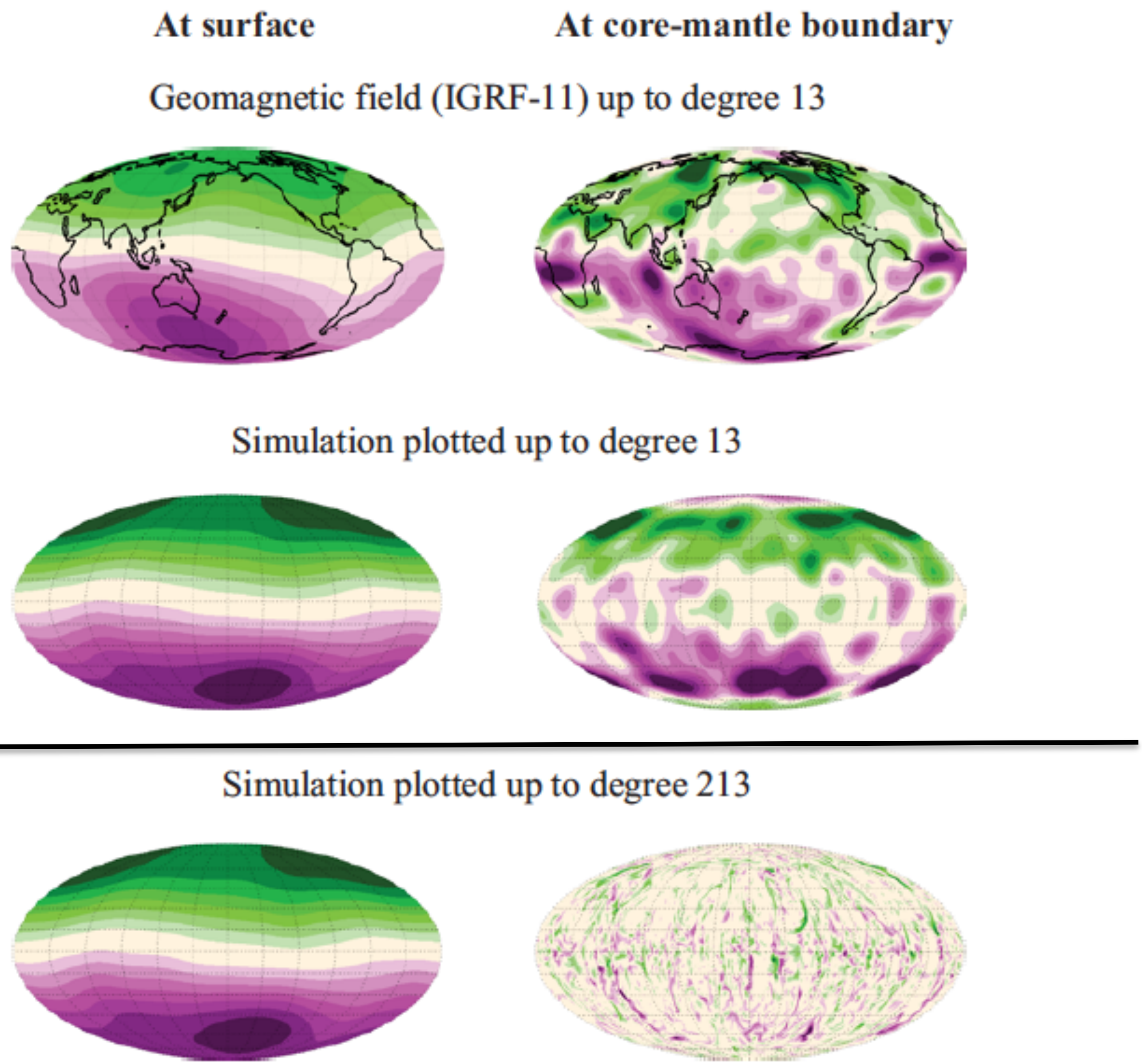
Geomagnetic field lines around Earth at year 2010 (Main field)





Maps of radial component are often used to understand geomagnetic field distribution and its time variation.

Present field & dynamo-modeled field



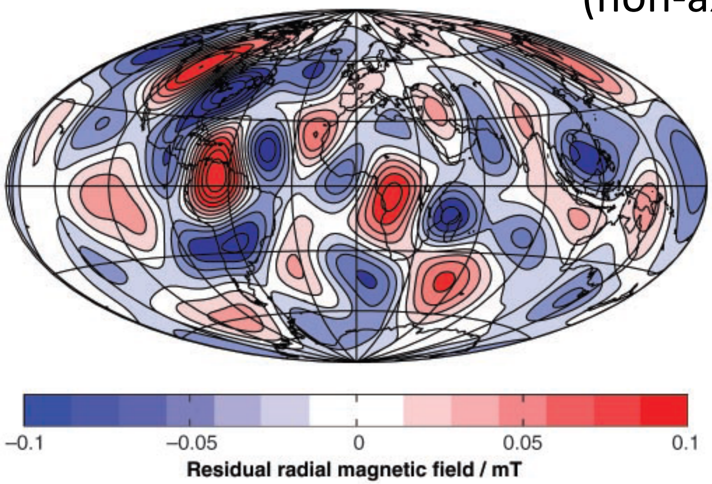
radial magnetic field
(magnetic flux density)

Roberts and King (2013)

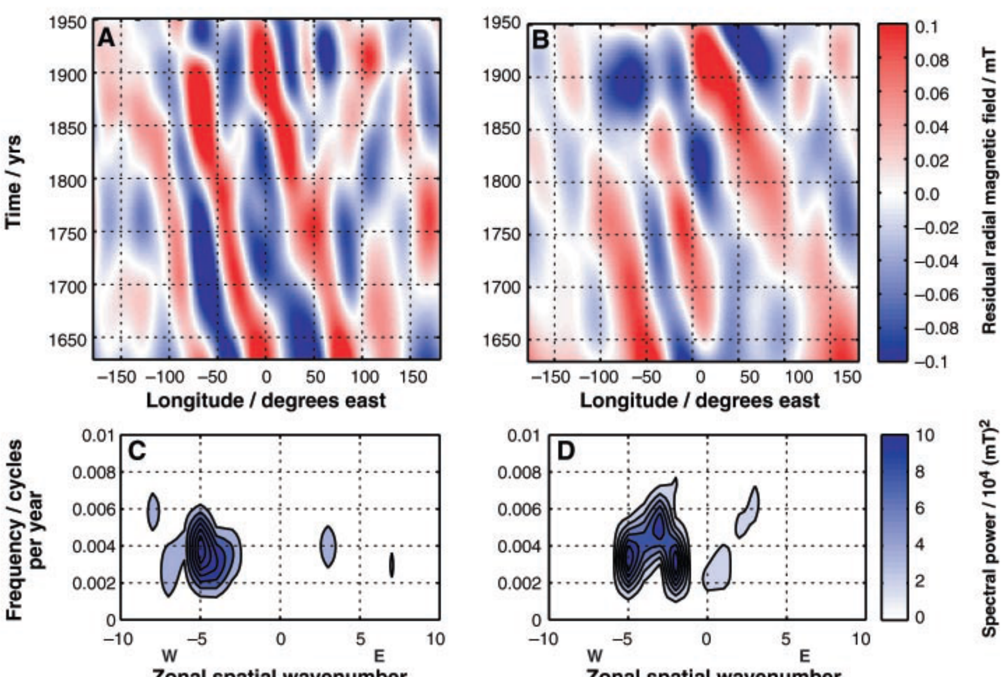
Geomagnetic Field Variation

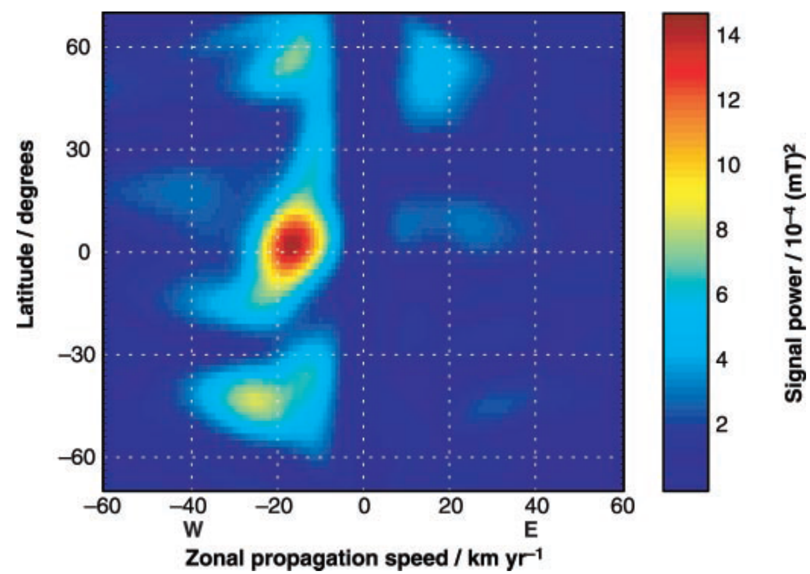
Secular variation after 1590

(non-axisymmetric component)



@CMB
year 1850



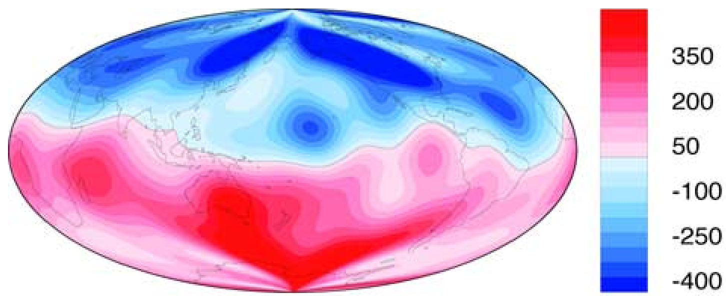


Finlay and Jackson (2003)

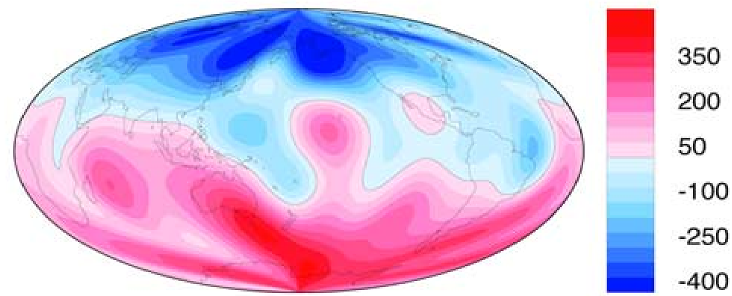
Geomagnetic Field Variation

Time-averaged field with various time-scales

400 yrs



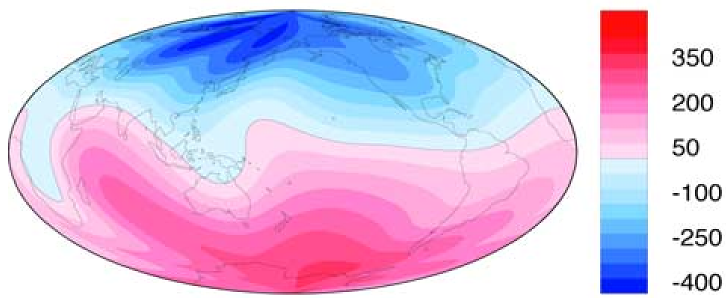
(a) Model GUFM1



(e) Model LN1

5 Myrs

7000 yrs

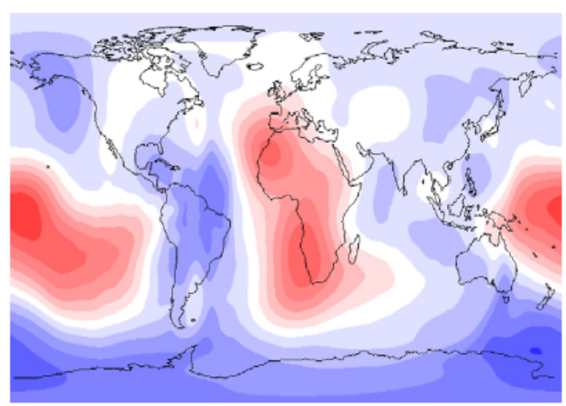


(b) Model CALS7K.2

(radial component at the CMB, unit: μT)

Johnson et al. (2008)

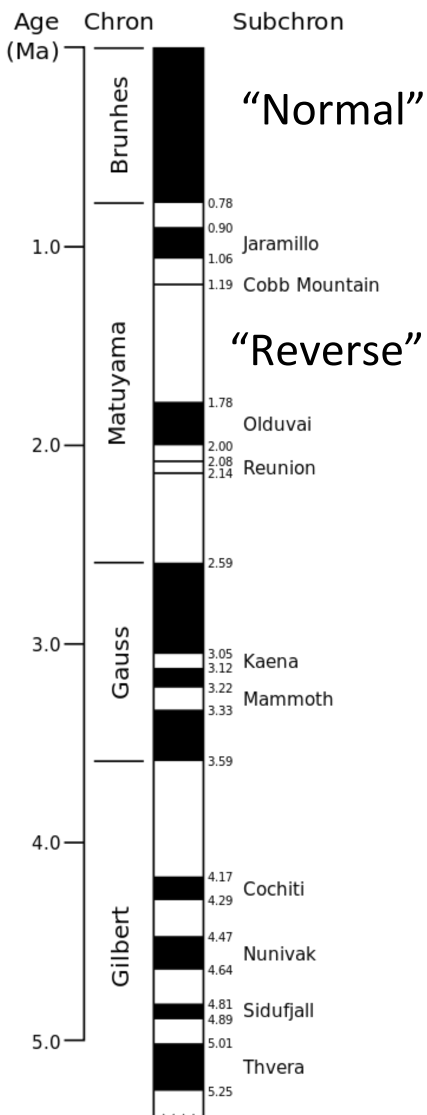
Vs distribution in the bottom 250 km of the mantle



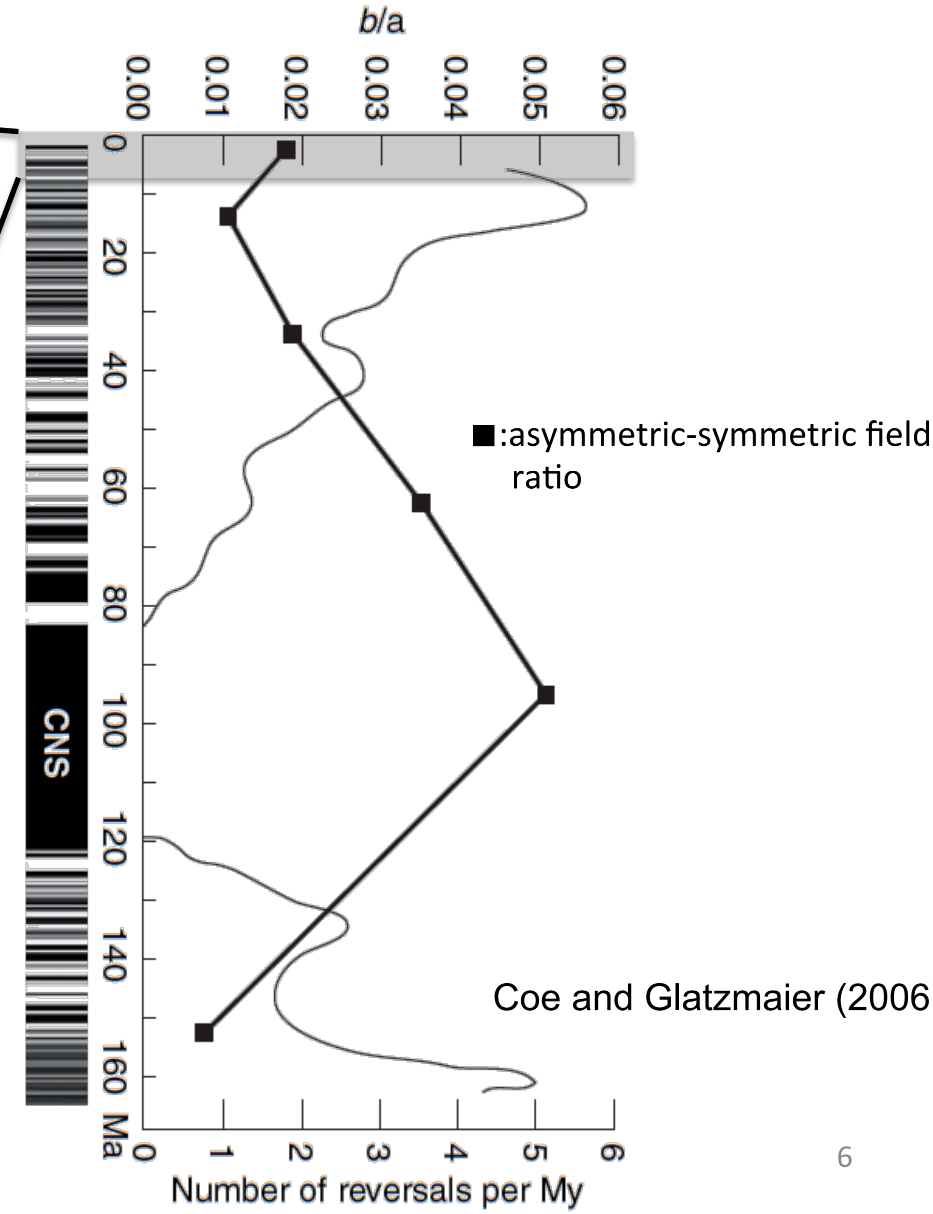
Masters et al. 1996, Gubbins et al., 2007

Geomagnetic Field Variation

Reversal of the geomagnetic field

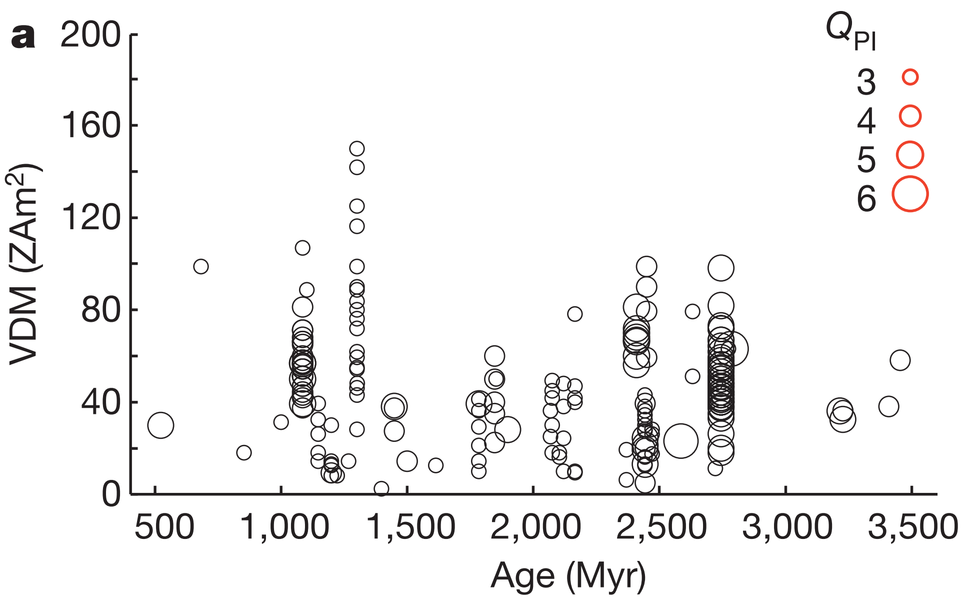


Mankinen and Wentworth (2003)

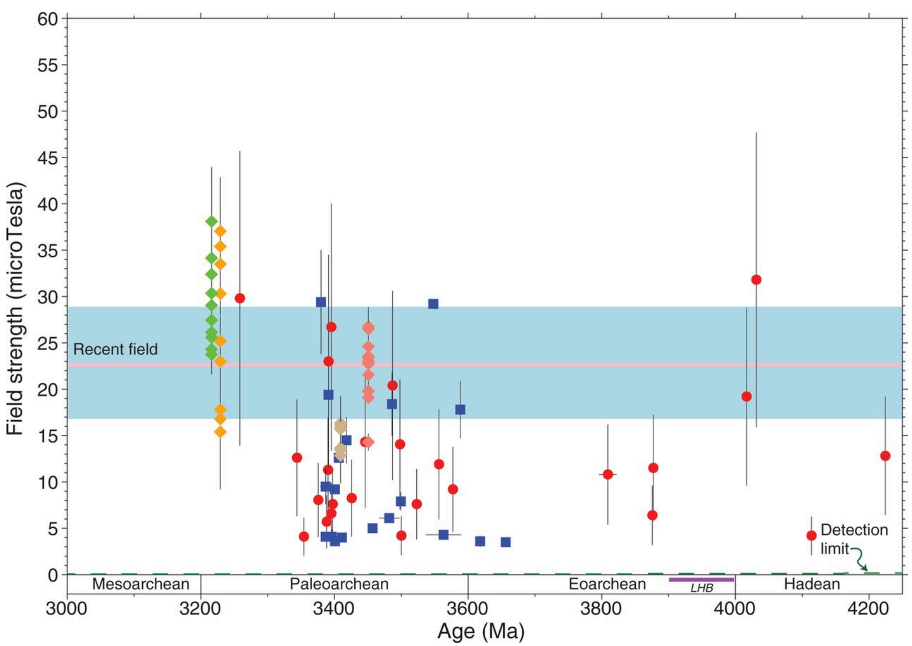


Coe and Glatzmaier (2006)

Geomagnetic Field Variation
Paleomagnetic field intensity



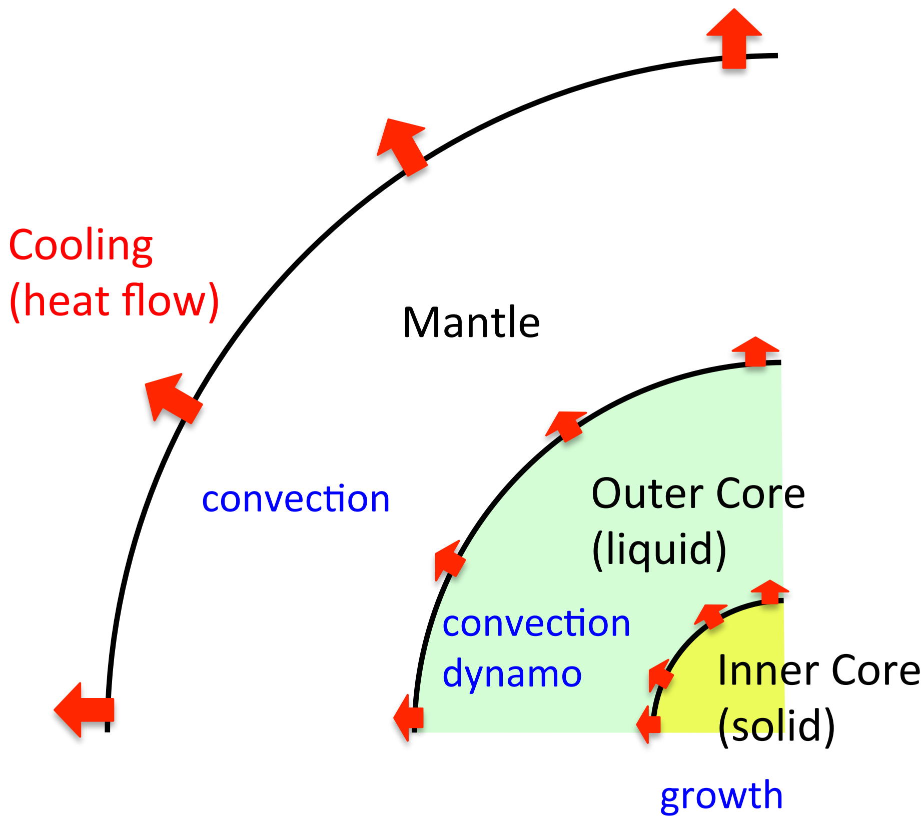
Biggin et al. (2015)

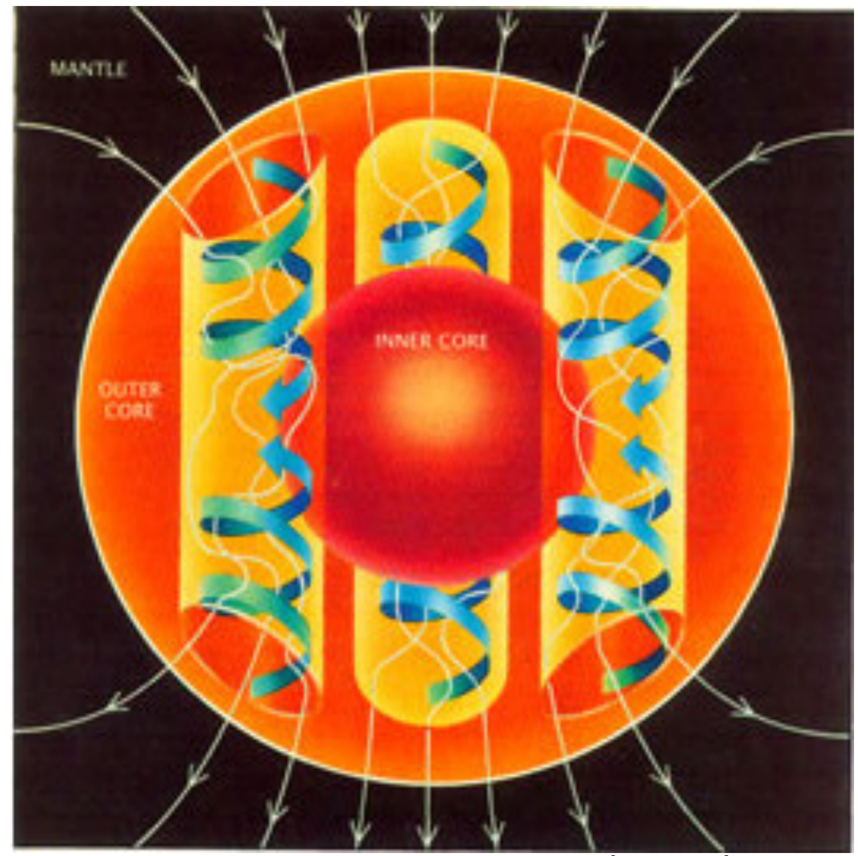


Tarduno et al. (2015)

(Z: zetta=10^{21})

Geodynamo





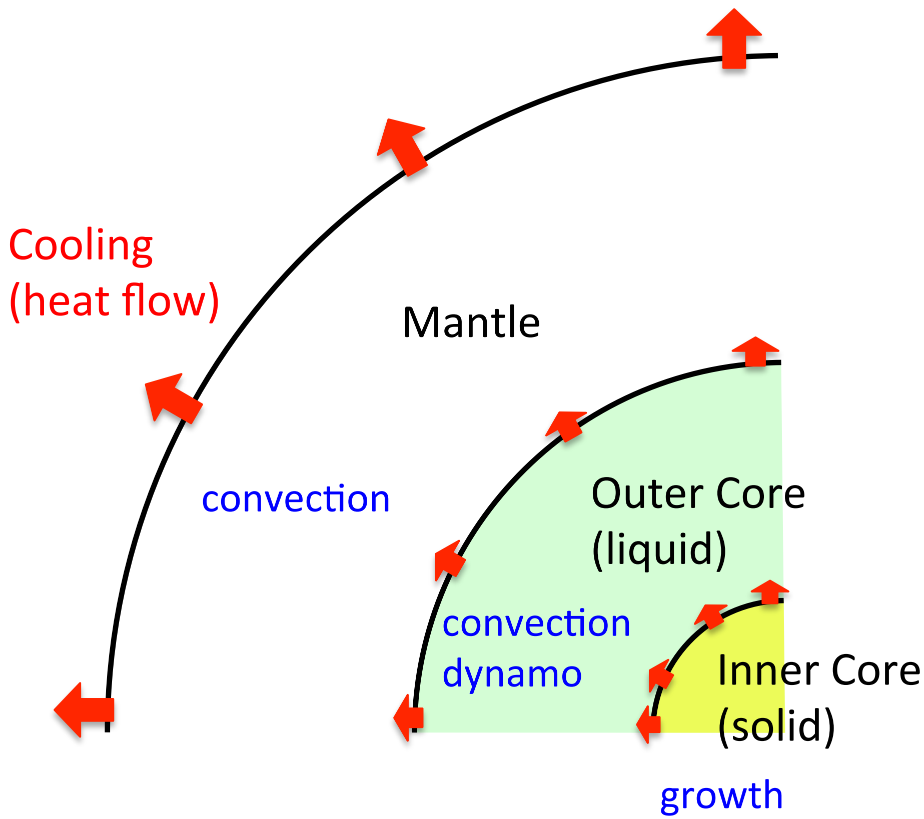
U.S. Geological Survey

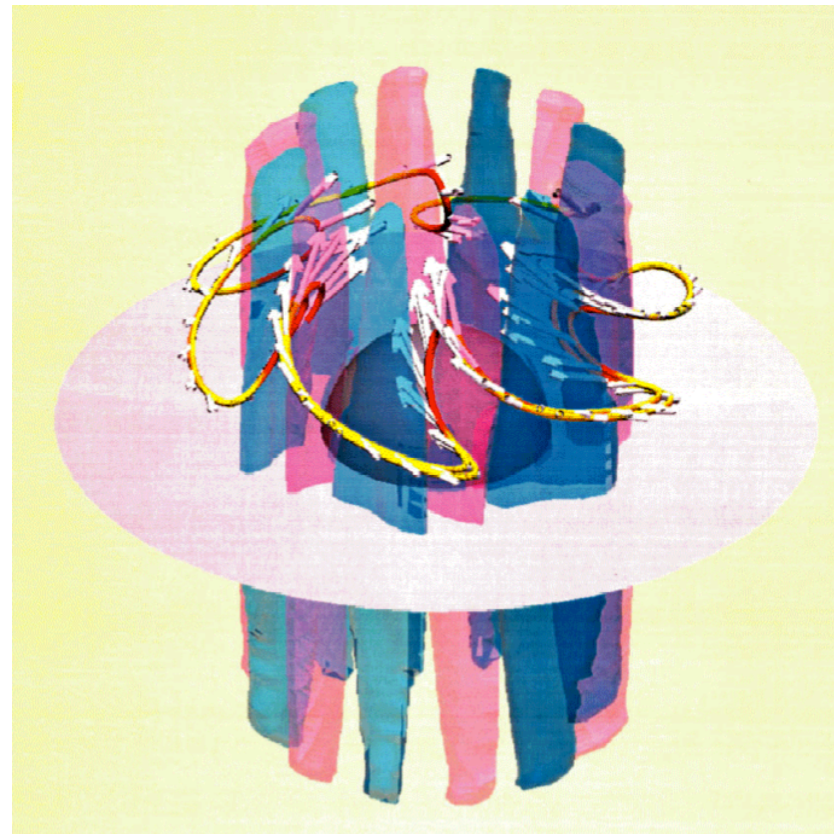
Sufficiently fast flow in the electrically conducting outer core -> Geodynamo

- cooling and convection
- inner core growth
- Earth's rotation
- heterogeneity in the mantle

$$Rm = \sigma \mu_0 R U \geq Rm_C$$

Geodynamo





Kageyama&Sato,1997

Sufficiently fast flow in the electrically conducting outer core -> Geodynamo

cooling and convection

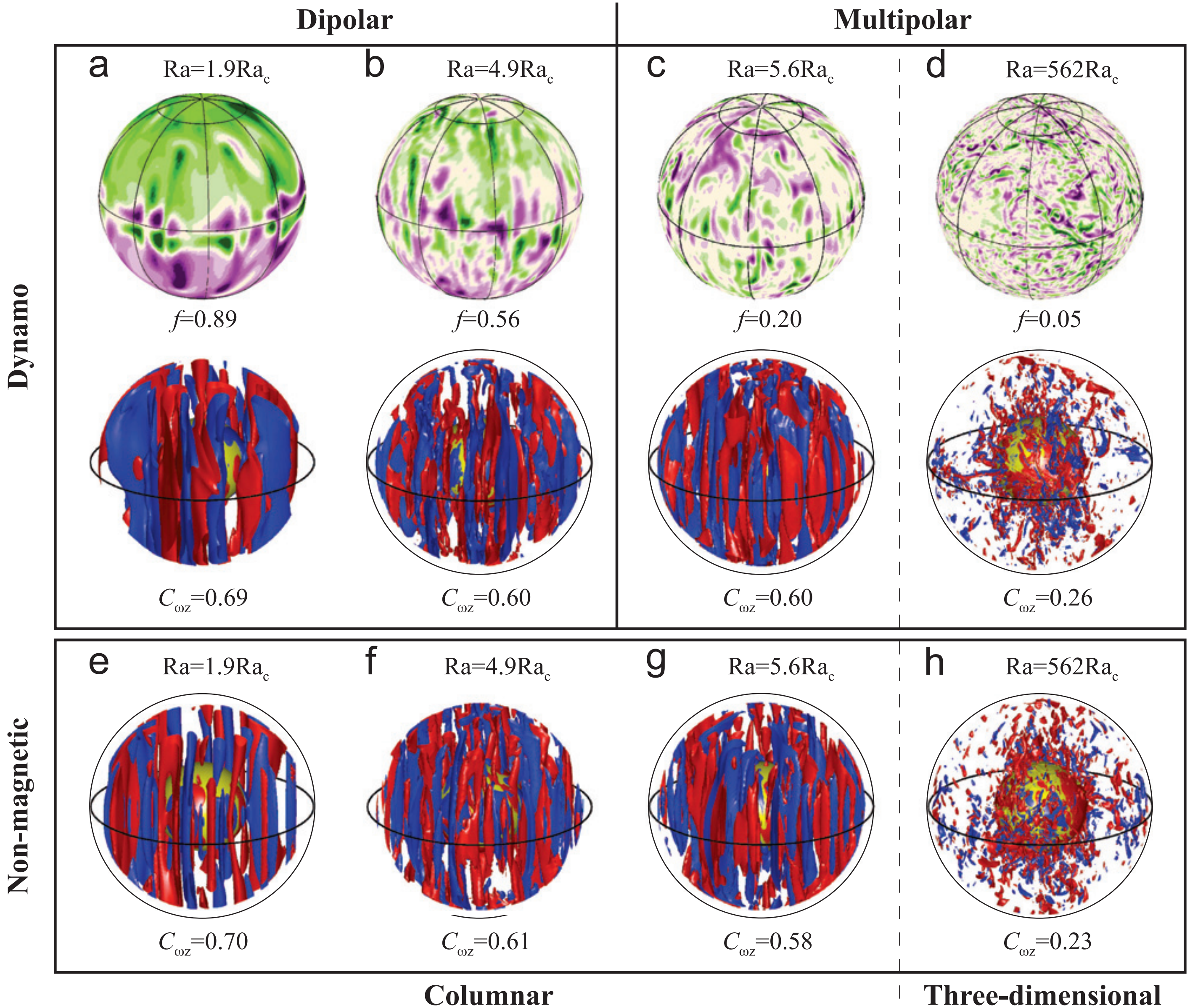
inner core growth

Earth's rotation

heterogeneity in the mantle

$$Rm = \sigma\mu_0 RU \geq Rm_C$$

Effect of Cooling rate/thermal diffusivity on flow and magnetic field



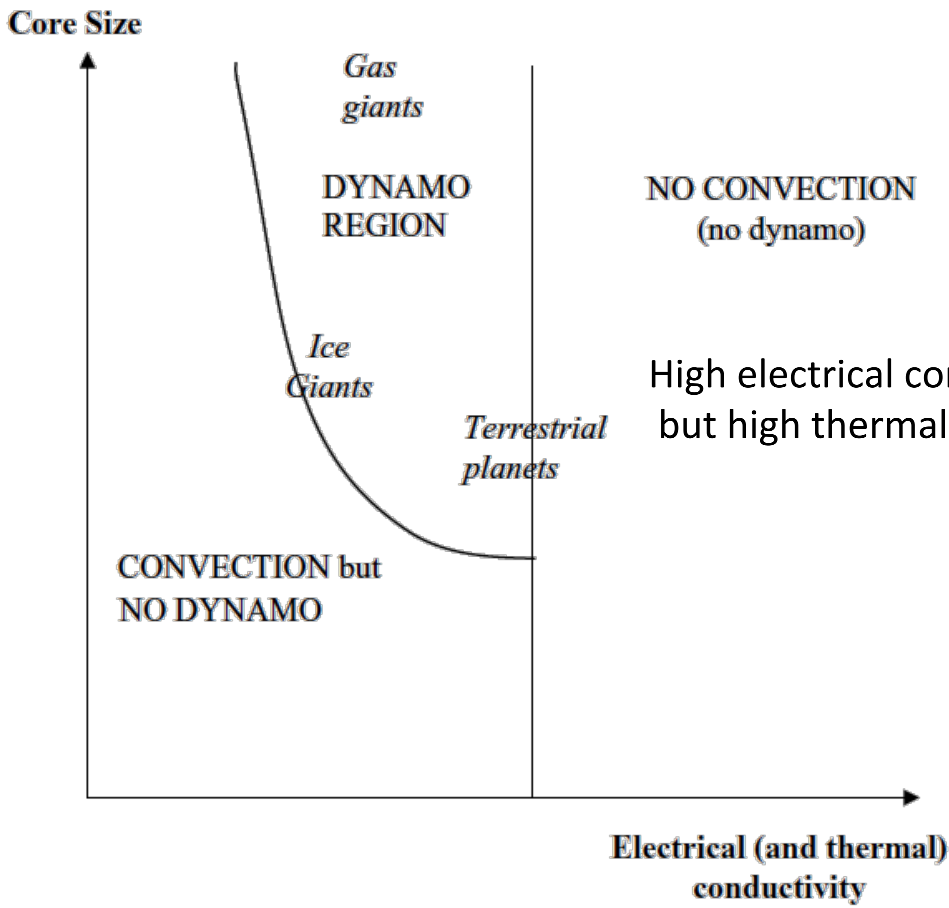
Soderlund et al. (2012)

Thermal convection in the core and planetary dynamo

Wiedemann-Franz law for metal

$$\frac{k}{\sigma T} = L \approx 2 \times 10^{-8} \quad \mathrm{W/SK^2}$$

$$Rm = \sigma \mu_0 R U$$



High electrical conductivity (σ) -> dynamo
but high thermal conductivity (k) -> no convection

Stevenson, 2003

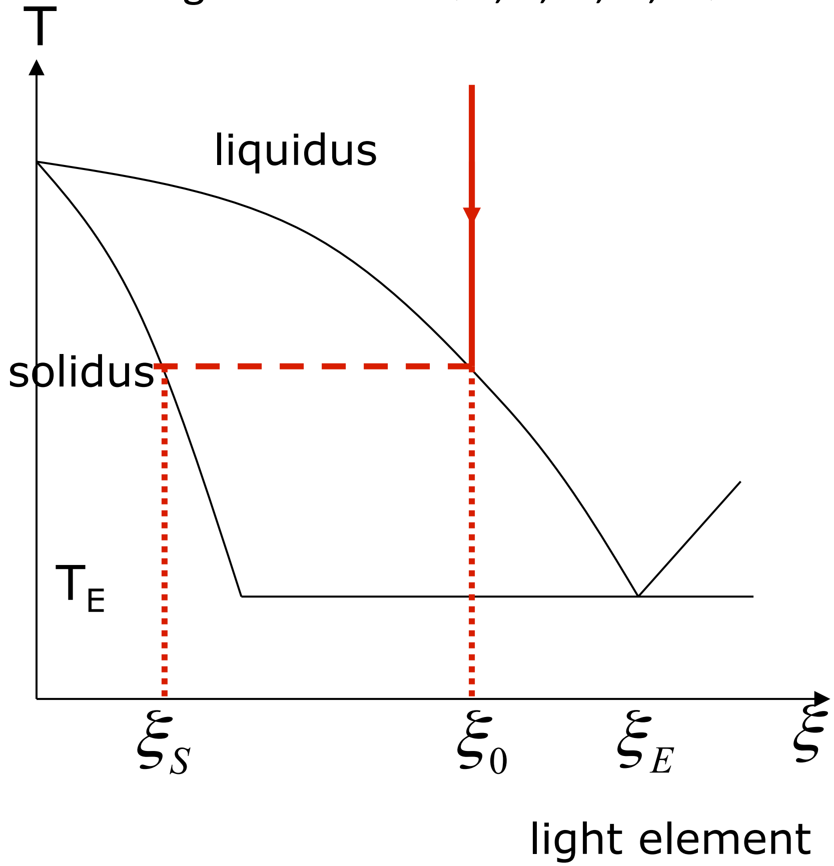
Thermal conductivity of iron + light components at core condition
(high pressure and temperature)

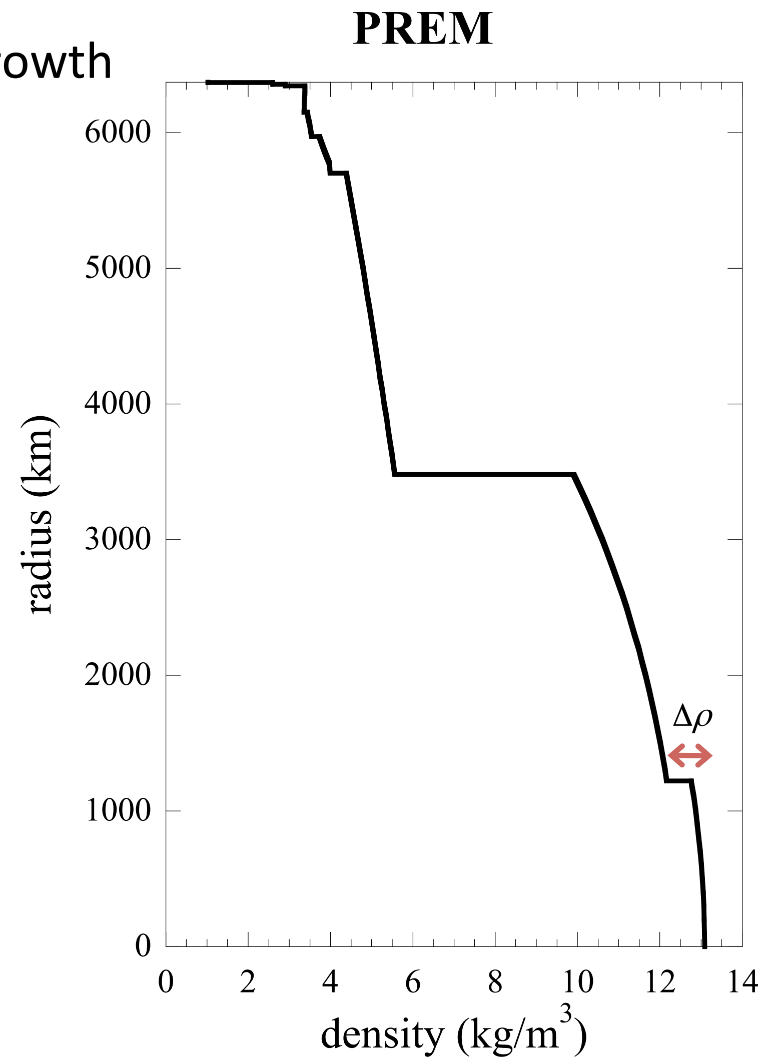
Compositional buoyancy by inner core solidification

Release of light element due to inner core growth

Outer core： Fe（＆Ni）

＋light elements（O, S, Si, H,….）



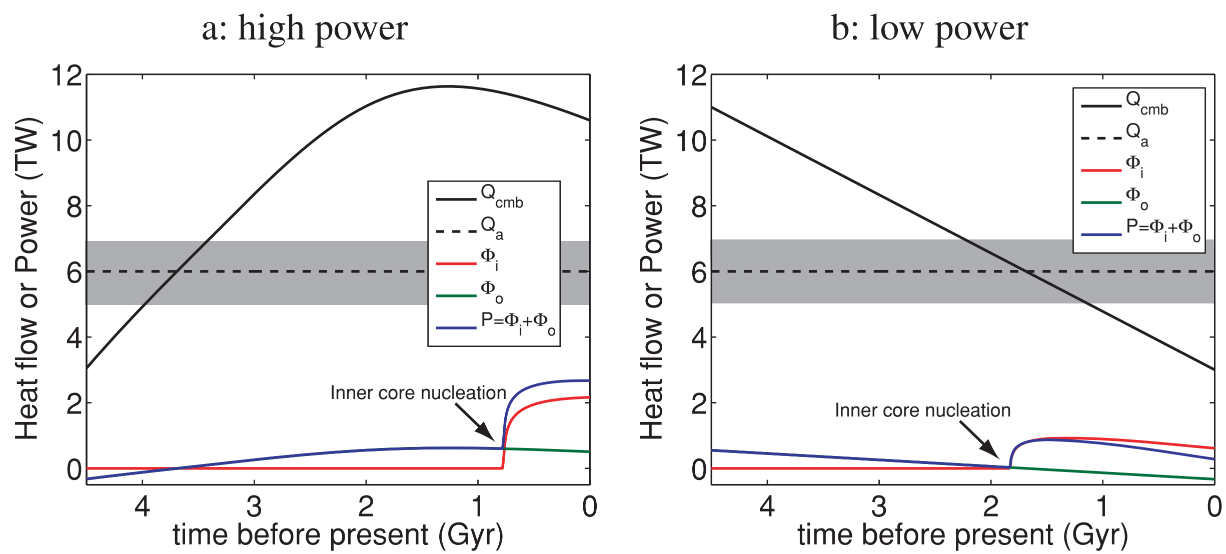


Phase relation is different for each light element.

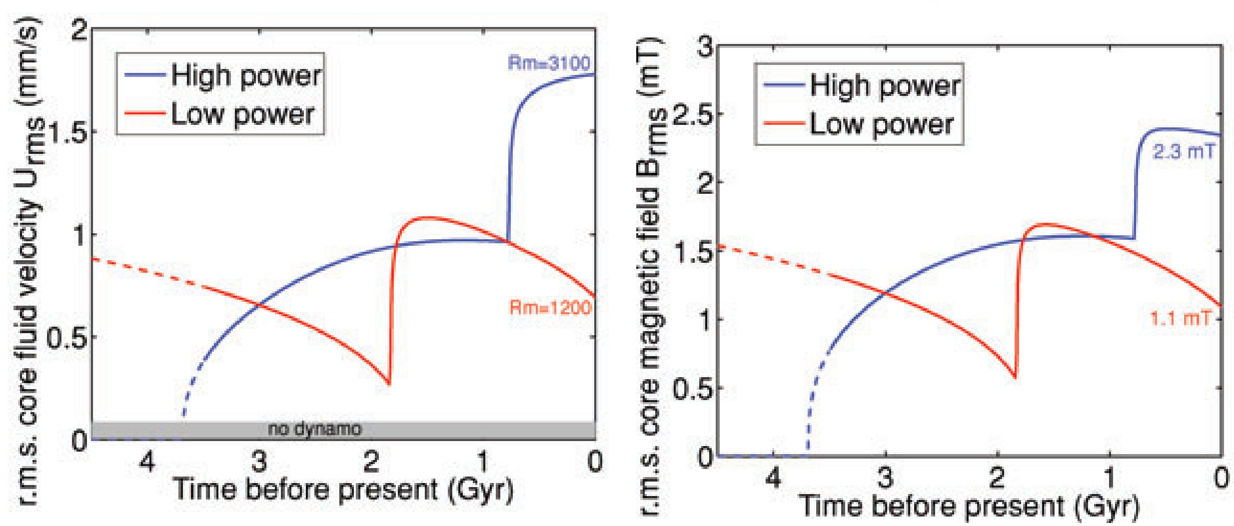
Paleo-geodynamo modeling

thermal history, inner core growth, dynamo

thermal history



flow

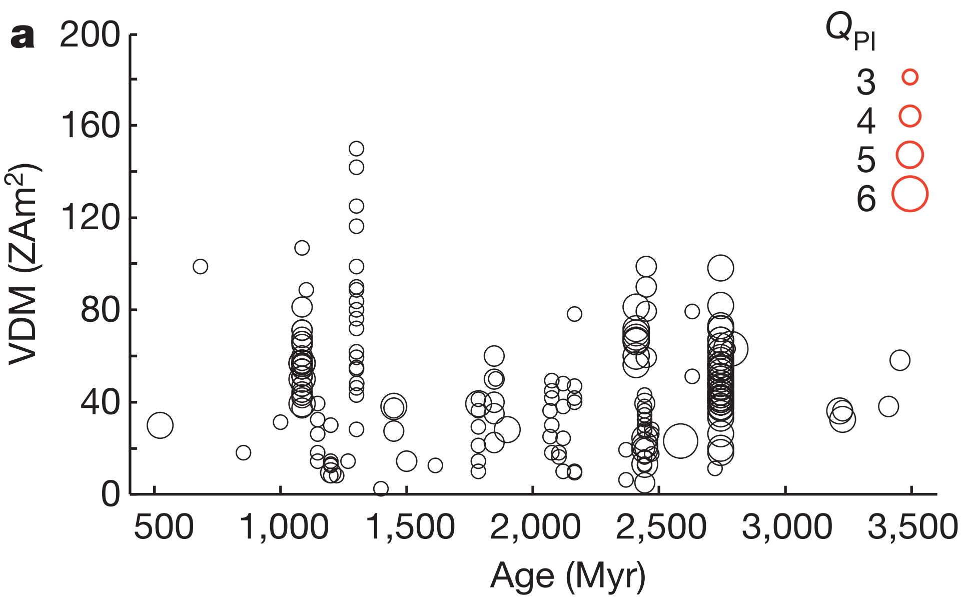


magnetic flux density

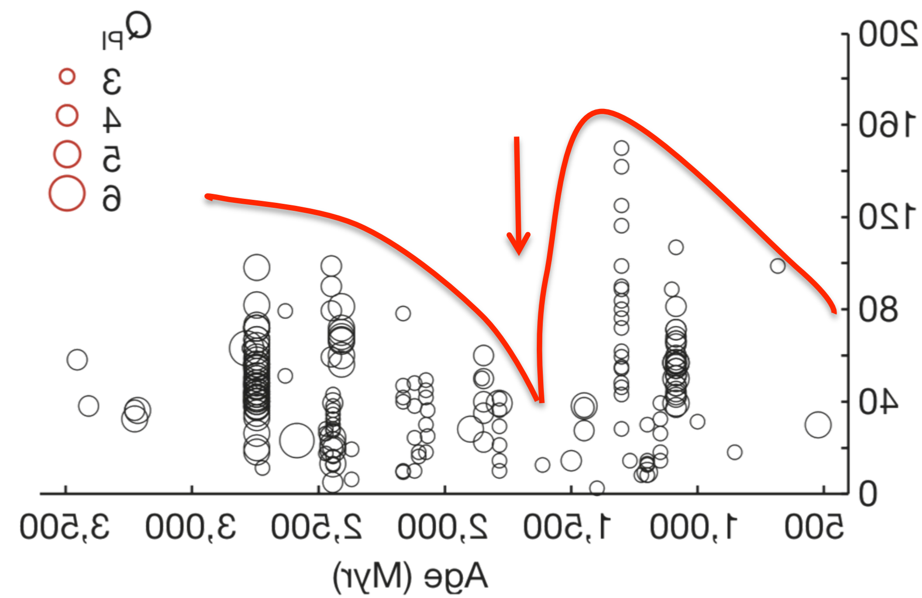
Aubert et al. (2009)

Geomagnetic Field Variation

Paleomagnetic field intensity



Biggin et al. (2015)



Biggin et al. (2015)

inner core nucleation?

“Standing” field and mantle’s heterogeneity (heat flow distribution at the CMB)

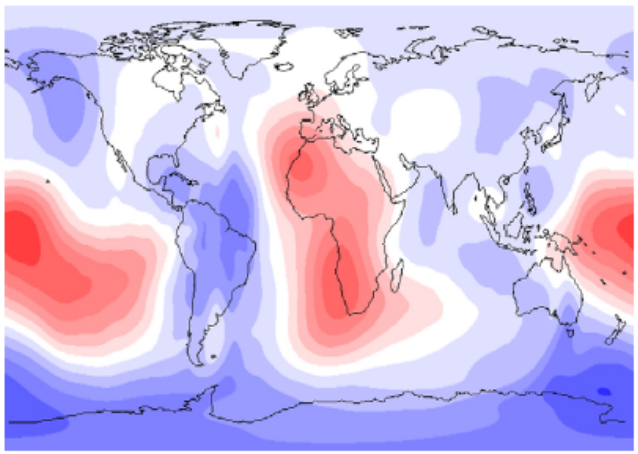
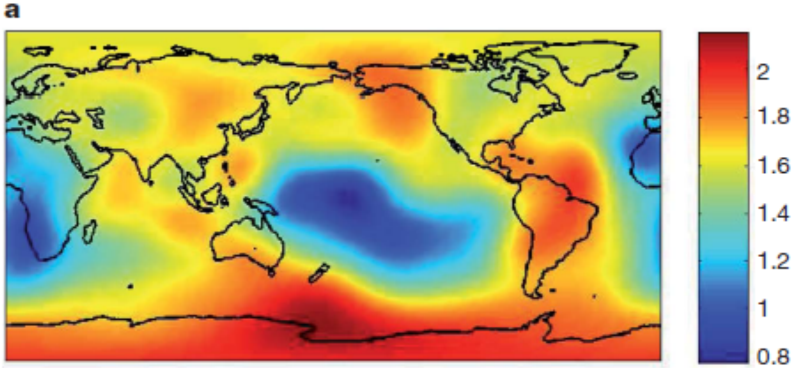


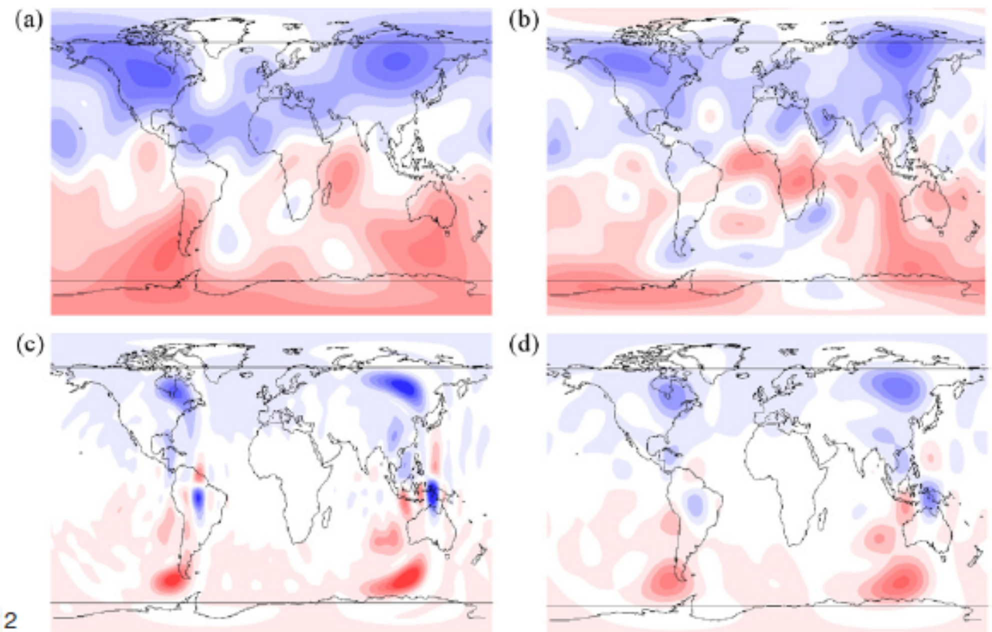
Fig. 1. Shear wave velocity in the lowermost 250 km of the mantle after Masters et al. (1996). Note the longitudes of high velocity, suggesting cold mantle, around the Pacific and particularly beneath Siberia and the Alaska/Canada border.

a



Br @ CMB

1750 1990

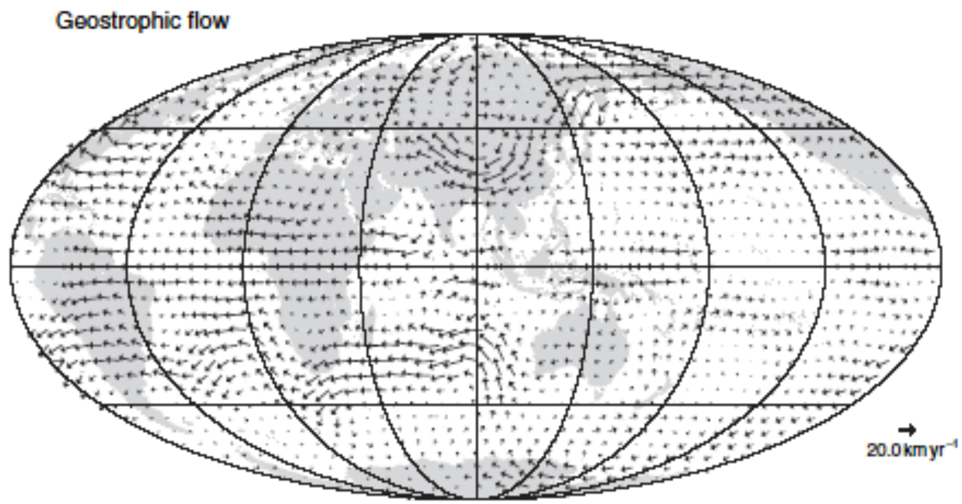


dynamo model w/ heterogeneous CMB heat flux

Gubbins et al. (2007)

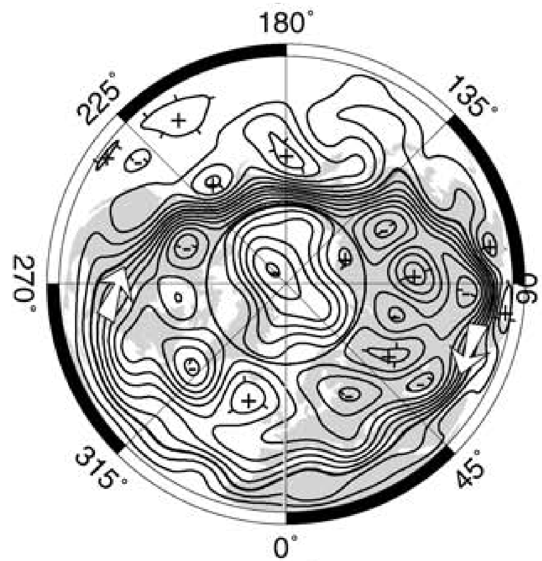
Core-surface flow obtained using geomagnetic field and its secular variation

around year 2002

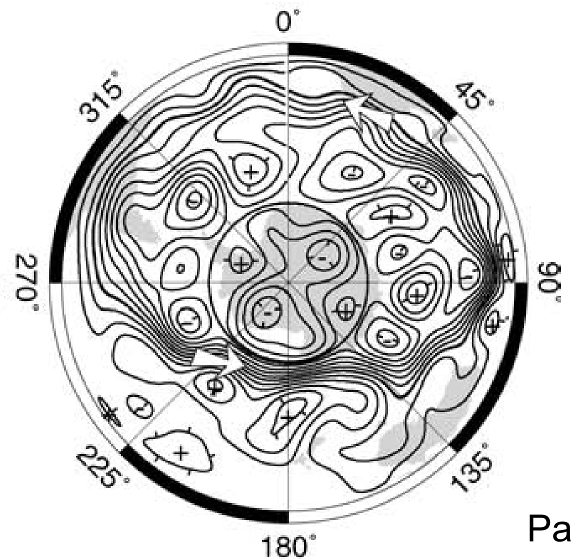


Holme and Olsen (2006)

Northern hemisphere



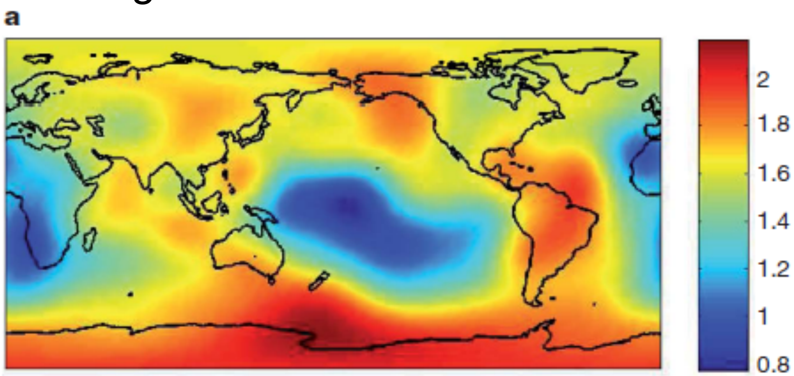
Southern hemisphere

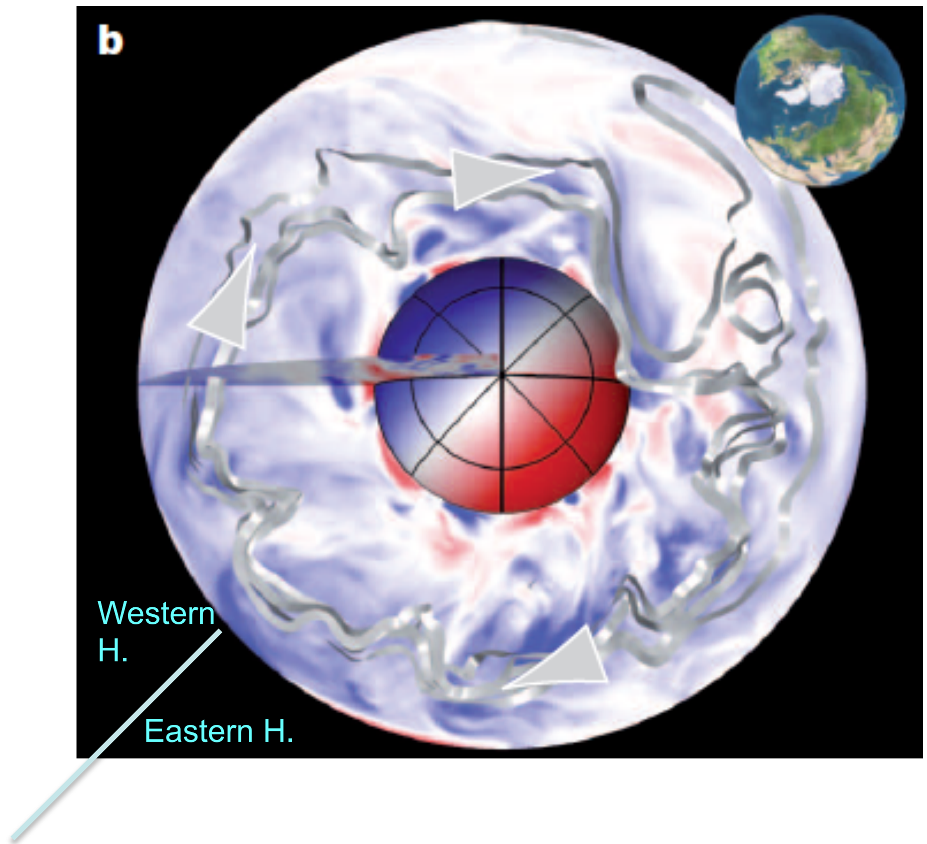


Pais and Jault (2008)

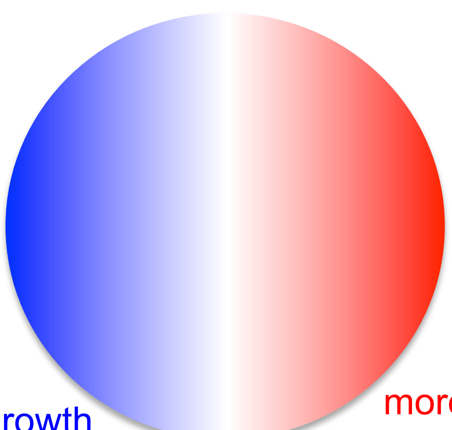
Coupled dynamo and core-flow

Heterogeneous heat flux at the CMB





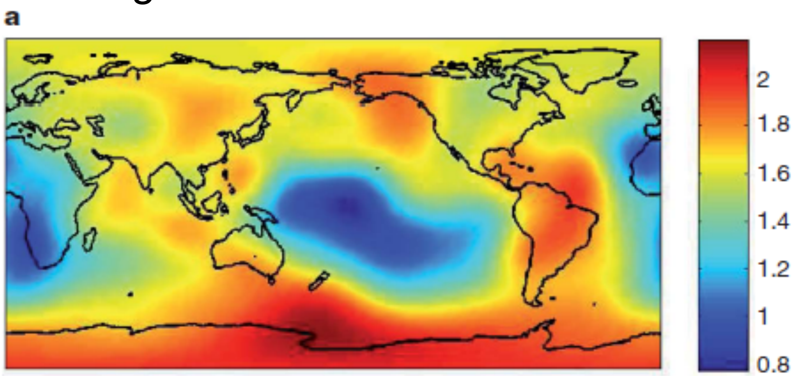
Heterogeneous growth of the inner core



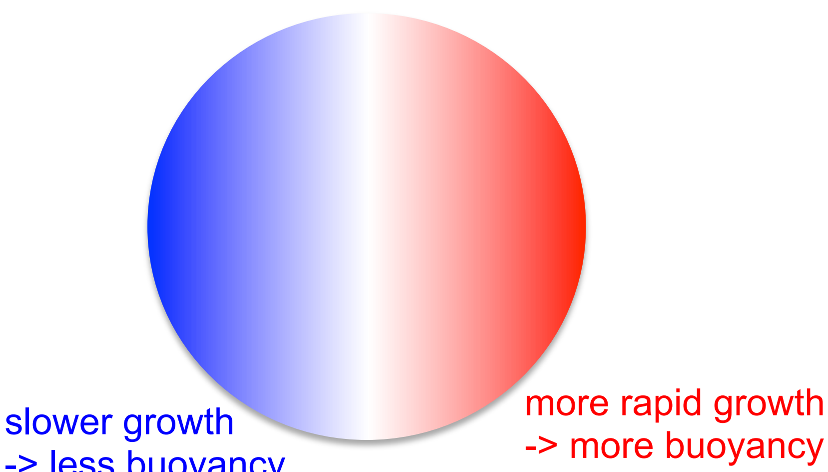
Aubert et al. (2013)

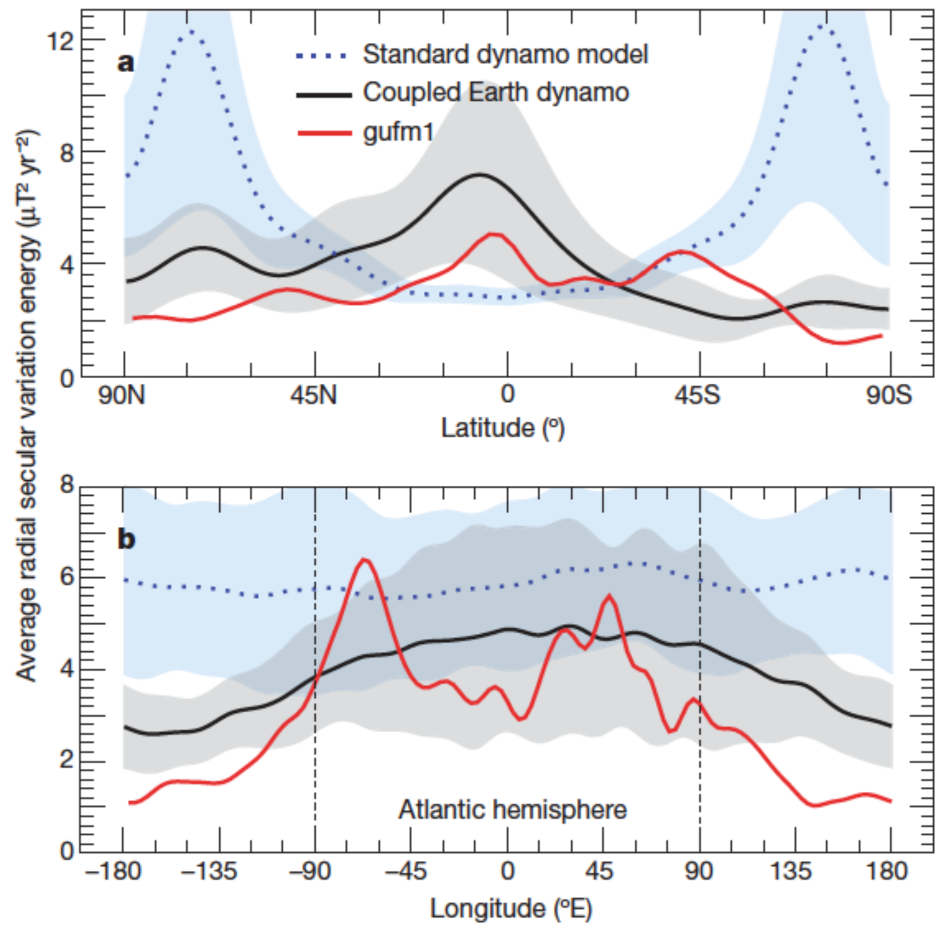
Coupled dynamo and magnetic field distribution

Heterogeneous heat flux at the CMB



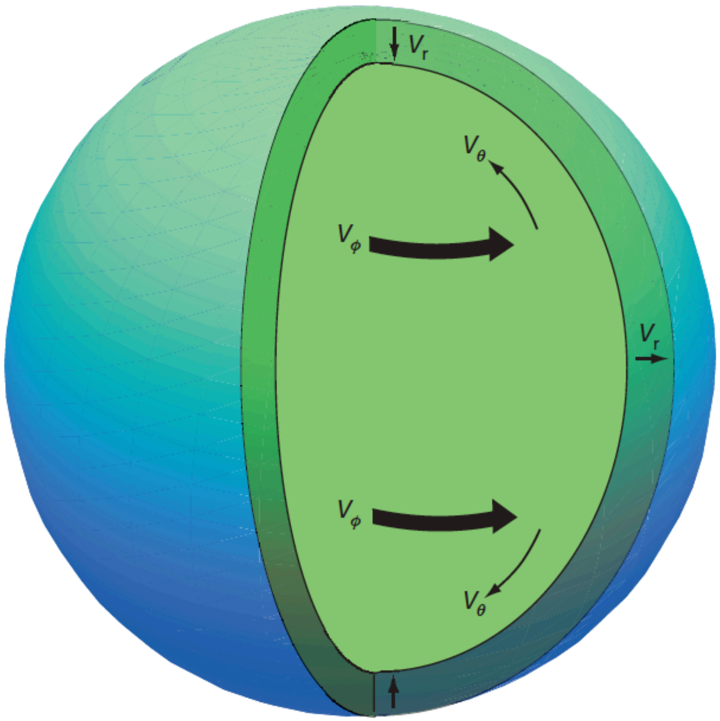
Heterogeneous growth of the inner core





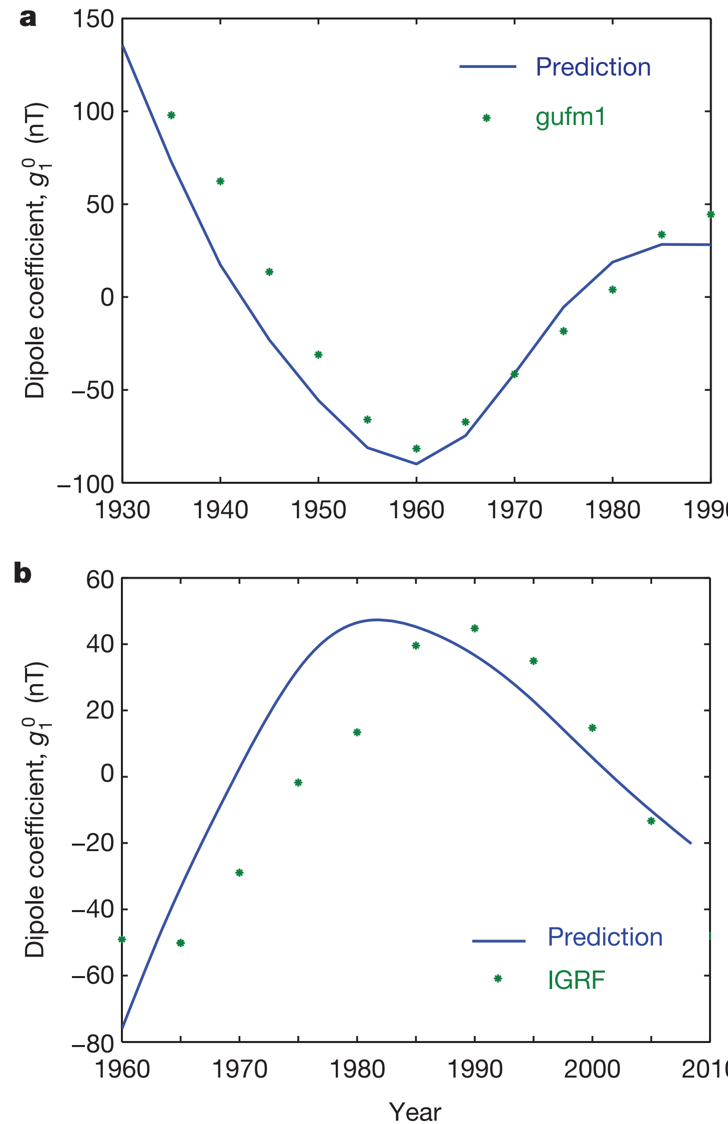
Aubert et al. (2013)

Stable stratification at the core surface and MAC wave



$$d \sim 140 \text{ km}$$

$$N = \sqrt{-\frac{g}{\rho}\frac{\partial \rho}{\partial r}} \sim \Omega$$



Buffett (2014)

Compositional flux and stratification at the core surface

Flux of light material

barodiffusive flux
(to minimize the gravitational potential energy)

Diffusive flux

$$I_D = \rho D g S(r)\left[\rho \frac{dC}{dp} + \frac{\alpha_c}{\mu_c}\right]$$

$$S(r) = 4\pi r^2$$

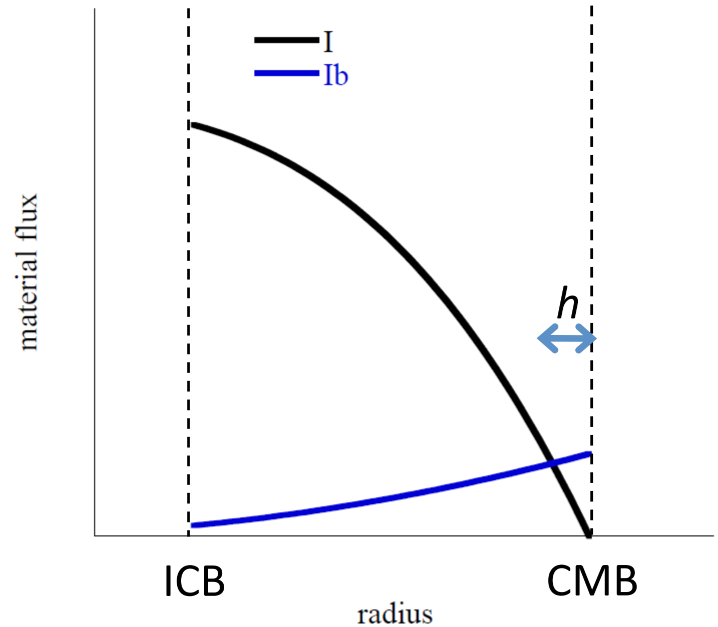
Well-mixed quasi-steady state

$$I = \frac{\Delta\rho \dot{M}}{\rho_i \alpha} \frac{r_o^3 - r^3}{r_o^3 - r_i^3}$$

Thickness of the stratified layer

$$h = \frac{g_o V_o \rho_i \rho D \alpha_c^2}{\mu_c \Delta\rho \dot{M}}$$

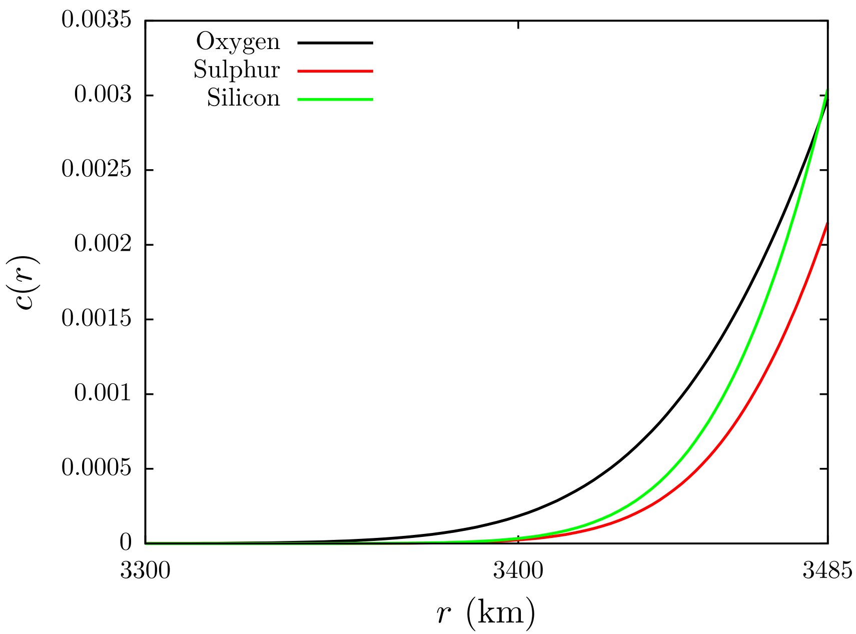
(mofidied from Loper and Roberts, 1983)

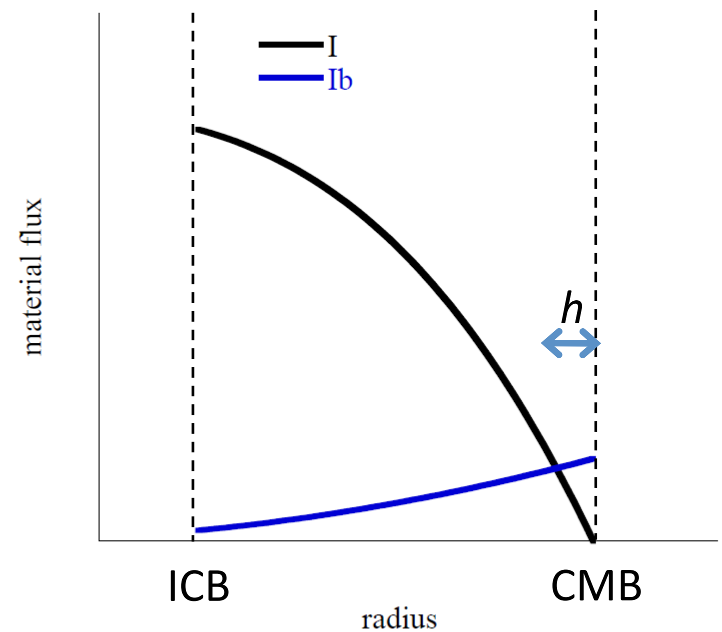


compositional stratification at the core surface
diffusivities? Δρ at the ICB?

Note: thermal stratification may also exist.

Compositional flux and stratification at the core surface





Gubbins and Davis (2013)

compositional stratification at the core surface

diffusivities? $\Delta\rho$ at the ICB?

Note: thermal stratification may also exist.

Summary

- Composition of the outer core (light element) may influence geodynamo through

  - growth of the inner core
    amount of buoyancy to drive compositional convection
    heterogeneous growth of the inner core

  - and thermal conductivity.

- Geodynamo modeling results and geomagnetic secular variation support heterogeneous growth of the inner core.

- Decadal scale geomagnetic field variation support the existence of stably stratified layer at the core surface.

- It is not known the diffusivities and phase diagram employed for geodynamo modeling are appropriate to represent the outer core. We need

  - experiments and modelings to estimate diffusivities and phase diagram of Fe alloy in core condition

  - to constrain light elements existing in the core using various methods.