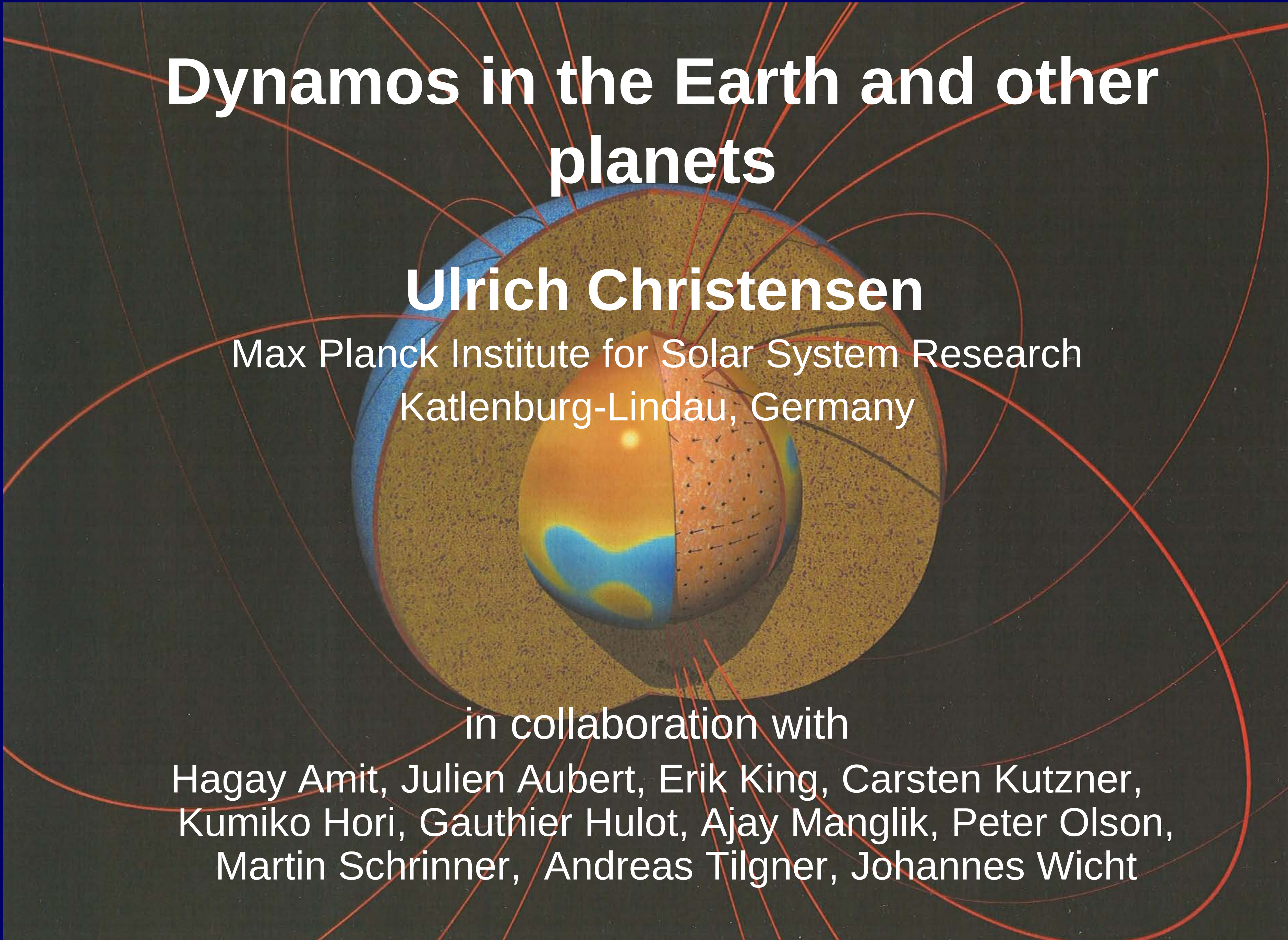

Dynamos in the Earth and other planets

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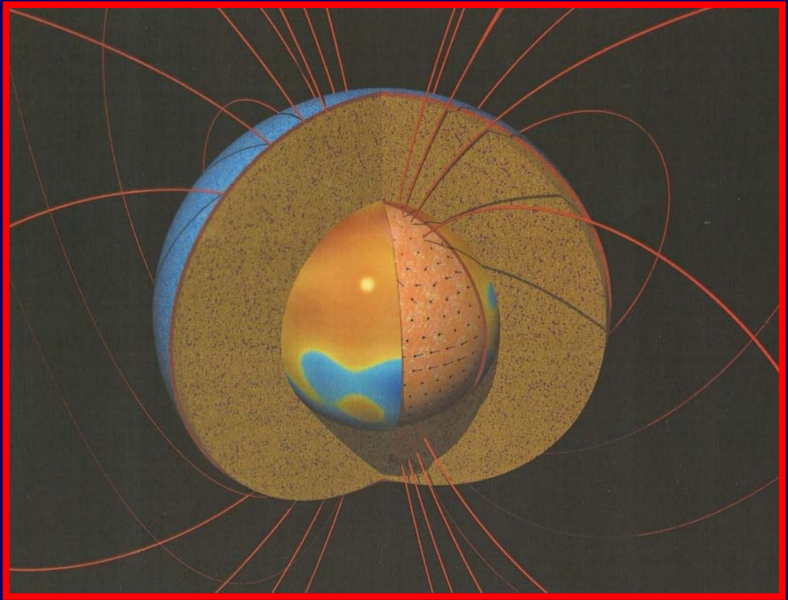
in collaboration with

Hagay Amit, Julien Aubert, Erik King, Carsten Kutzner, Kumiko Hori, Gauthier Hulot, Ajay Manglik, Peter Olson, Martin Schrinner, Andreas Tilgner, Johannes Wicht

Magnetic fields: Probes into the deep interiors of planets

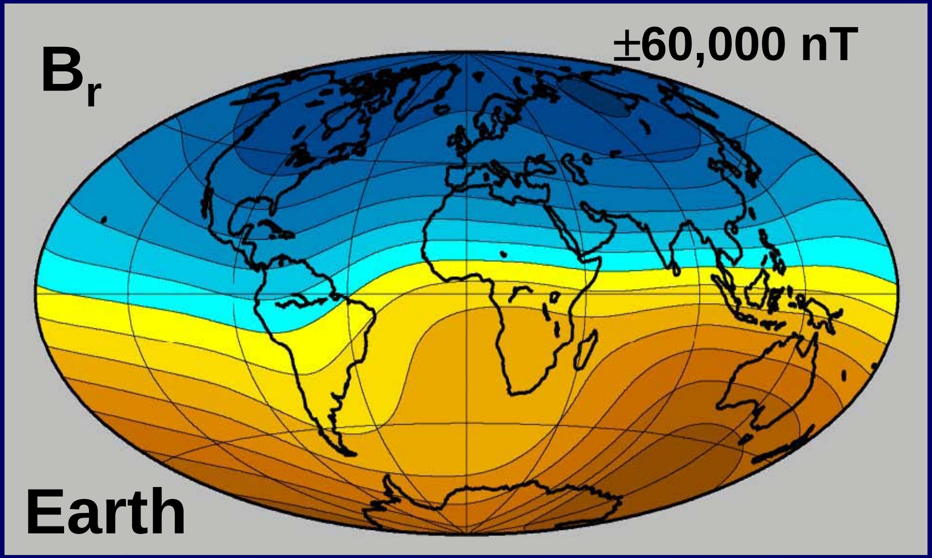
- Information pertaining to the deep interior of other planets scarce



- Field tells something on interior structure, energy budget and thermal evolution

- Understanding dynamo needed for interpretation

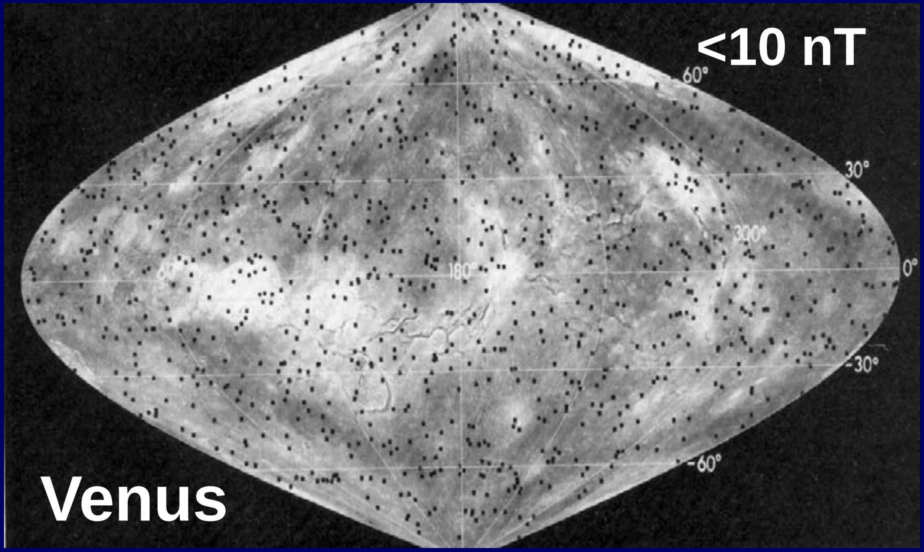
Global magnetic field

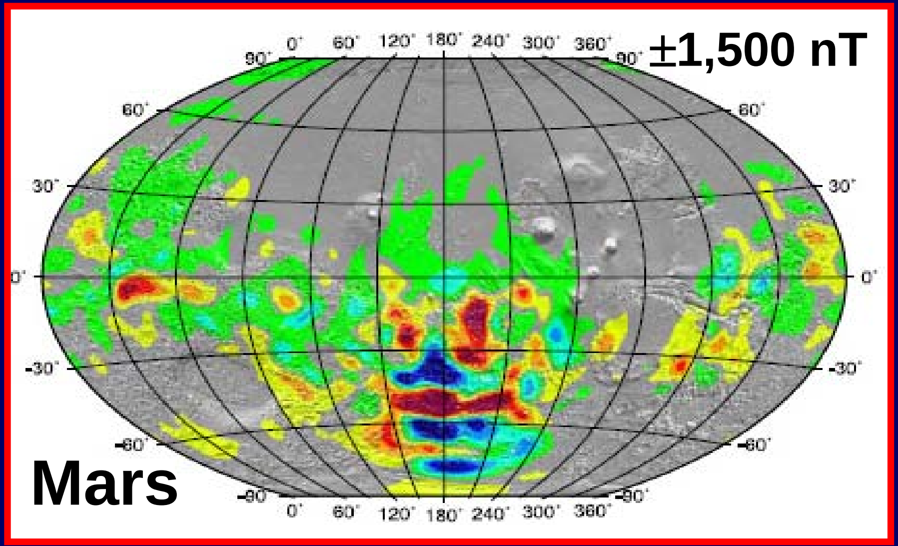


... at most planets

Except Mars & Venus.

Why ?

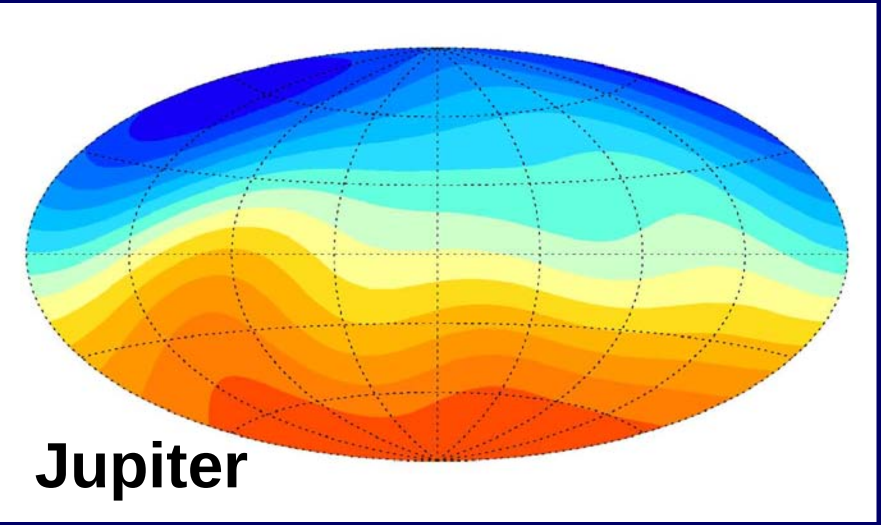


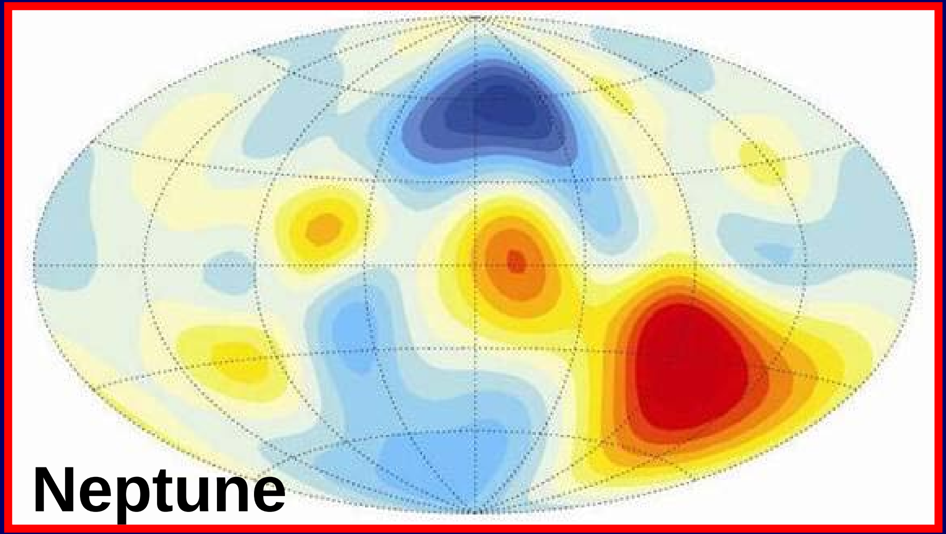


Dominant axial dipole

... at most planets

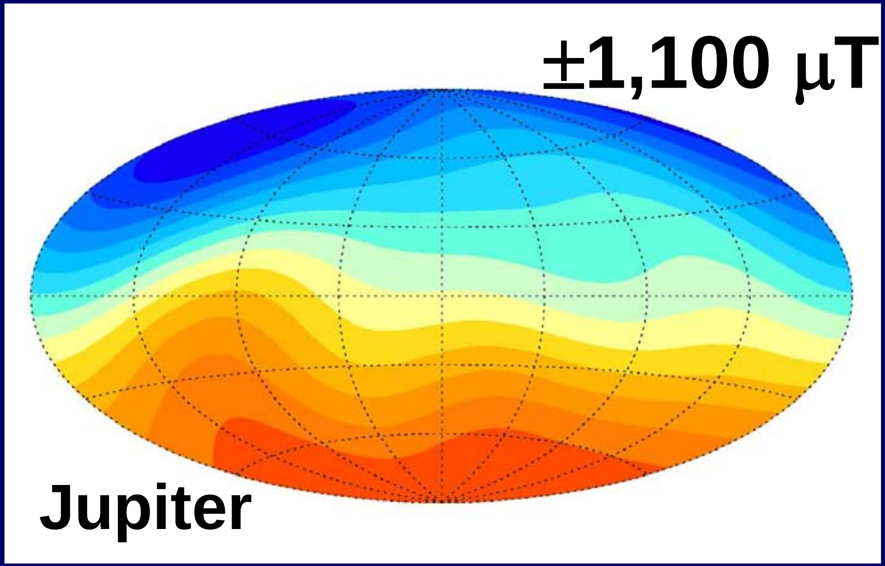
Except Uranus and Neptune

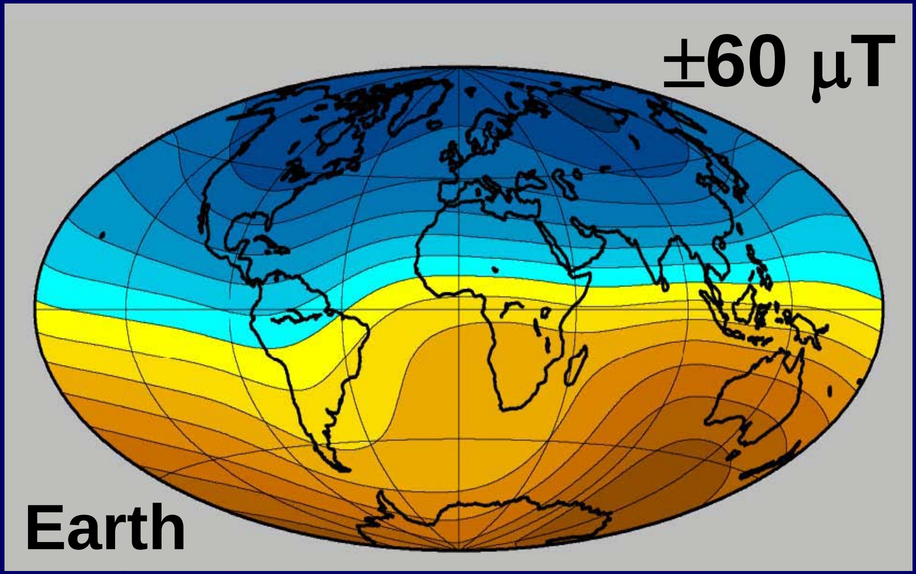


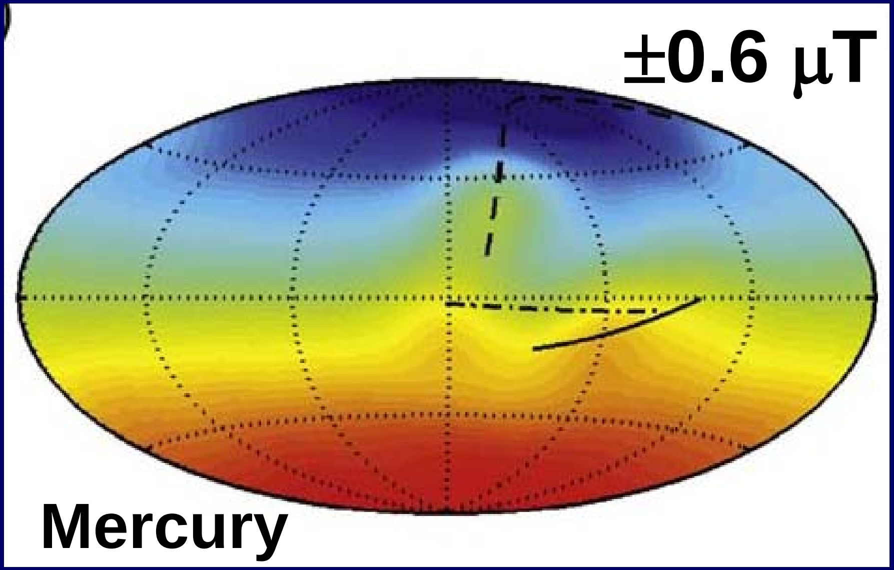


Holme and Bloxham, 1998

Huge range in field strength



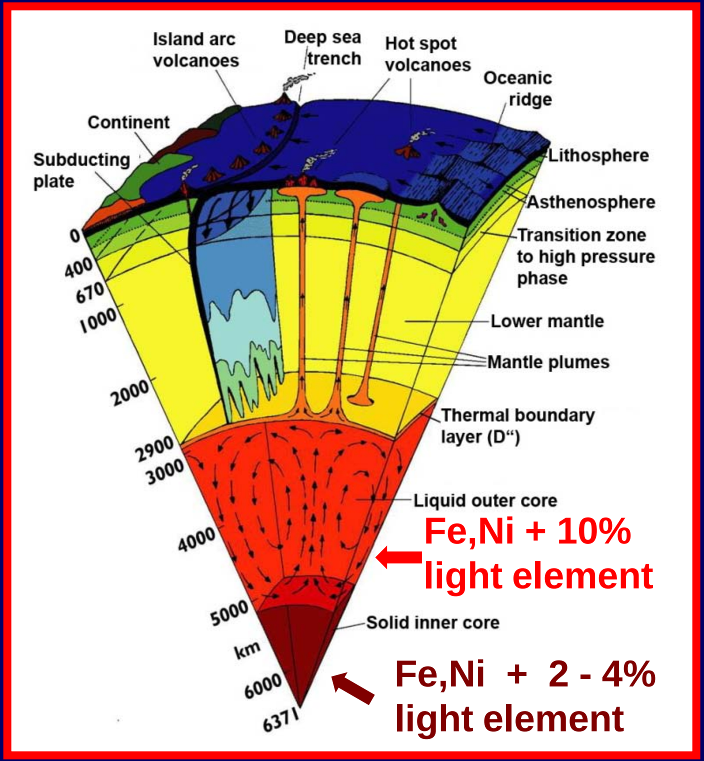




Why is Mercury's field so weak ?

Requirements for dynamo

- **Fluid electrically conducting layer** **(iron core in terrestrial planets)**
- **Sufficiently rapid motion: magnetic Reynolds number $Rm = UR/\eta > 50$** **(thermal / compositional con-vection, Earth: Rm ~ 1000)**
- **Suitable pattern of motion, e.g. helical** **(Coriolis forces important)**



Why lack Mars and Venus a dynamo ?

Core entirely frozen ? **Unlikely**

Thermal evolution modeling; Mars: tidal Love number k_2

Rotation too slow (Venus) ? **Unlikely**

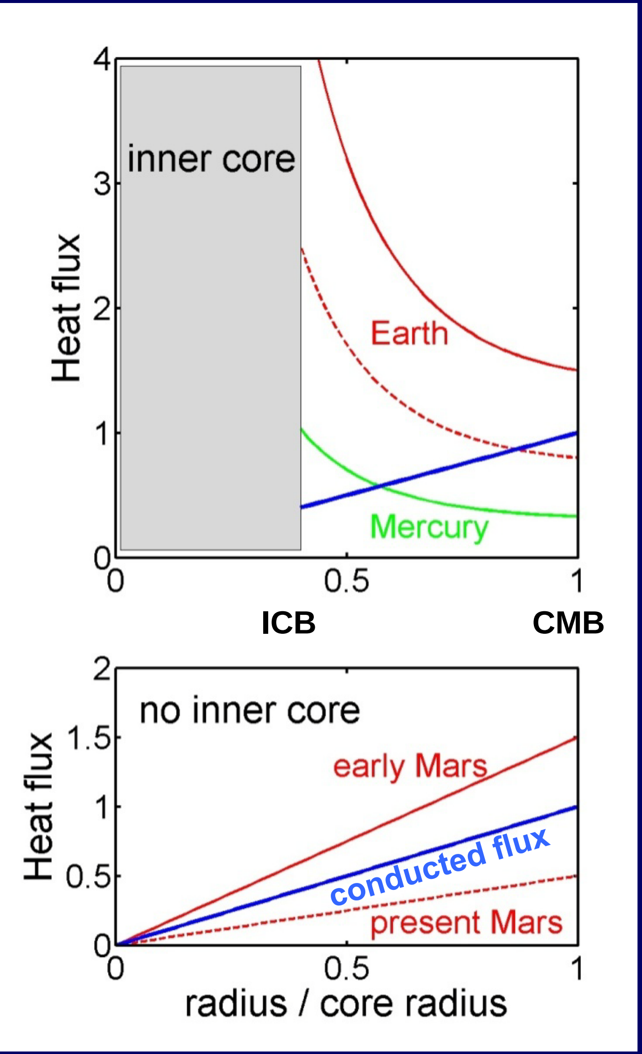
Coriolis force still plays significant role in force balance

Core not convecting ? **Likely**

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

- Mantle convection controls heat flux out of core. Mantle is master, core is slave.
- Large heat flux q_{cond} conducted along adiabatic T gradient (blue line)
- Growing solid inner core can drive dynamo, even if $q < q_{cond}$ at CMB: latent heat and light element flux
- Mars & Venus $q < q_{cond}$ likely
- Lack of inner core likely in Mars and Venus (slower cooling)
- Early Martian dynamo driven by $q > q_{cond}$. It stopped when $q < q_{cond}$



What determines magnetic field strength, morphology, reversals ?

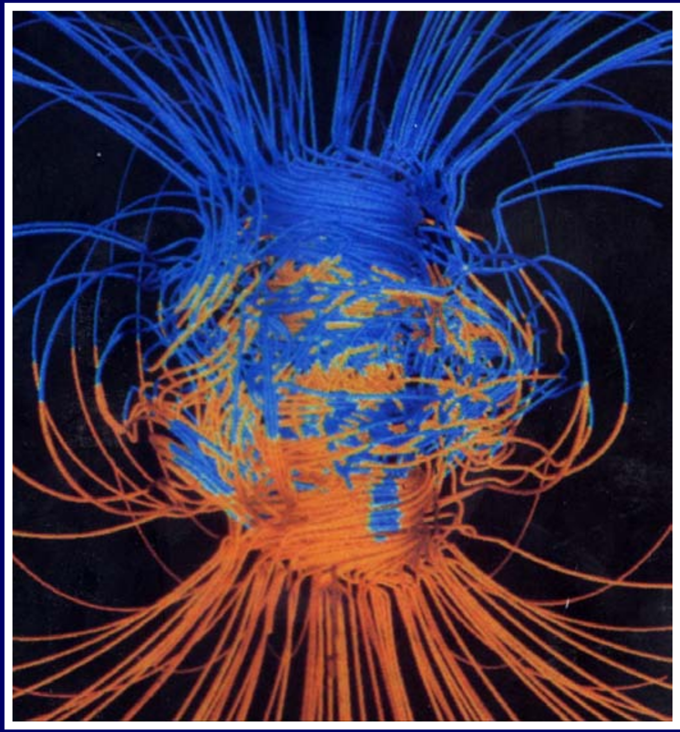
- Systematic variation of dynamo properties with control variables such as rotation rate, heat flux, electrical conductivity, ...   ?
- Special conditions in the dynamo region of each individual planet ?
- A combination of both ?

Geodynamo modeling

The first numerical mantle convection models (2D in Cartesian box) have been published around 1970.

The first convincing models of the geodynamo were published in 1995. Why did it take so long?

Cowling's theorem: A homogeneous dynamo cannot generate an axisymmetric magnetic field. The field (hence the numerical set-up) must be 3D.



Glatzmaier & Roberts, 1995

Planetary dynamo models

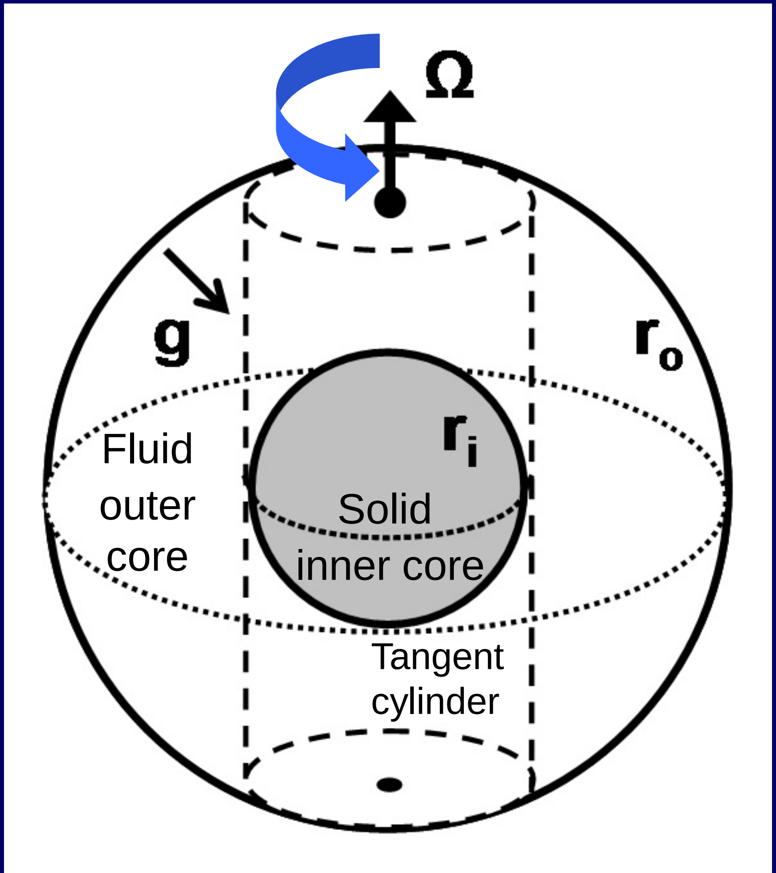
solve equations of thermal / compositional convection and magnetic induction in a rotating and electrically conducting spherical shell

Success of geodynamo models:

reproduce morphology and strength of geomagnetic field, secular variation, reversals, ...

even though

some control parameters are very different from real Earth parameters



Governing equations

$$\left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u}\right) + 2\vec{e}_z \times \vec{u} + \vec{\nabla} P = E \nabla^2 \vec{u} + Ra^* \frac{\vec{r}}{r_o} T + (\vec{\nabla} \times \vec{B}) \times \vec{B}$$

Inertia Coriolis Viscosity Buoyancy Lorentz

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \vec{\nabla} T = \frac{E}{Pr} \nabla^2 T$$

Advection Diffusion

$$\frac{\partial \vec{B}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{B} = \vec{B} \cdot \vec{\nabla} \vec{u} + \frac{E}{Pm} \nabla^2 \vec{B}$$

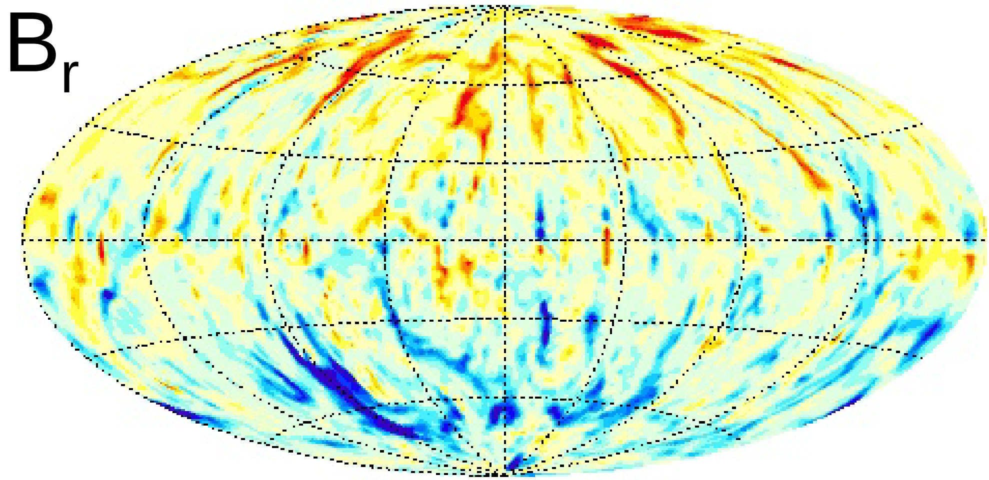
Advection Induction Diffusion

$$\vec{\nabla} \cdot \vec{u} = 0 \qquad \vec{\nabla} \cdot \vec{B} = 0$$

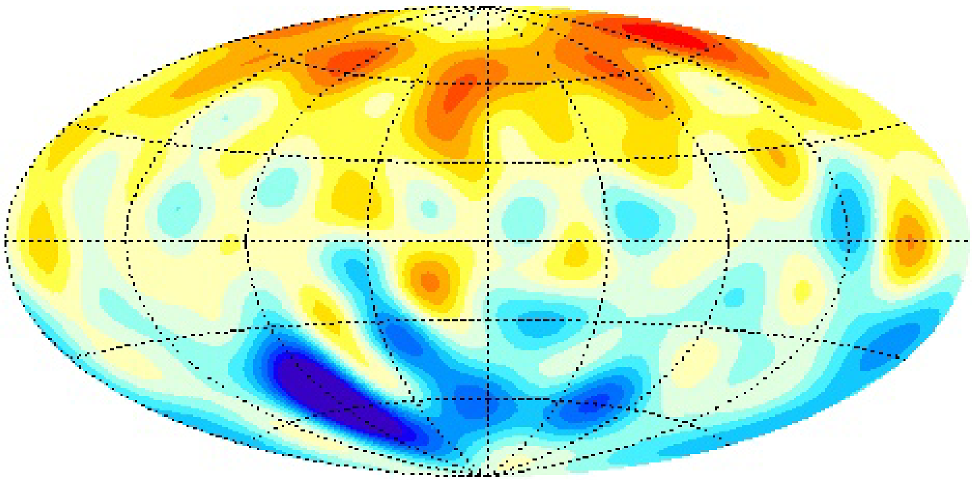
Control parameter values

	Name	Force balance	Earth value	Model values
Ra*	Rayleigh number	Buoyancy / Retarding forces	5000 x critical	< 100 x critical
E	Ekman number	Viscosity / Coriolis force	10^{-14}	$\geq 10^{-6}$
Pr	Prandtl number	Viscosity / Thermal diffusion	0.1 - 1	0.1 - 10
Pm	Magnetic Prandtl #	Viscosity / Magnetic diffusion	10^{-6}	0.06 - 10

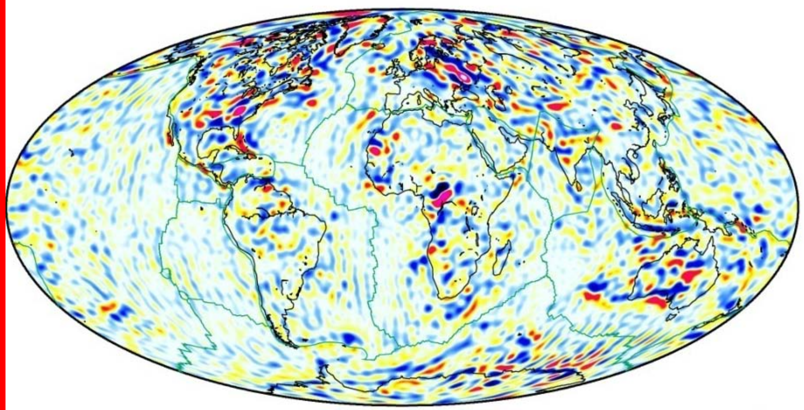
Magnetic field morphology



Dynamo model, full resolution

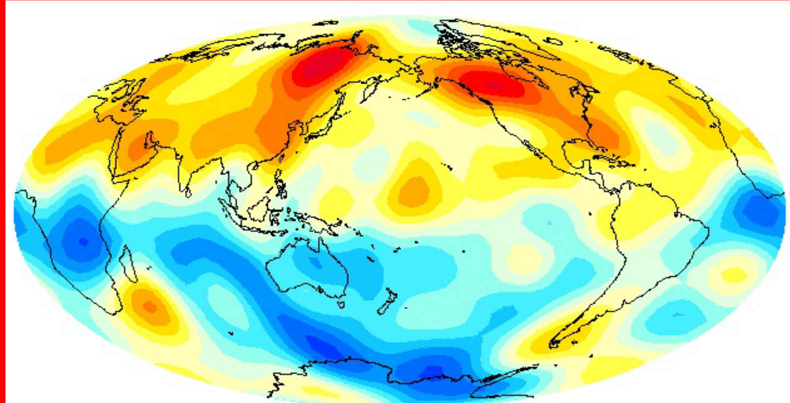


Dynamo model, filtered

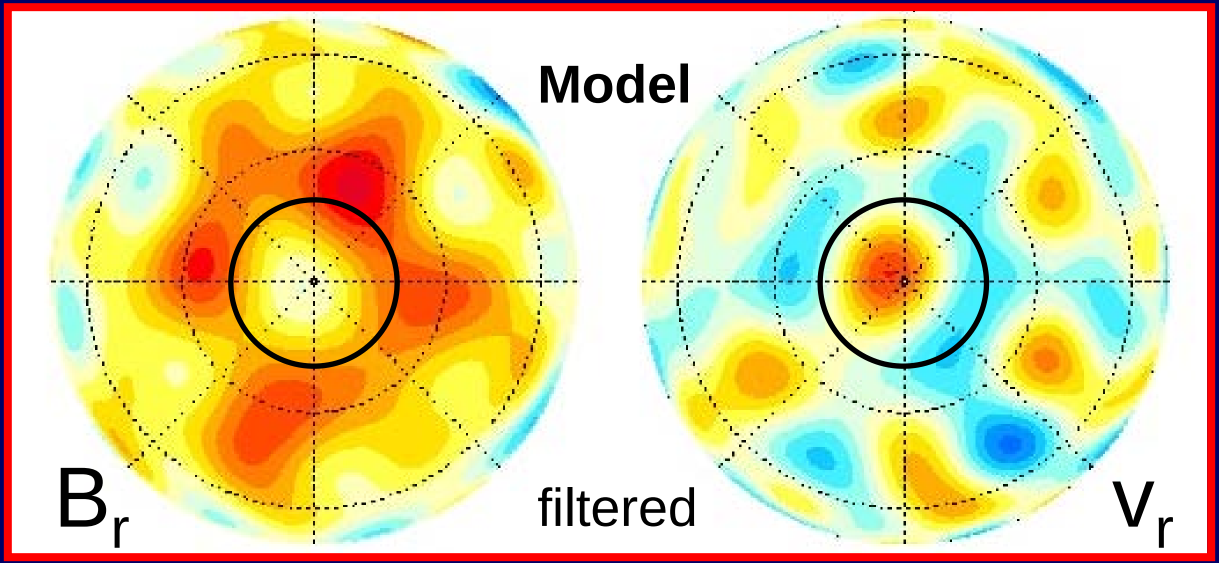


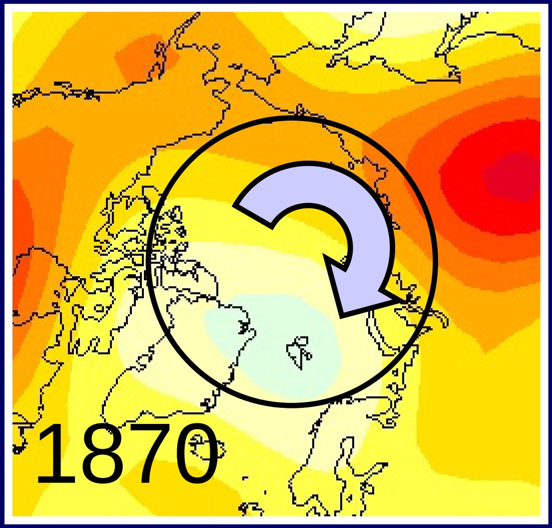
Crustal field masks small-scales of core field

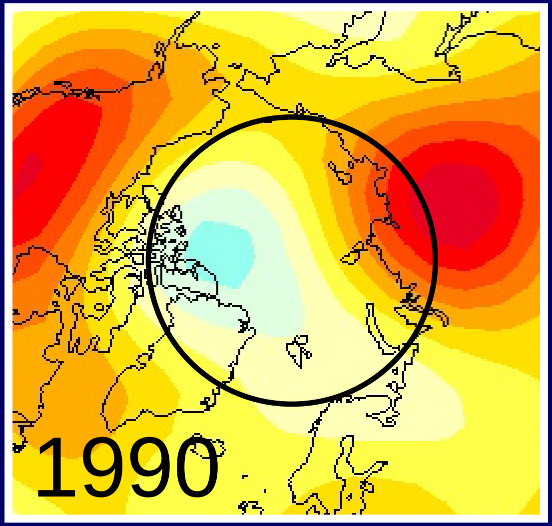
Earth‘s field at core-mantle boundary

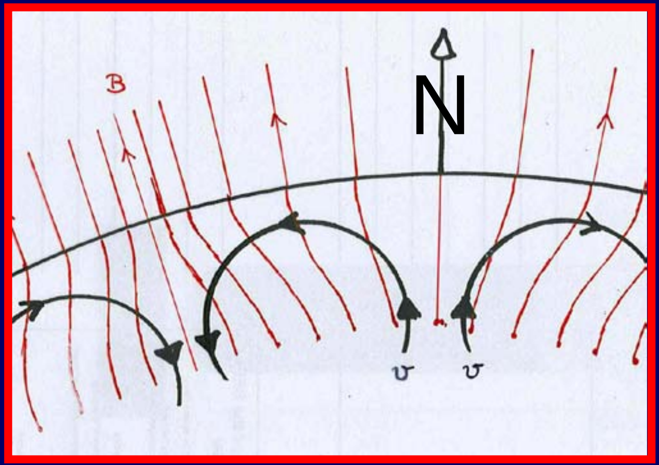


Field structure & core dynamics

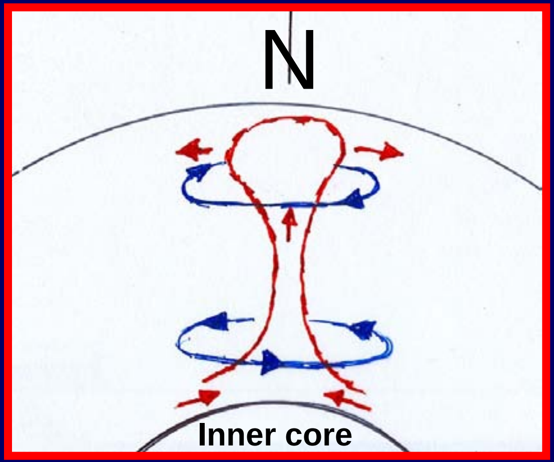








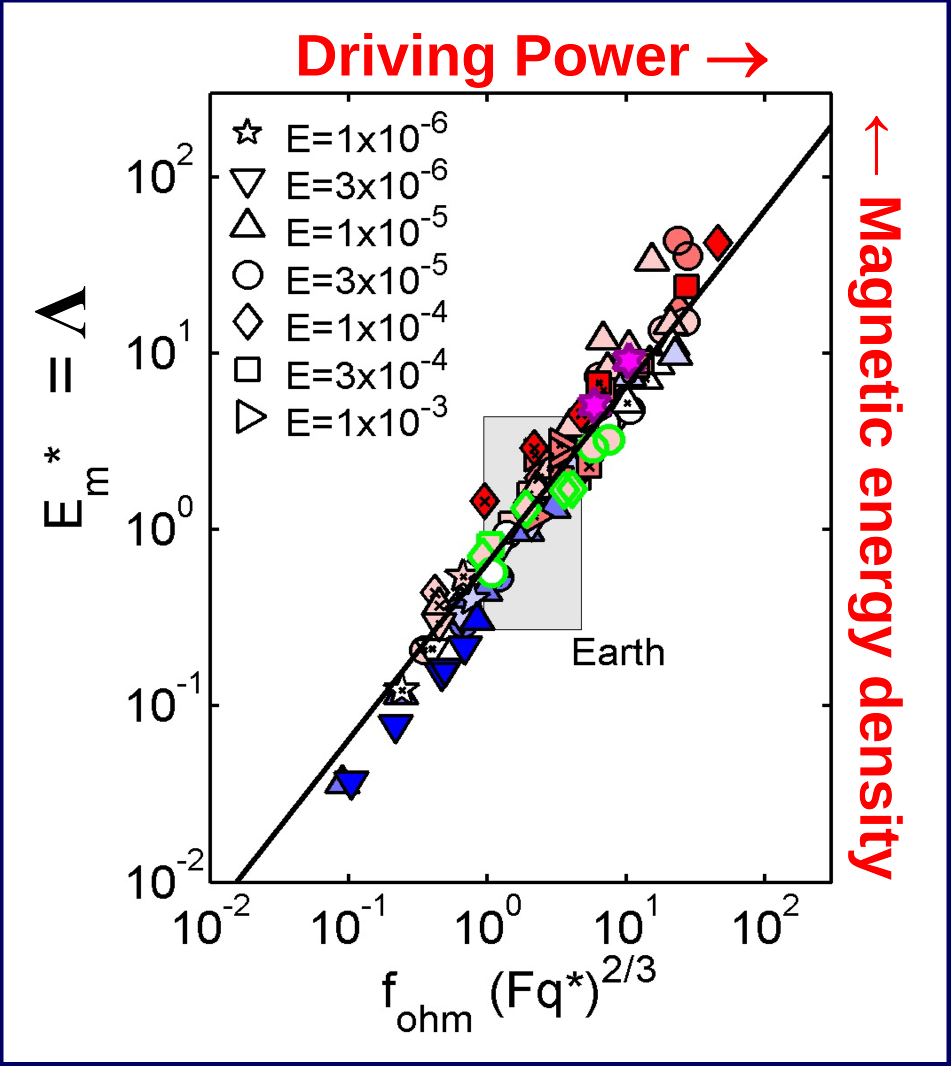
Advection of fieldlines



Polar plume

Earth's field N polar cap

Magnetic field strength



q^* : non-dimensional heat flux

F: thermodynamic efficiency

f_o: ohmic / total dissipation

E_m^*: non-dim. magnetic energy density = Elsasser #

$$E_m^* = 0.63\, f_o\, (Fq^*)^{2/3}$$

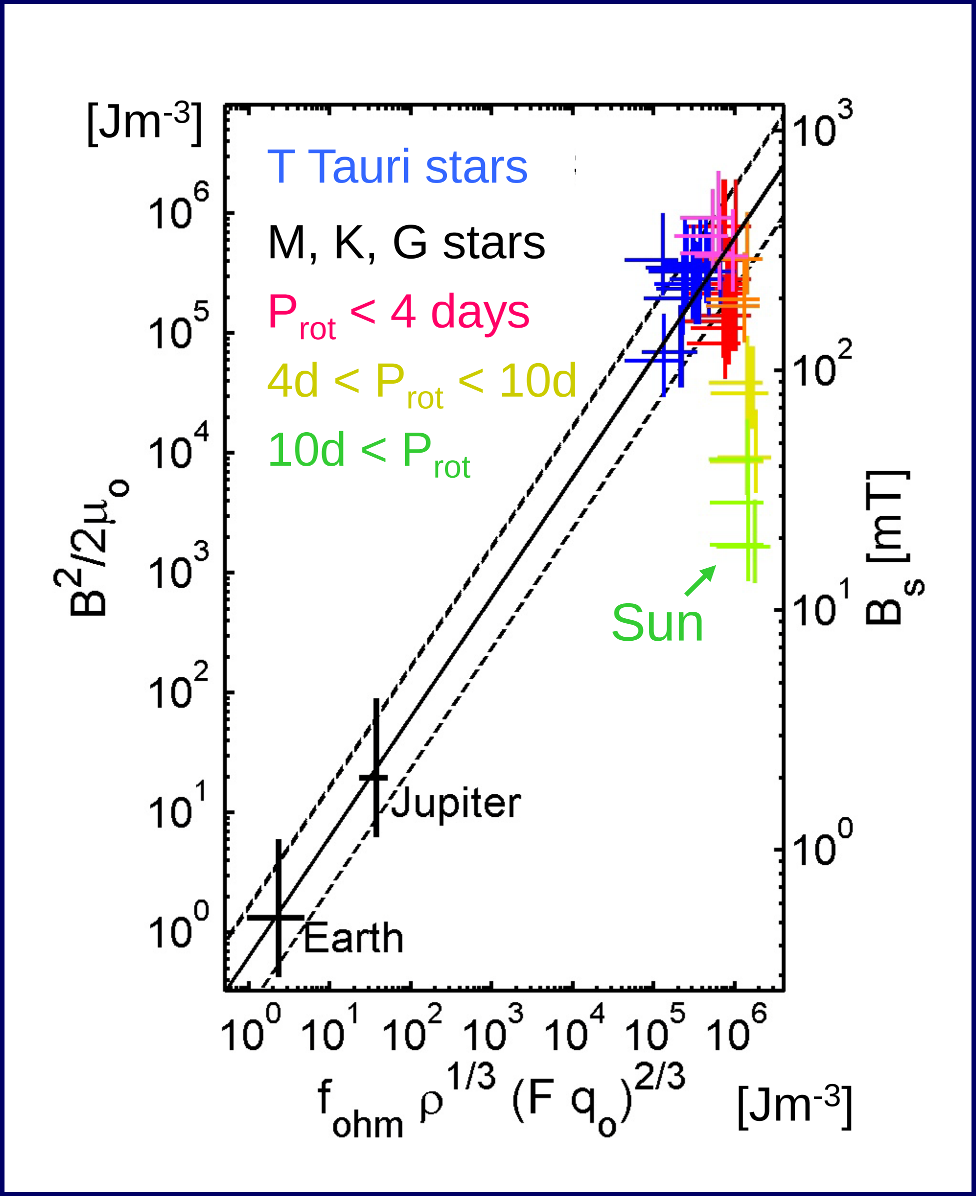
in dimensional form:

$$B^2 = 1.2 \mu_o\, f_o\, \rho^{1/3}\, (Fq)^{2/3}$$

Christensen & Aubert, GJI, 2006

Christensen et al., Nature, 2009

Planets and stars



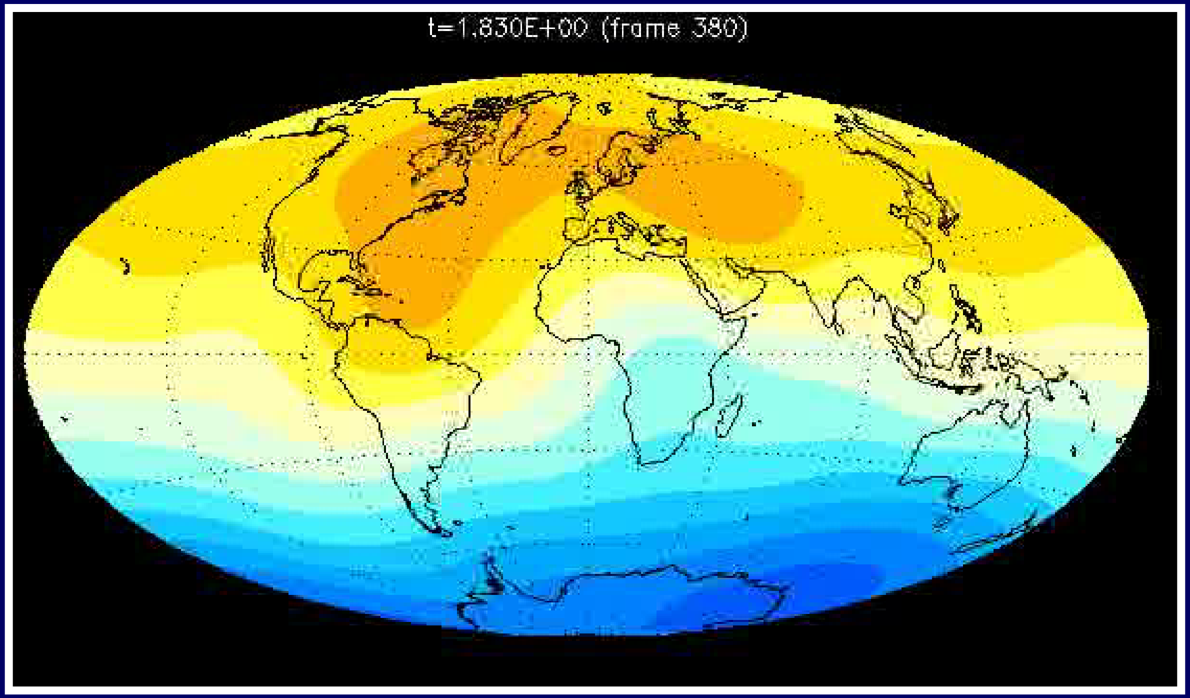
The observed fields of rapidly rotating low-mass stars agree with the prediction as well as that of Jupiter and Earth

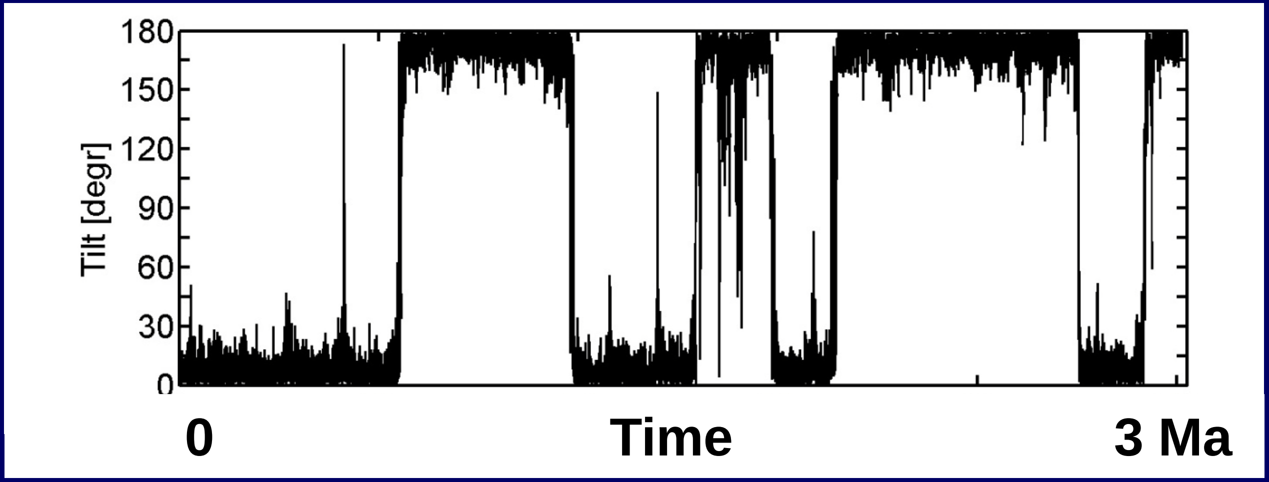
⇒ confirmation for scaling law

⇒ dynamos in planets and (some) stars may be similar

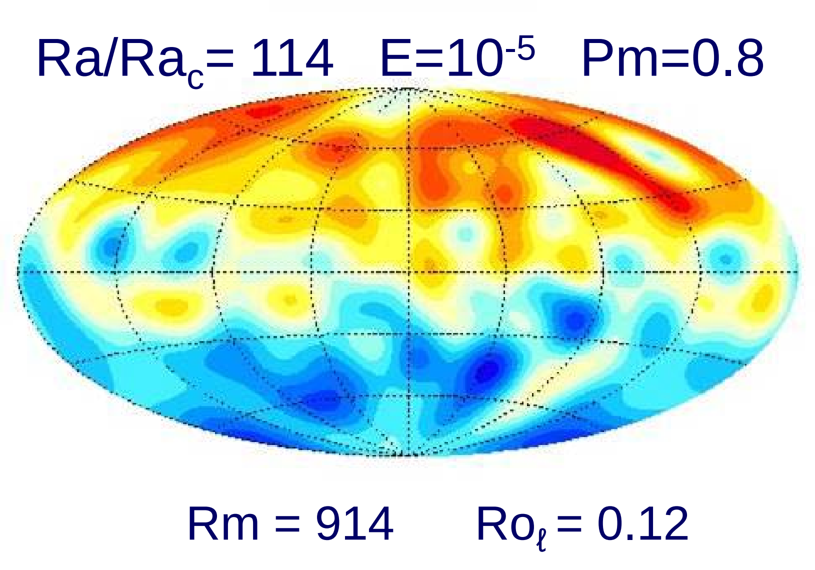
Christensen et al, Nature, 2009

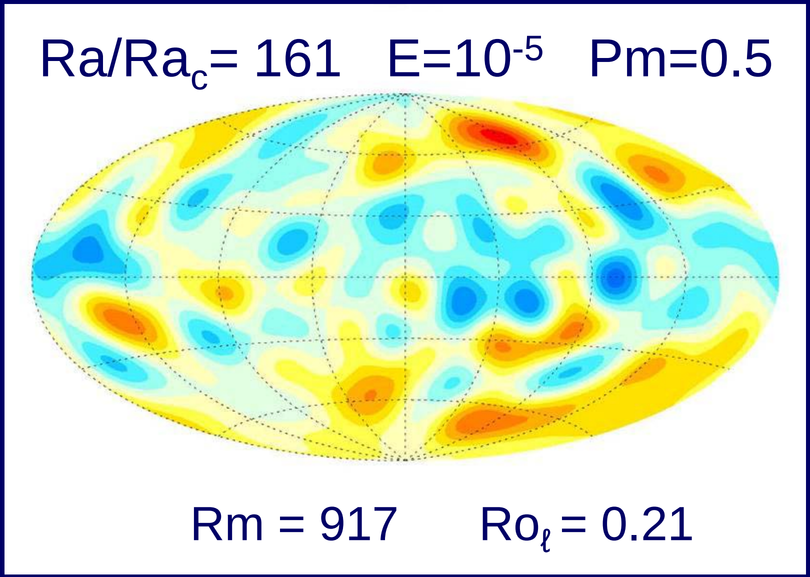
Geomagnetic reversals

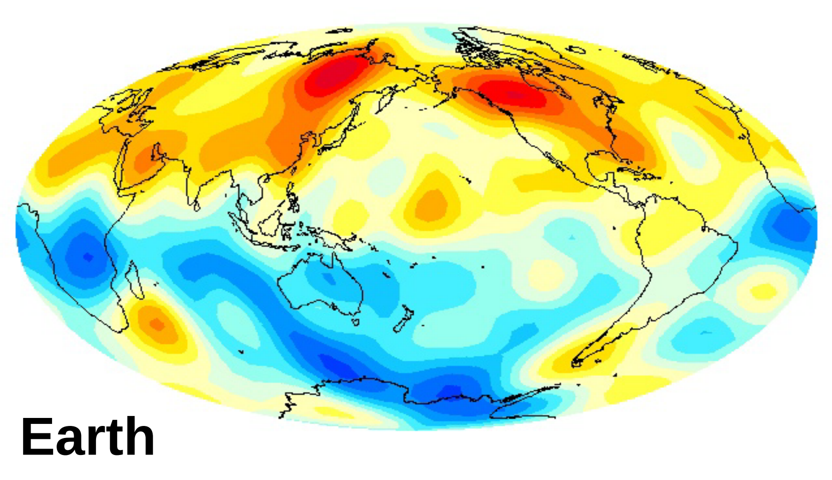


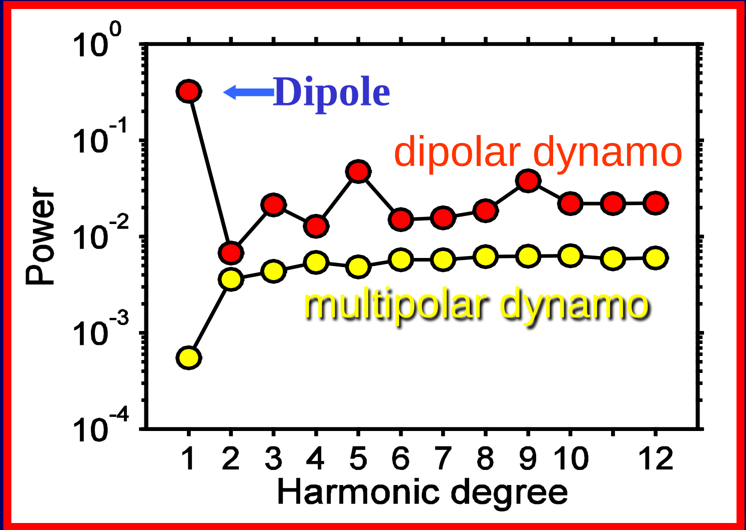


Field morphology: two regimes

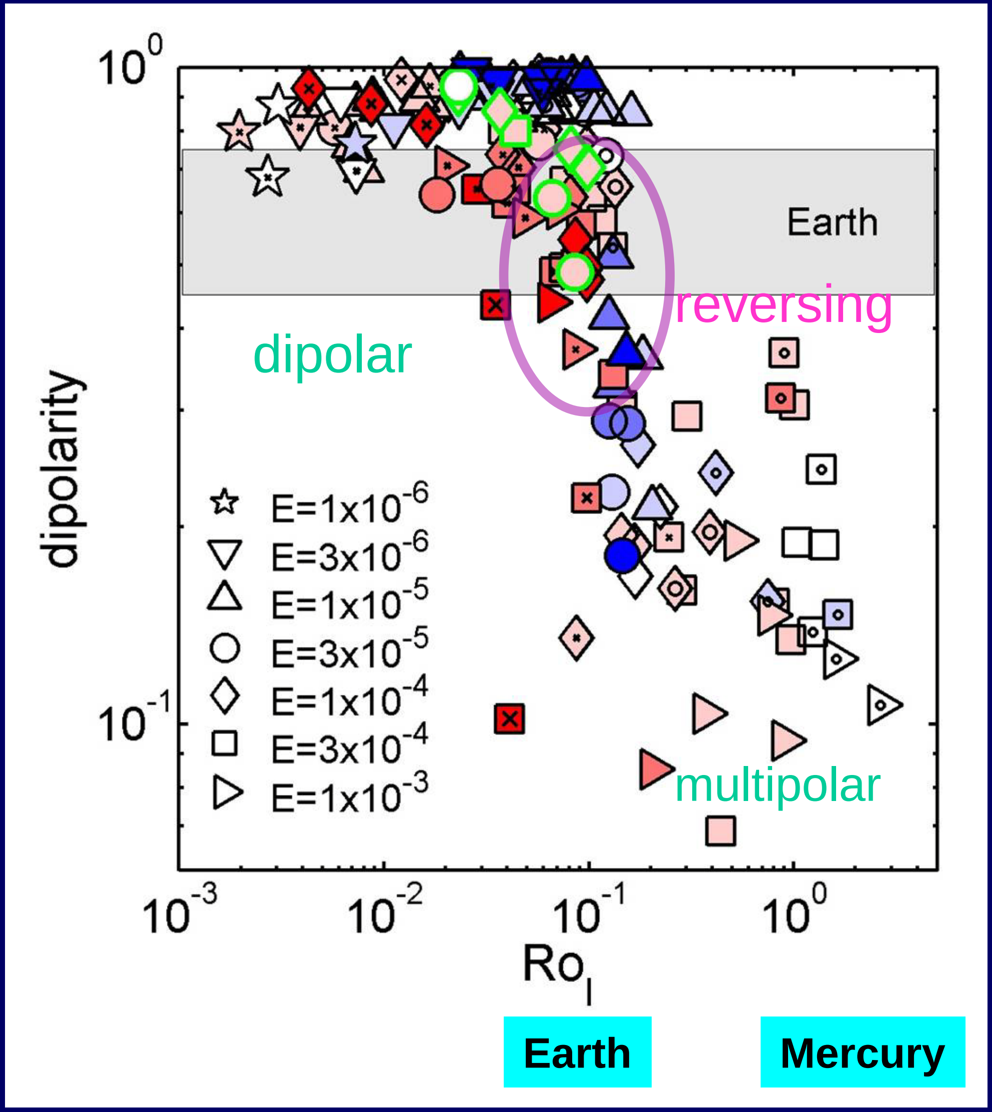








Morphology controlled by rotation



Inertial vs. Coriolis force:

Rossby number Ro_ℓ calculated with mean length scale ℓ in the kinetic energy spectrum

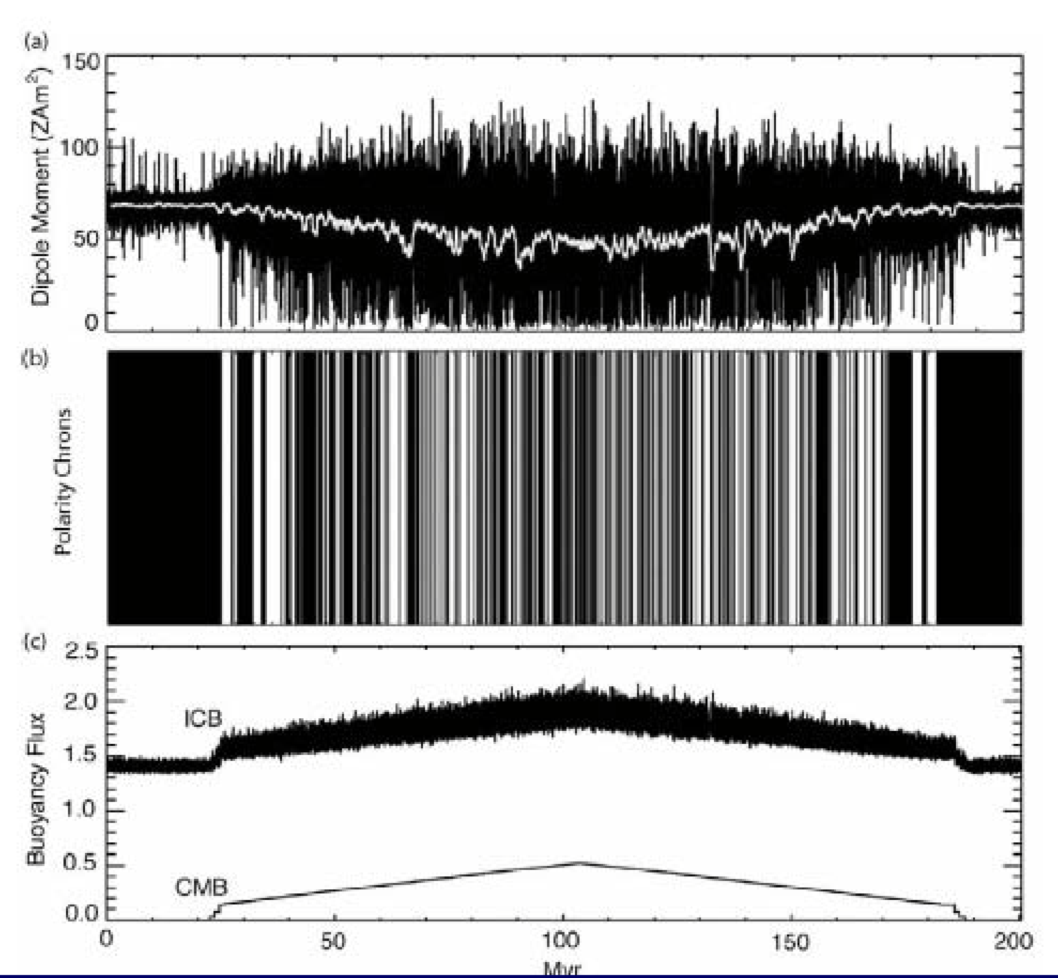
$$Ro_\ell = U/\Omega\ell$$

Regime boundary at

$Ro_\ell \approx 0.12$

Christensen & Aubert, GJI, 2006; Olson & Christensen, EPSL, 2006 – updated.

Change in reversal rate

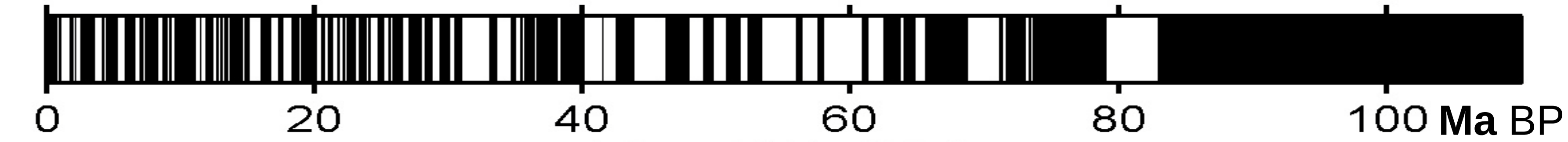


Dynamo simulation over 200 Myr

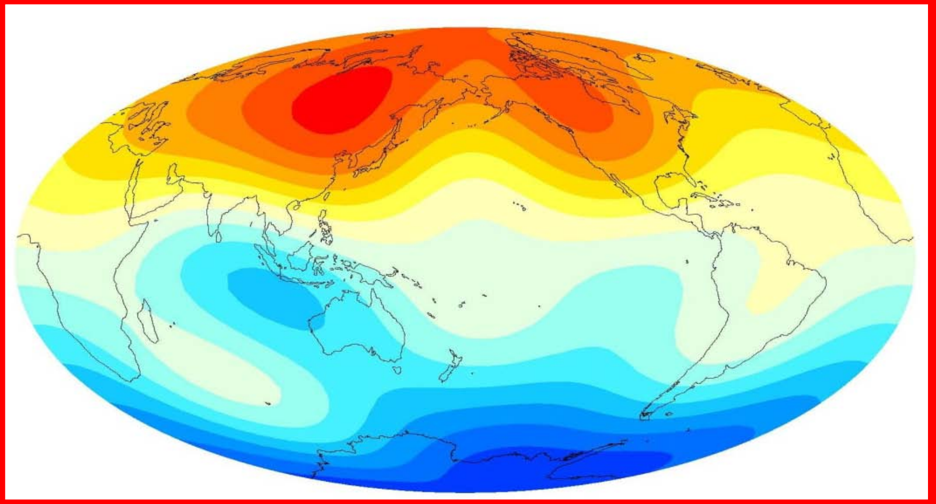
Gradual change in CMB heat flux

Change between non-reversing (superchron) and reversing state

(Driscoll and Olson, GRL, 2011)

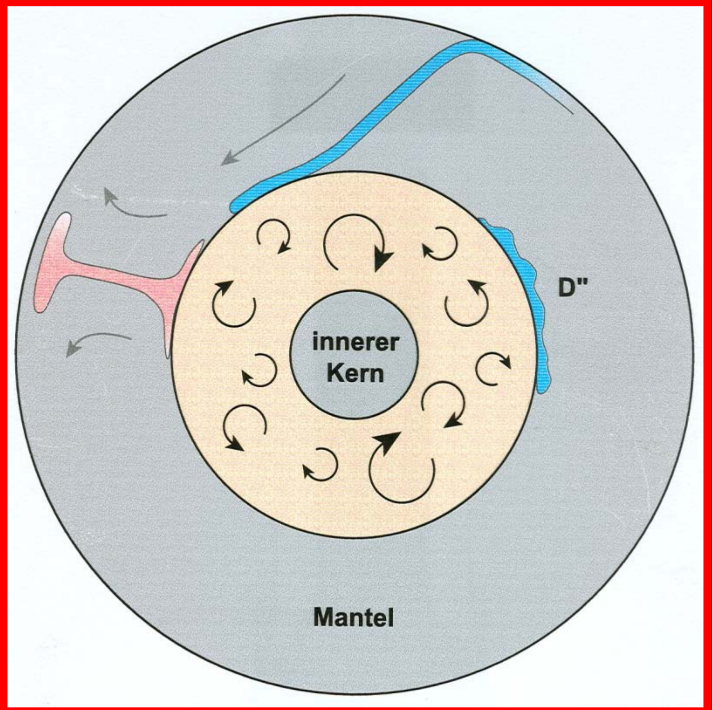


Heterogeneous CMB heat flow



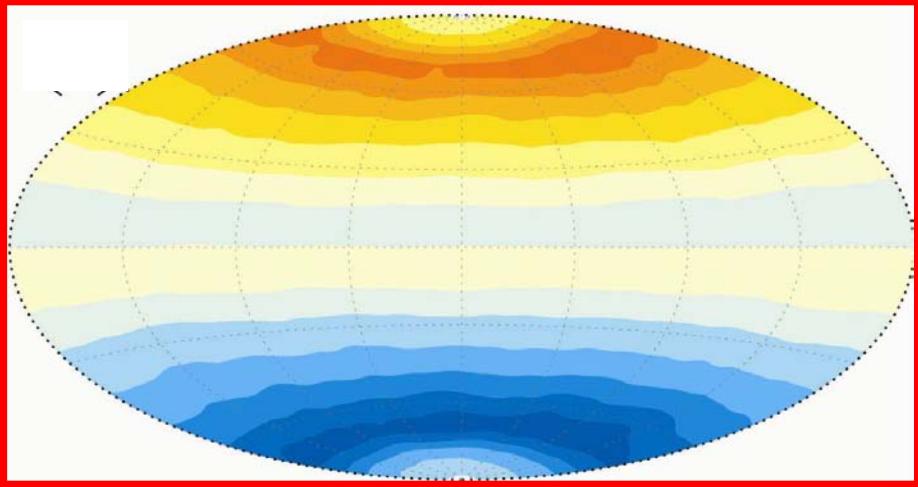
Time-average CMB field, Kelly & Gubbins, 1997

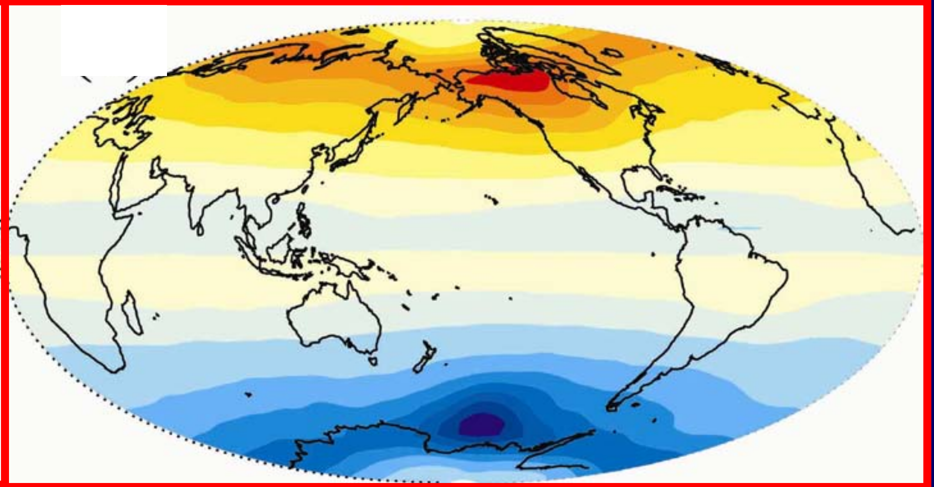
Non-axisymmetric structure in time-average geomagnetic field → external influence



Thermal core-mantle coupling:
Thermal structure of lower mantle imposes heterogeneous heat flow condition at core-mantle boundary

Models with imposed heat flow

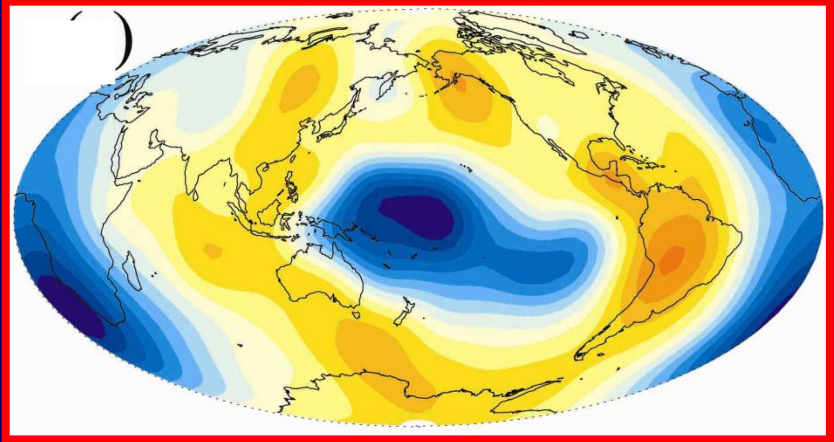




Uniform heat flow **Heterogeneous heat flow**

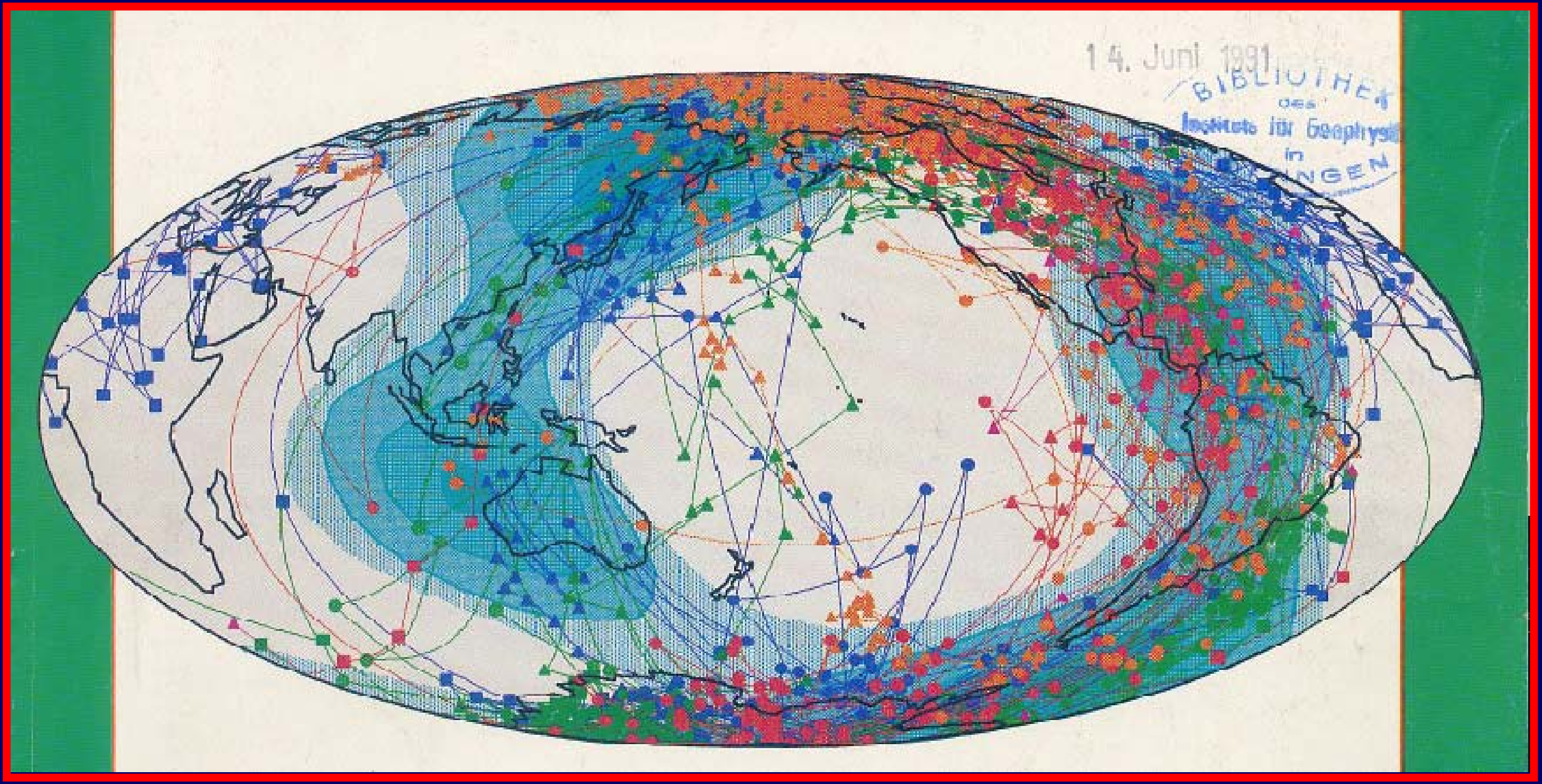
Time-average field (1 Myr)

Models confirm that thermal core-mantle coupling can explain non-axisymmetric structure in time-average geomagnetic field



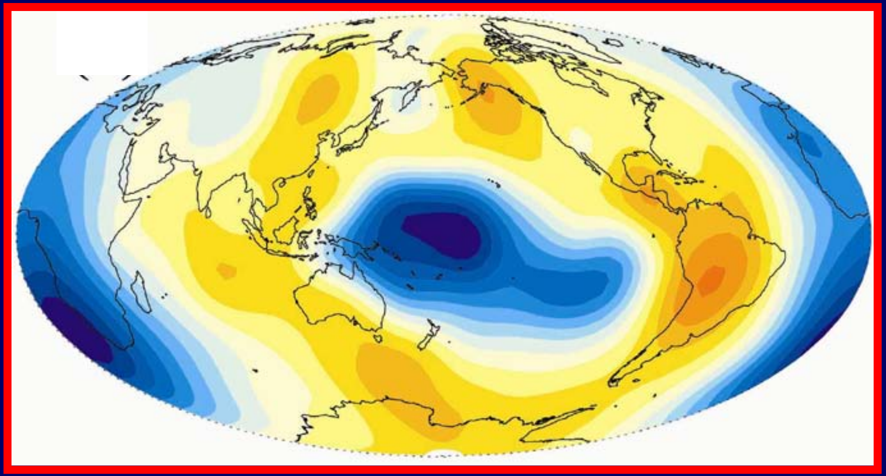
Core heat flow from S-wave anomaly in D"

Preferred paths of the virtual geo-magnetic pole (VGP) at reversals ?

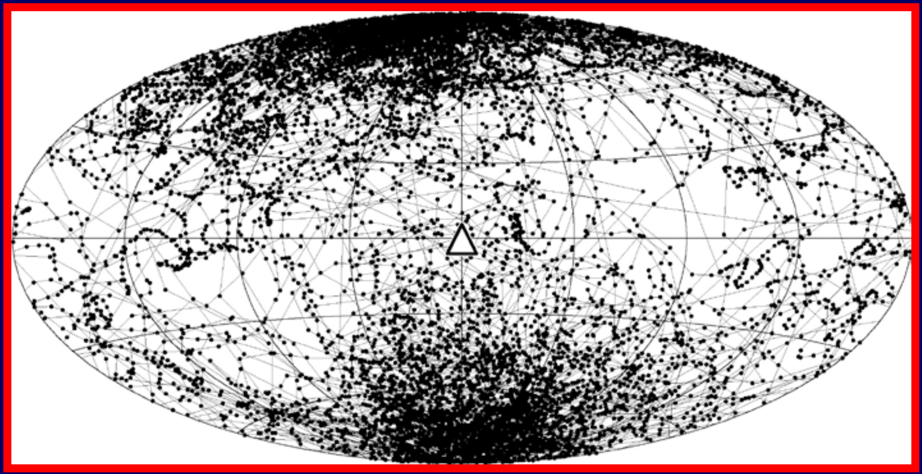


Concentration of transient VGP positions at American and East Asian longitudes (Laj et al., 1991), coincident with fast seismic *S*-velocity in the lowermost mantle

Reversing dynamo model with heterogeneous heat flow

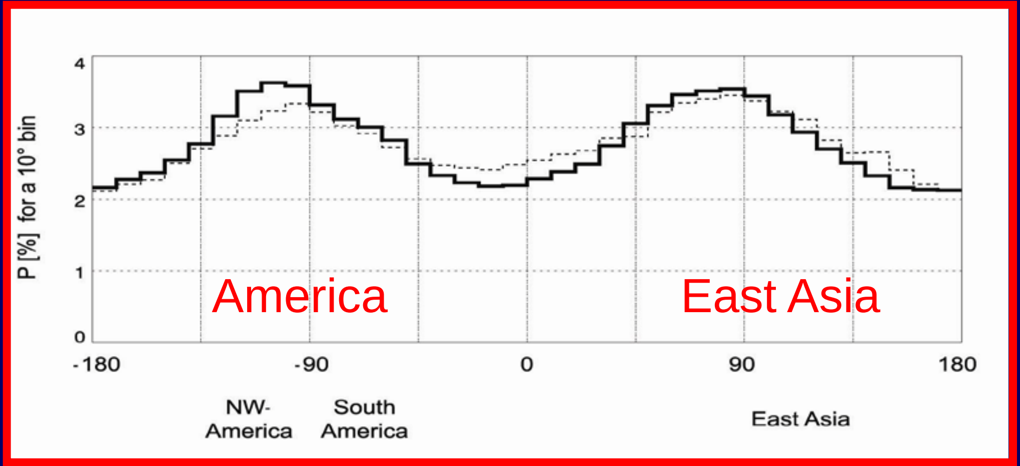


Core heat flow from S-wave anomaly in D“

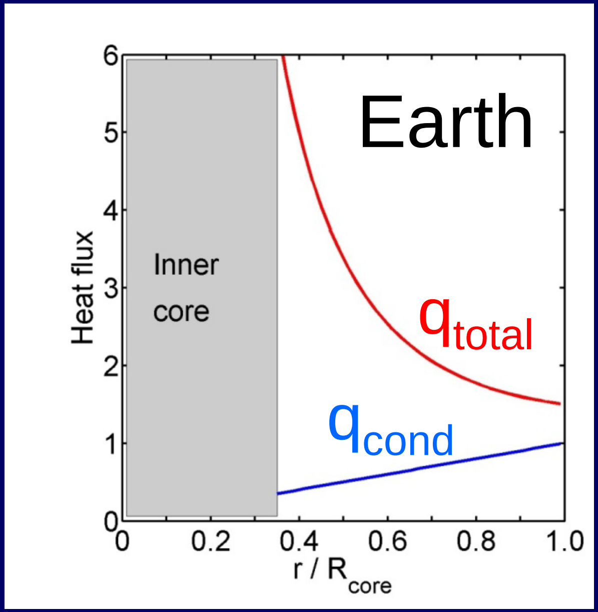


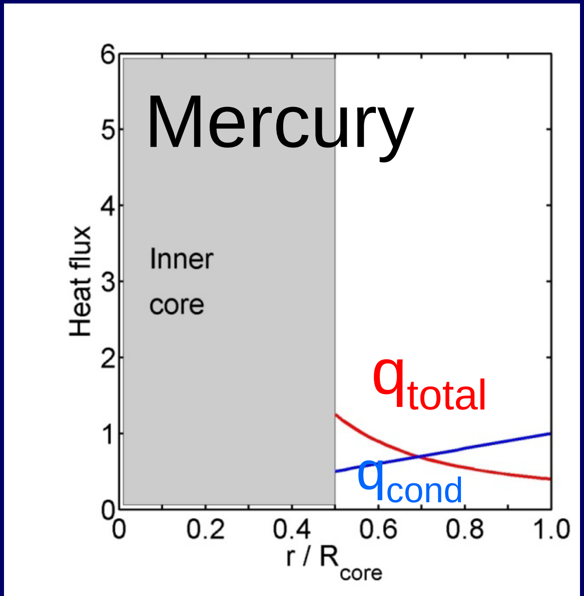
Simulated VGP positions

The model shows a statistical preference for the VGP to reverse along regions of high heat flow



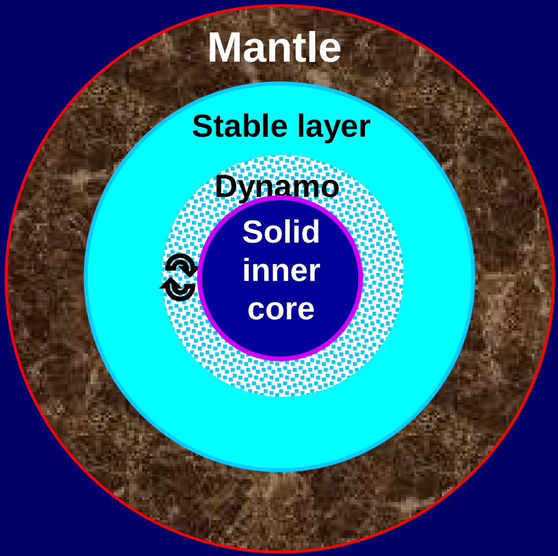
Mercury: deep-seated dynamo ?



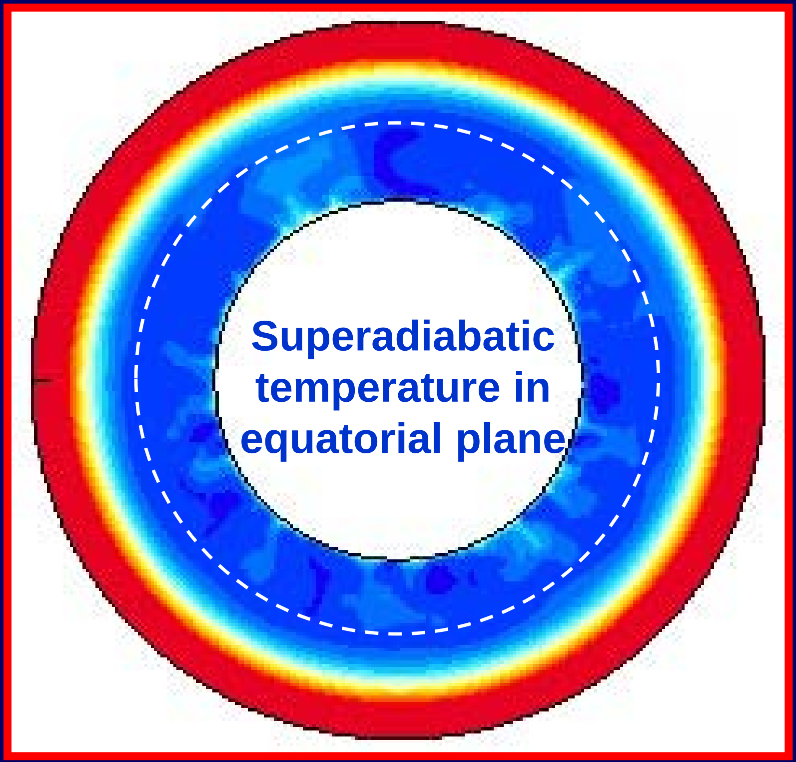


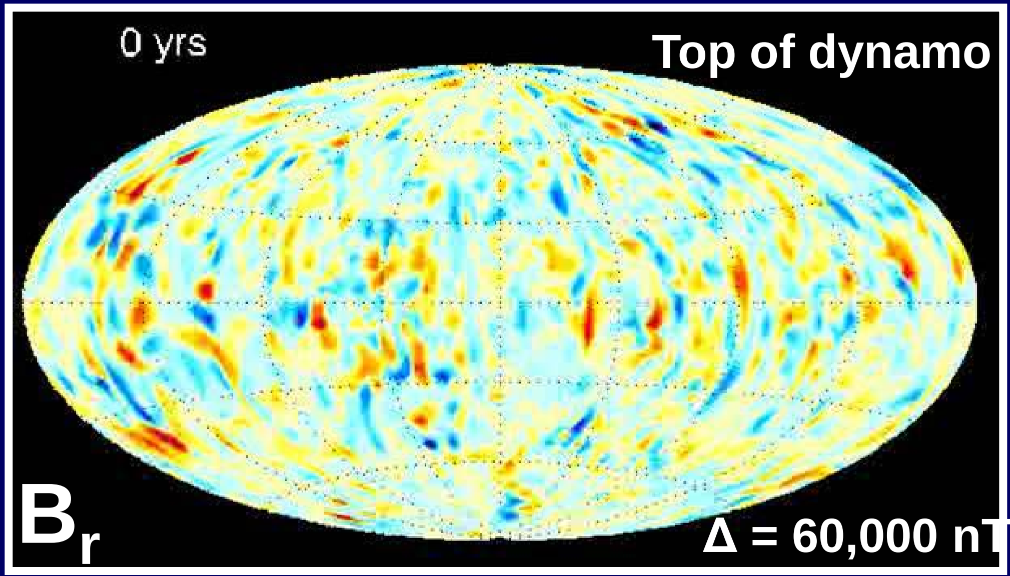
At Mercury's CMB heat flux $q < q_{cond}$ likely

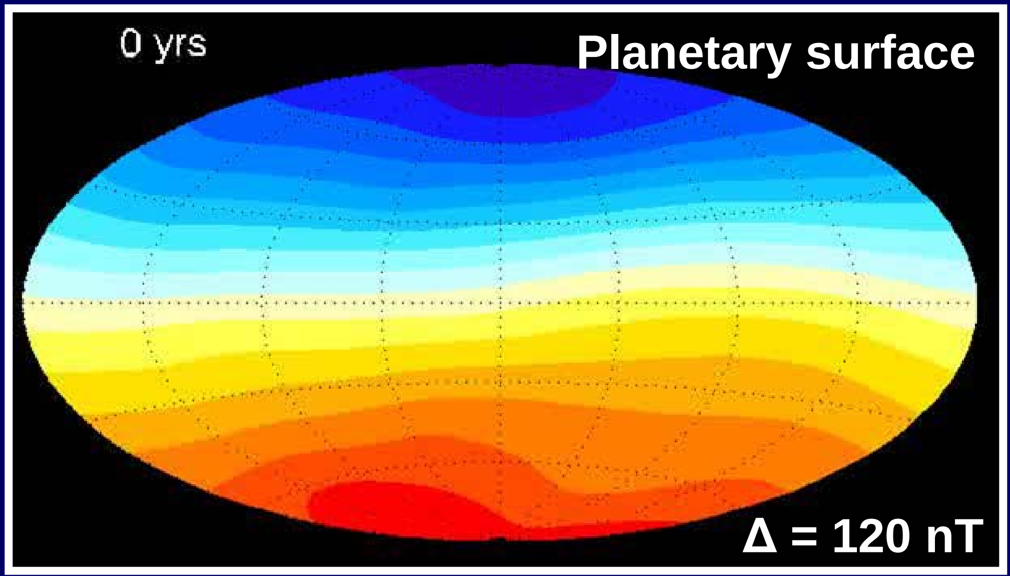
Dynamo operates only in deep convecting layer above inner core



Dynamo below stable fluid layer

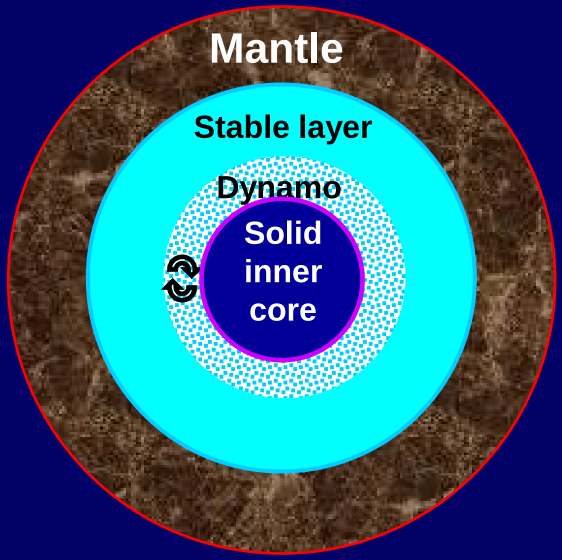




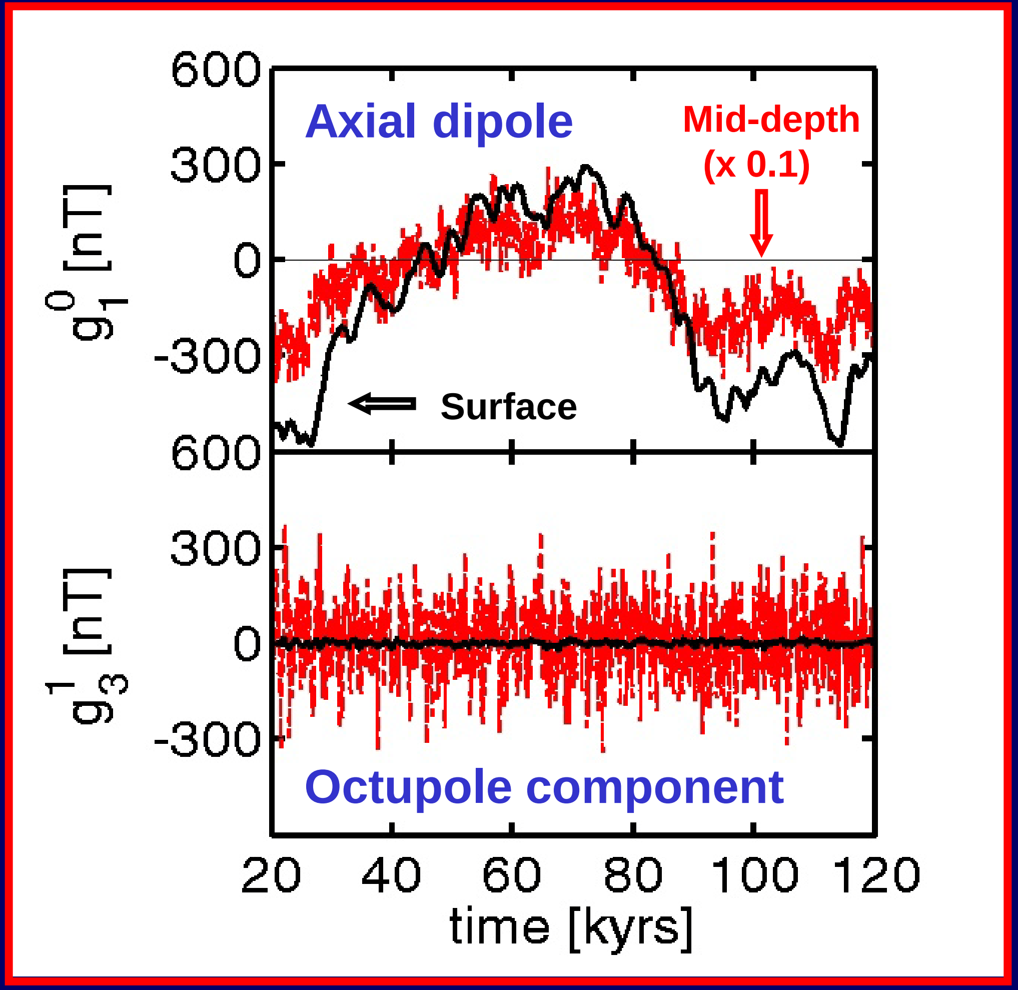


- Internal field strong & small-scale
- Surface field weak & large-scale

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



Skin effect



- Dynamo field must penetrate through stagnant conductor
- High frequencies damped.
- Higher multipoles fluctuate rapidly in dynamo region Low amplitude at surface.
- Dipole varies slowly and penetrates stagnant layer.

Mantle convection vs dynamo

Mantle convection models	Dynamo models
Fundamental model system simple. Material complexity.	Fundamental system complex. Material properties no issue.
2D models and cartesian models are meaningful.	3D models needed; sphere for magnetic field topology.
Simulations at Earth values of basic control parameters.	Some control parameter values far from Earth values.
Various geophysical and geo-chemical data to compare with.	Magnetic field (almost) only observation to compare with.

Challenges

Self-consistent plate tectonics in convection model.	Verify that models are in dynamical relevant regime.
Understand mantle mixing and isotopic signatures in mantle.	Explain different magnetic fields of individual planets.