Planetary dynamos: Dipole-multipole transition and dipole reversals

Ulrich Christensen

Max-Planck-Institute for Solar System Research

Katlenburg-Lindau, Germany

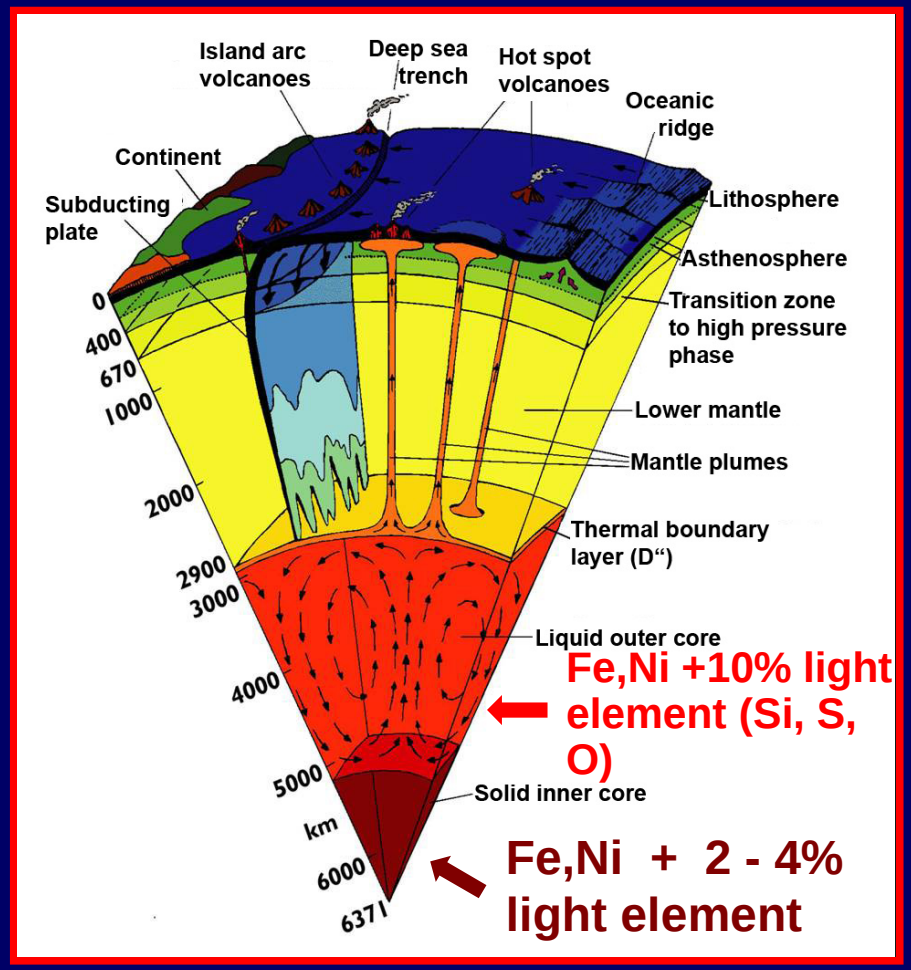
in collaboration with

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

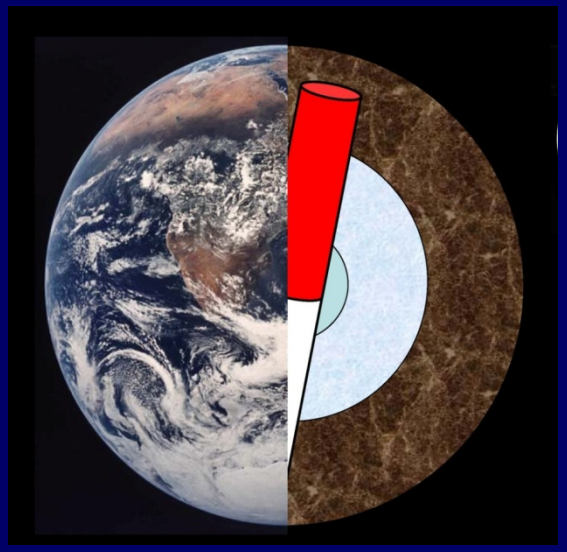
The geodynamo

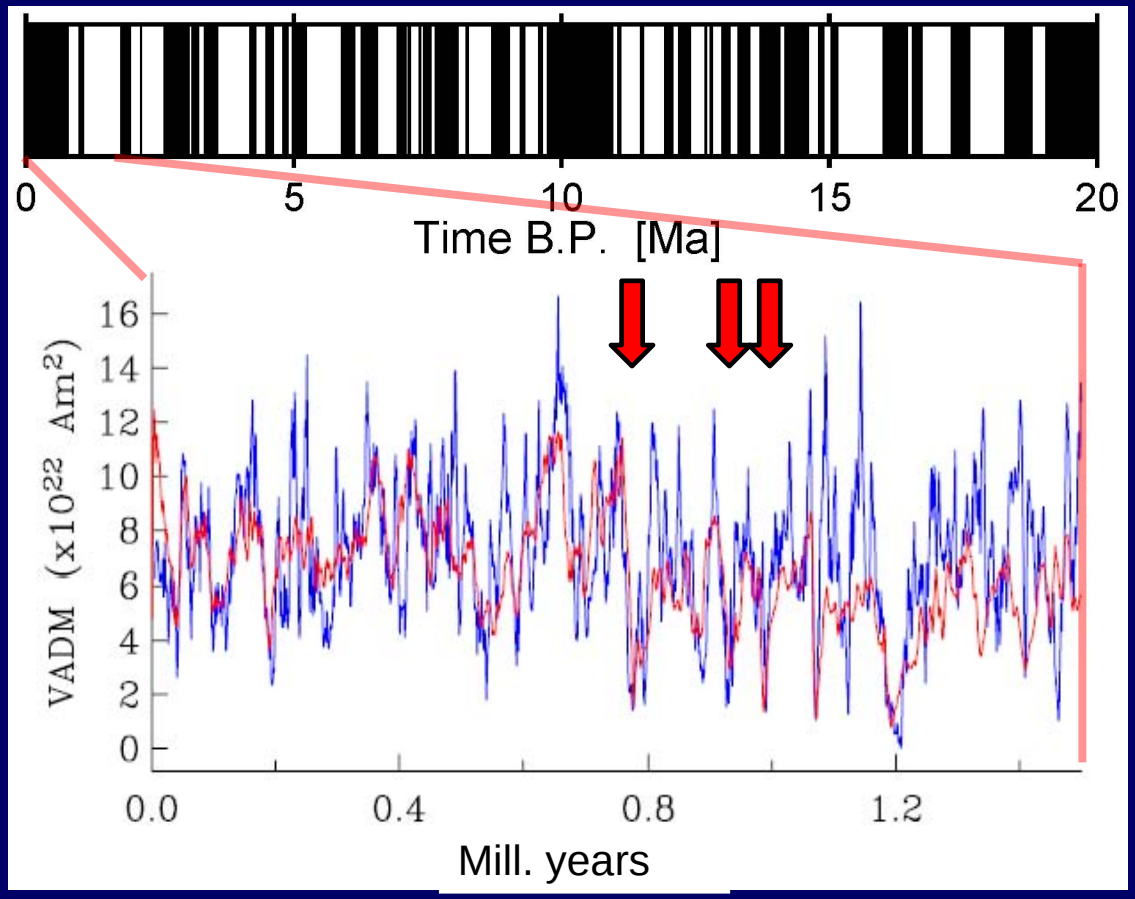
- Thermal /compositional convection in liquid outer iron core
- Electromagnetic induction by motion through the existing magnetic field sets up electrical current
- Currents produce magnetic field as needed for induction

⇒ Selfsustained dynamo



Dipole reversals





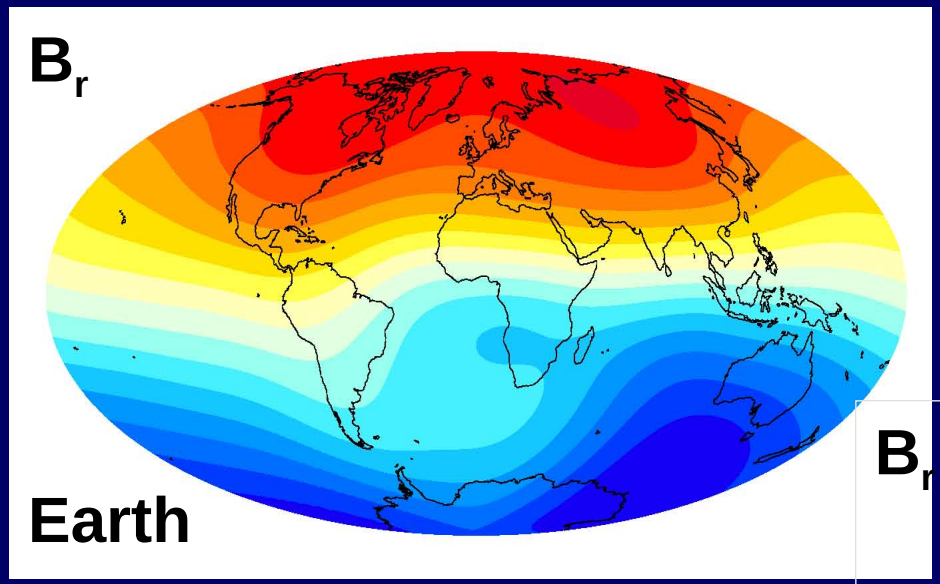
A few reversals per million years

Stochastic (vs. periodic at Sun)

Low magnetic field strength during reversal (but non-zero)

Field during reversal dominated by multipole components

Field morphology



Earth, Mercury, Jupiter and Saturn have dipole-dominated magnetic fields

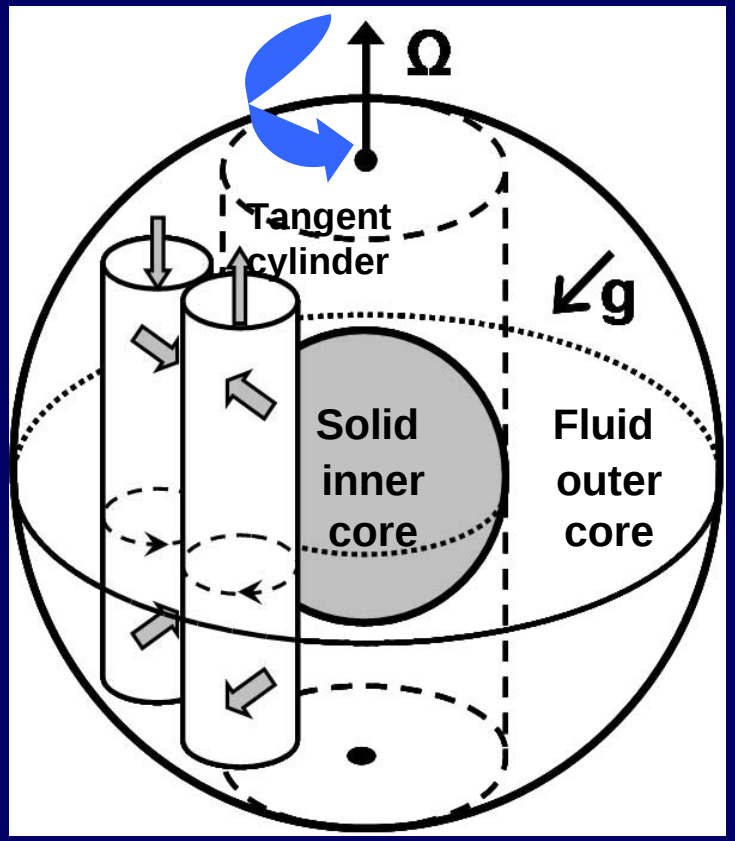
Uranus and Neptune have multipolar fields

Outline of geodynamo models

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

☺ **Direct numerical simulation of fundamental equations of magnetohydrodynamics**

☹ **Some parameters not Earth-like**



Governing equations

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

- **Inertia** **Coriolis** **Viscosity** **Buoyancy** **Lorentz**

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

Advection **Diffusion**

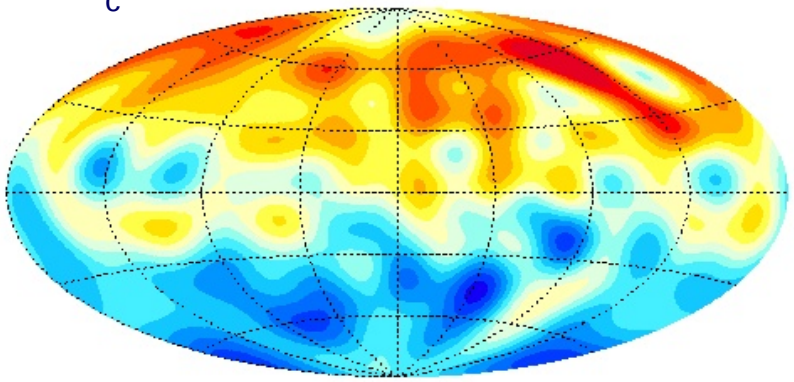
$$\frac{\partial \vec{B}}{\partial t}+\vec{u}\cdot\vec{\nabla}\vec{B}=\vec{B}\cdot\vec{\nabla}\vec{u}+\boxed{\frac{E}{Pm}}\nabla^2\vec{B}$$

Advection **Induction** **Diffusion**

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

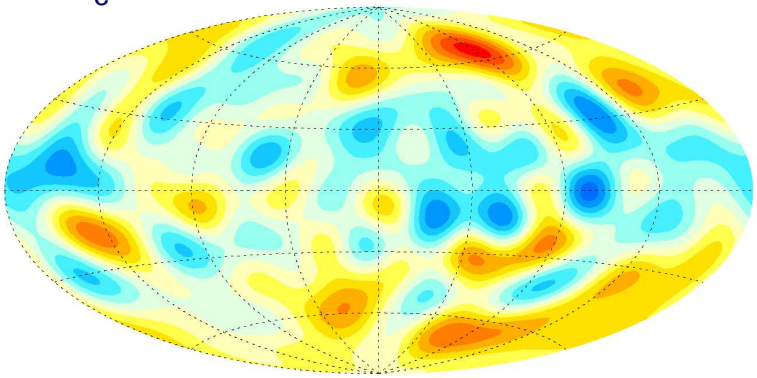
Magnetic field morphology

$Ra/Ra_c = 114$ $E=10^{-5}$ $Pm=0.8$

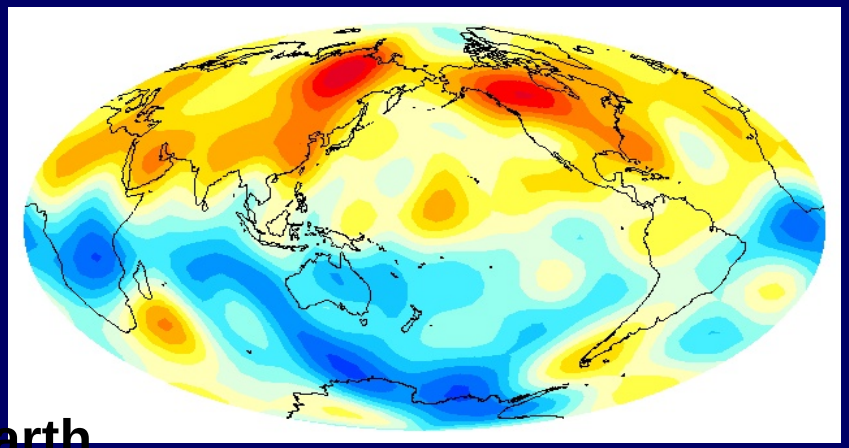


$Rm = 914$ $Ro_\ell = 0.12$

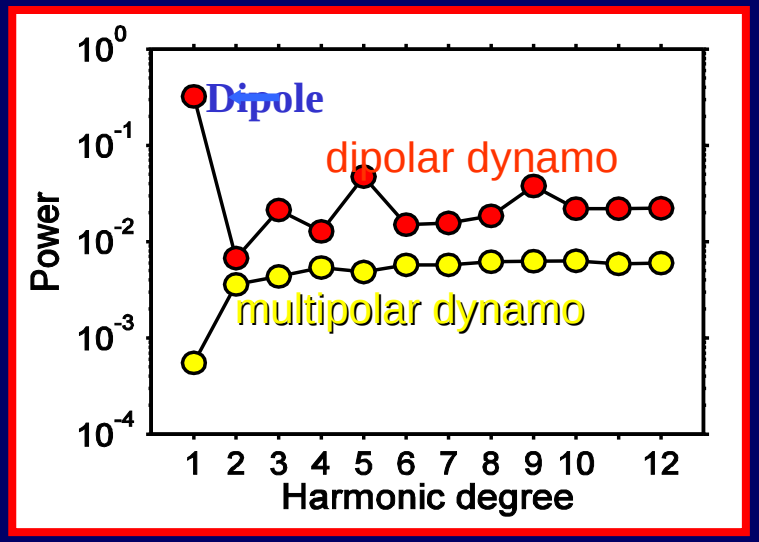
$Ra/Ra_c = 161$ $E=10^{-5}$ $Pm=0.5$



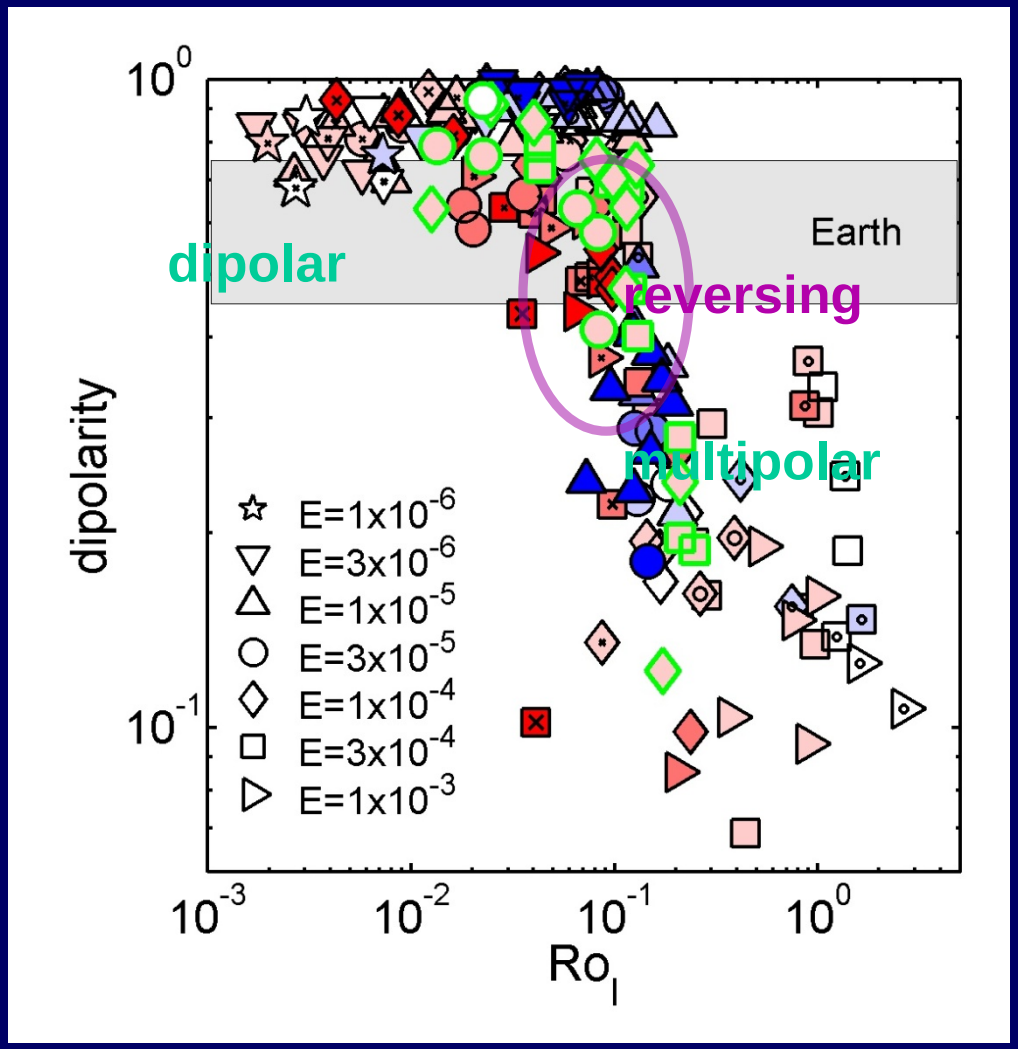
$Rm = 917$ $Ro_\ell = 0.21$



Earth



Selection of dynamo regime



Ratio inertia / Coriolis measured by

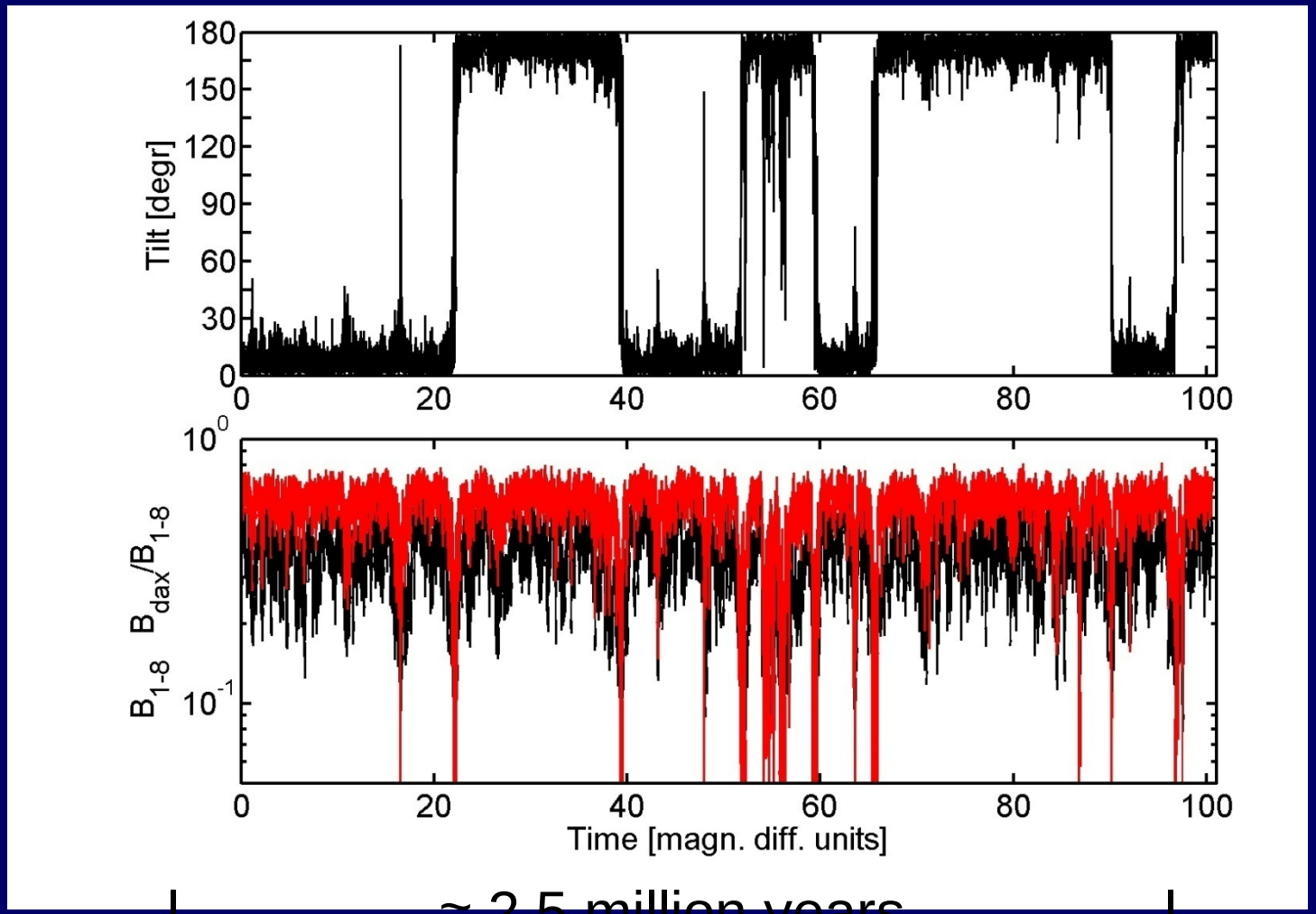
Rossby number

$$\mathbf{Ro_\ell = U/\Omega\ell}$$

critical point $Ro_\ell \approx 0.12$

reversing dynamos near transition point

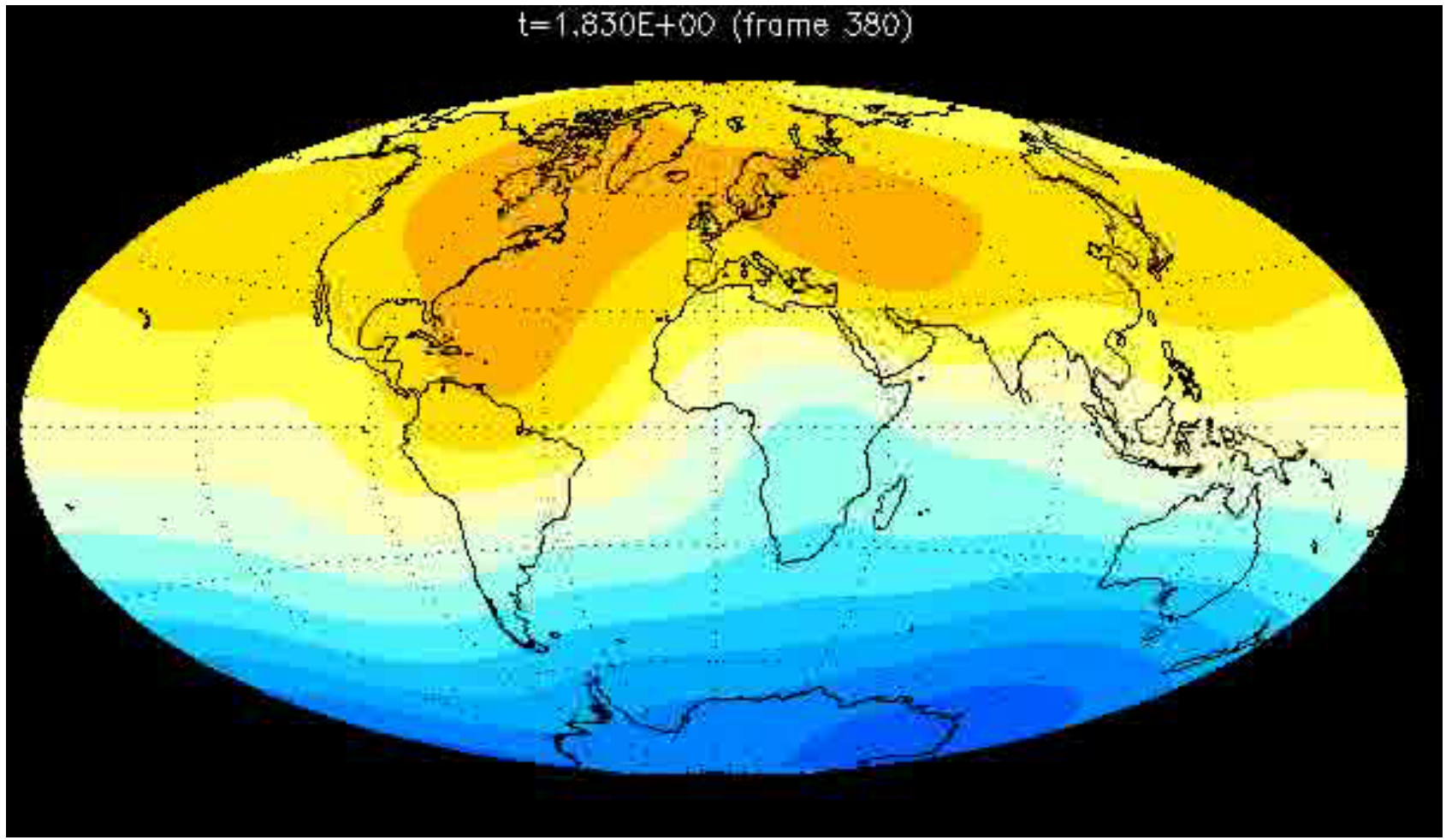
Simulated reversals



≈ 2.5 million years

Time

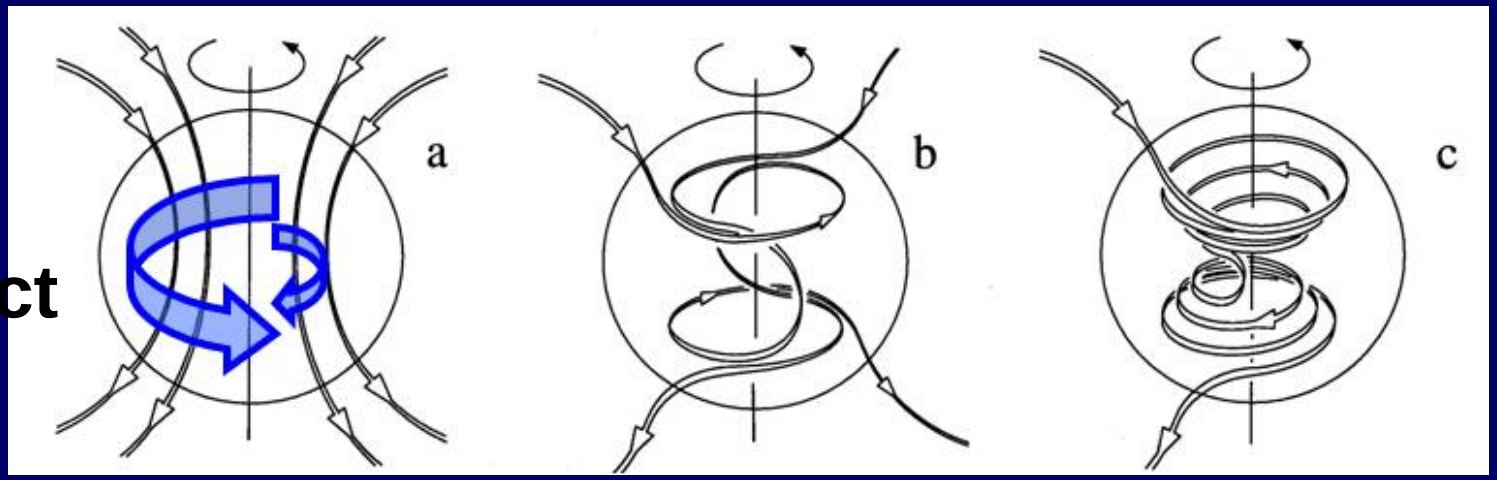
Geomagnetic reversal



Magnetic field of dynamo model at Earth's surface

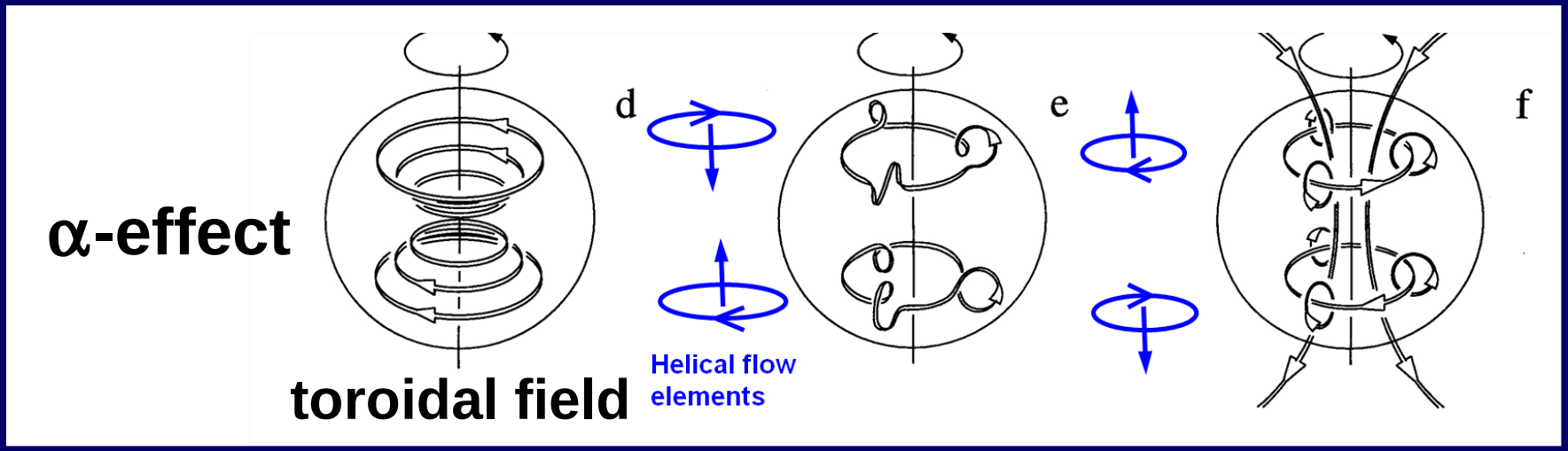
Generation of dipole field

Ω-effect



poloidal field

α-effect

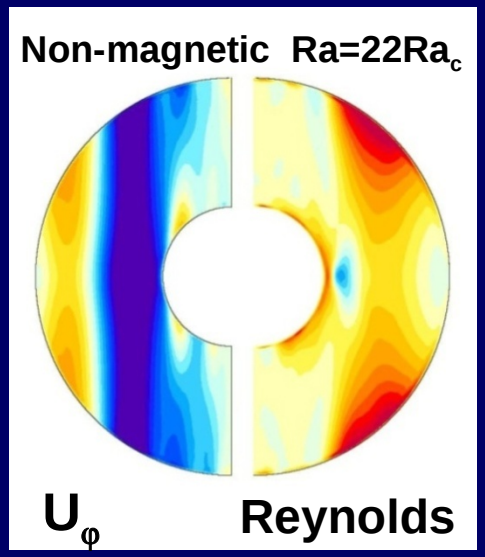


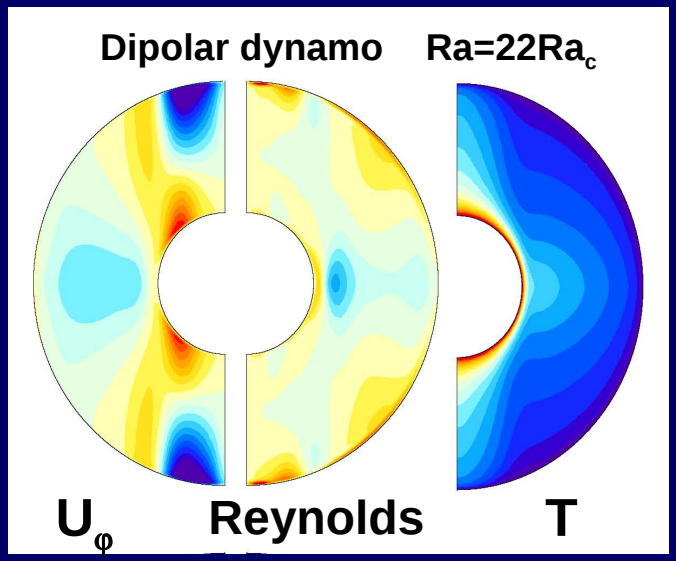
toroidal field

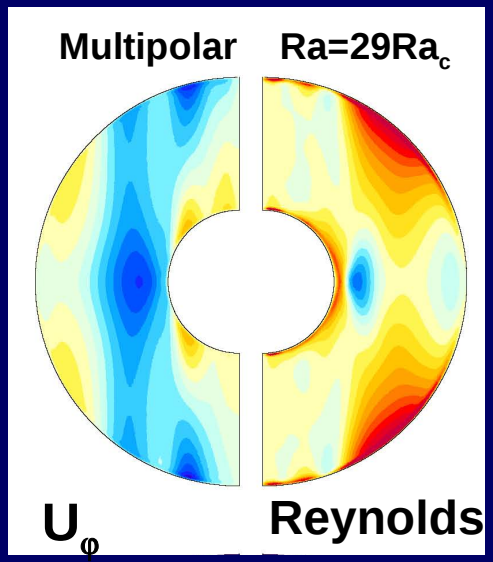
Differential rotation

Reynolds stress: inverse inertial cascade from small eddies

Thermal wind: Coriolis force acting on flow driven by temperature variation with latitude







Geostrophic
Reynolds stress

Ageostrophic
Thermal wind

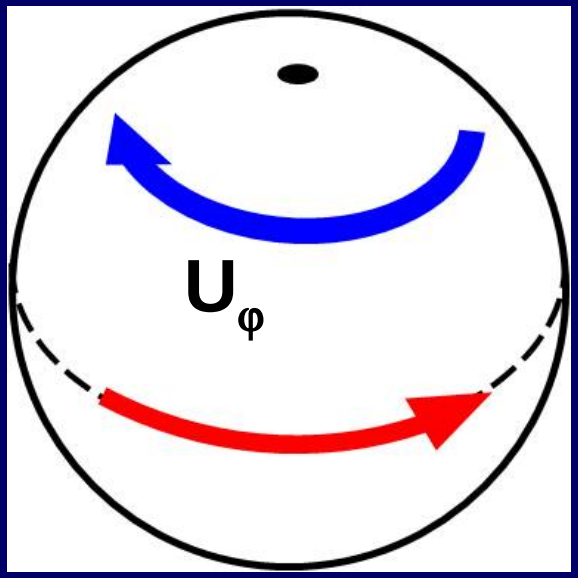
Largely geostrophic

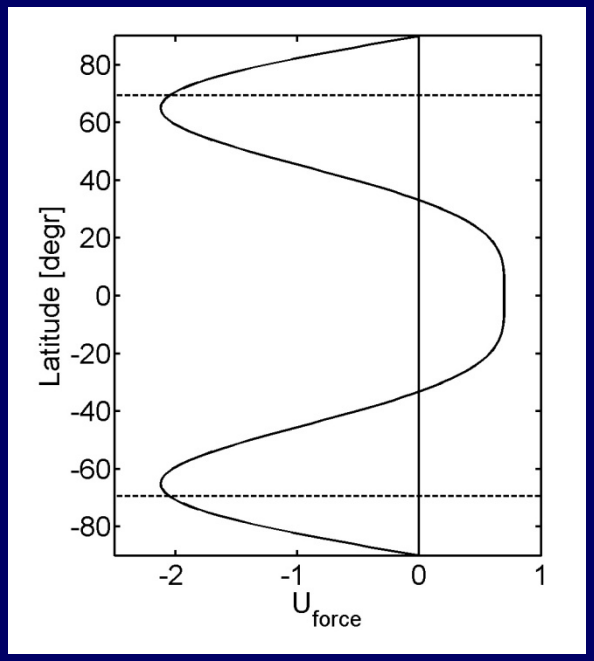
Aubert (2005); Simitev & Busse (2009)

Zonal flow change passive reaction to different magnetic field ?

or Different zonal flow pattern causes breakdown of dipole field ?

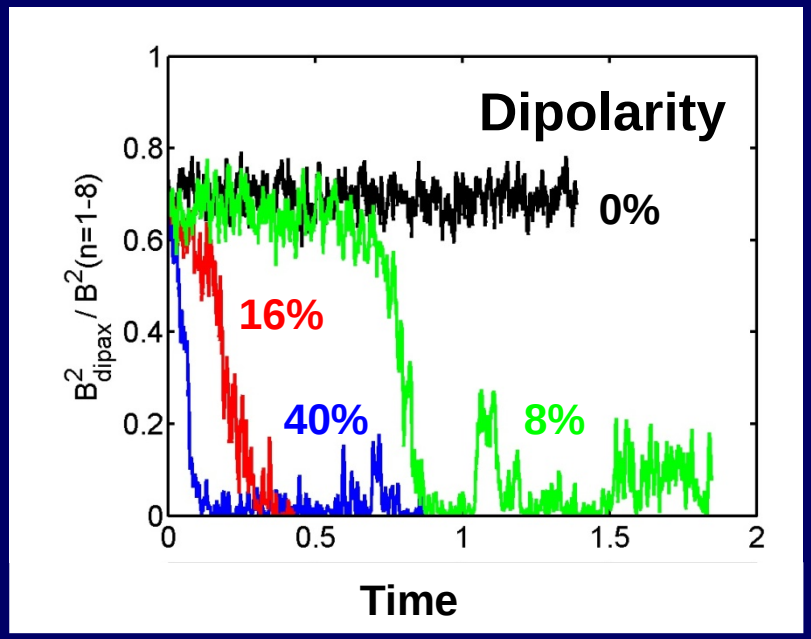
Forced zonal flow

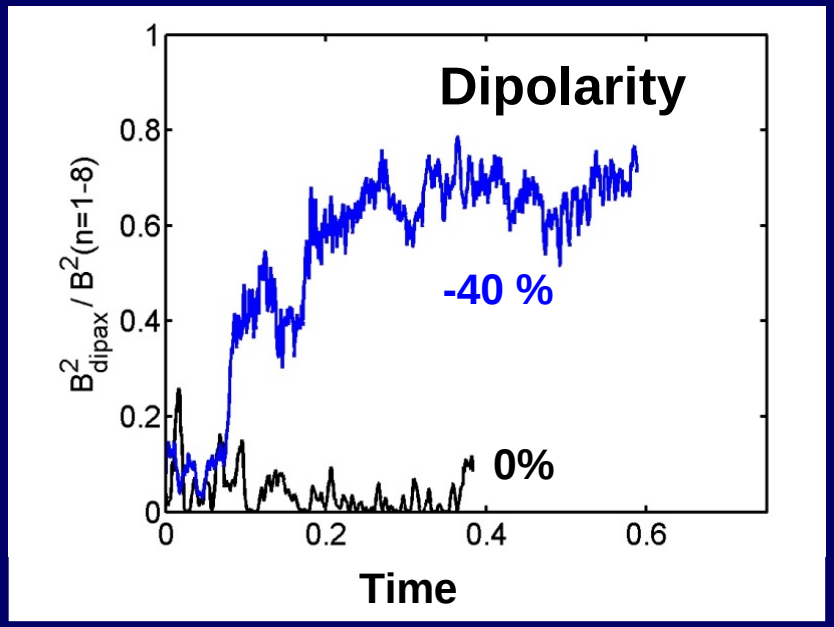




- **Manipulate zonal flow in dynamo by imposing velocity condition on outer boundary**
- **Shape of forced flow similar to that driven by Reynolds stress.**

Forced transitions

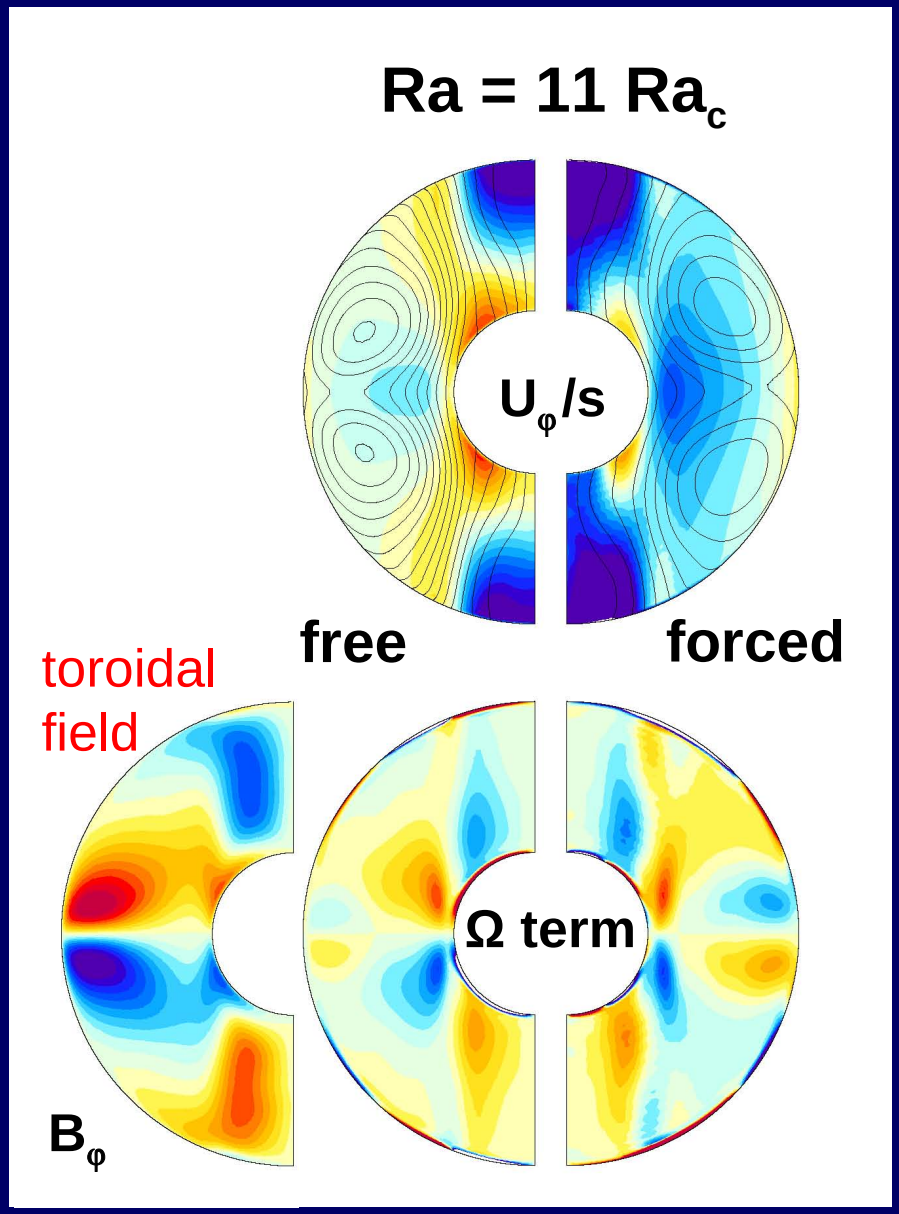




By forcing geostrophic differential rotation, an intrinsically dipolar dynamo can be turned multipolar

Undoing the differential rotation by inverse forcing, an intrinsically multipolar dynamo turns dipolar

Change in Omega effect



$$\partial B_\varphi/\partial t = s\, B_{pol} \cdot \nabla (U_\varphi/s) + \ldots$$

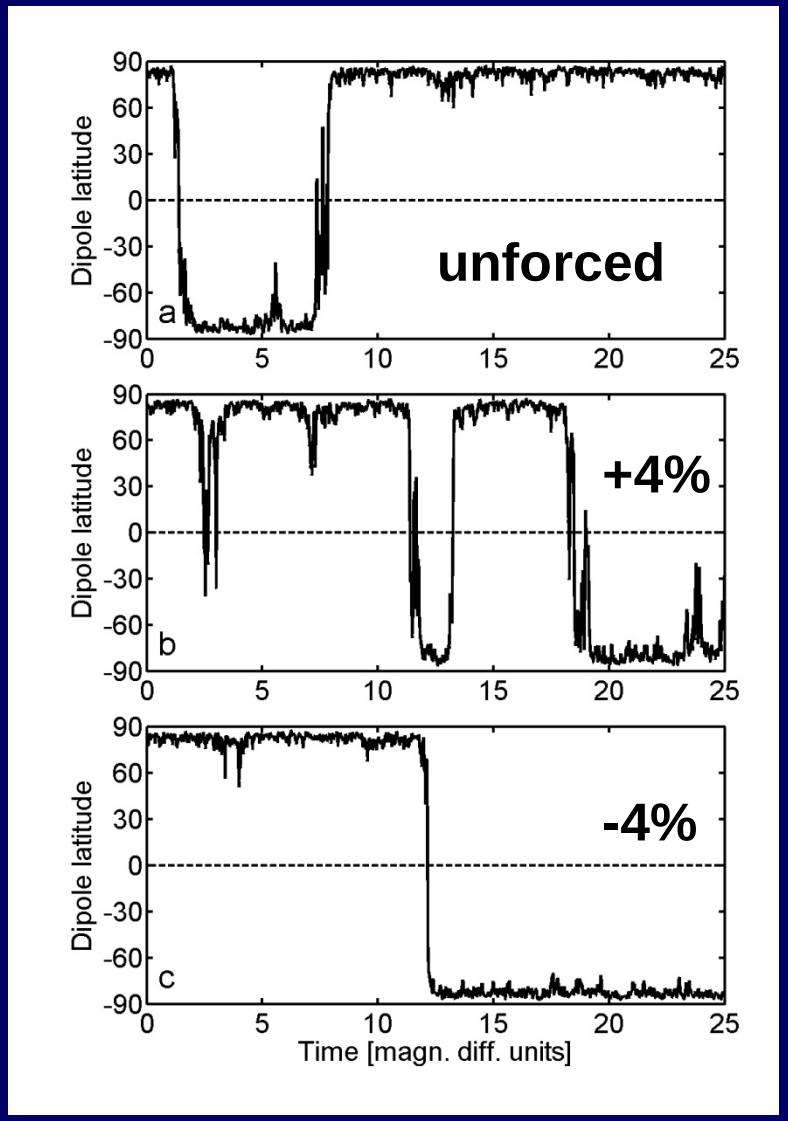
Ω-effect in forced dynamo (while field is still dipolar)

versus

Ω - effect in free dynamo

Geostrophic differential rotation: Ω-effect counterproductive for generating toroidal flux tubes

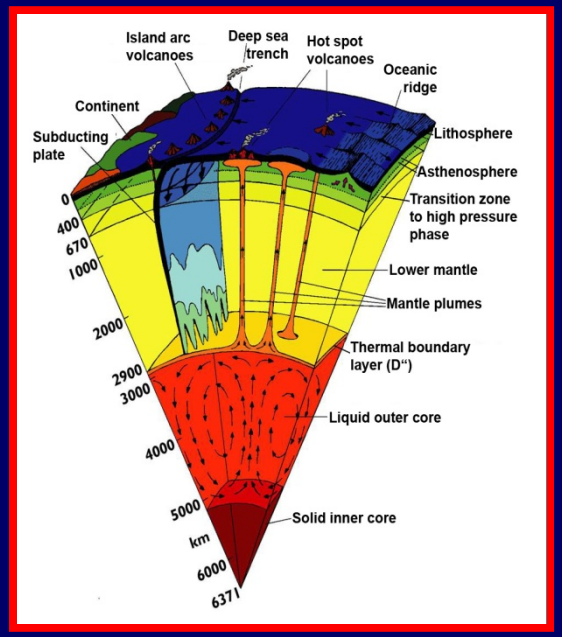
Forcing of reversing synamo

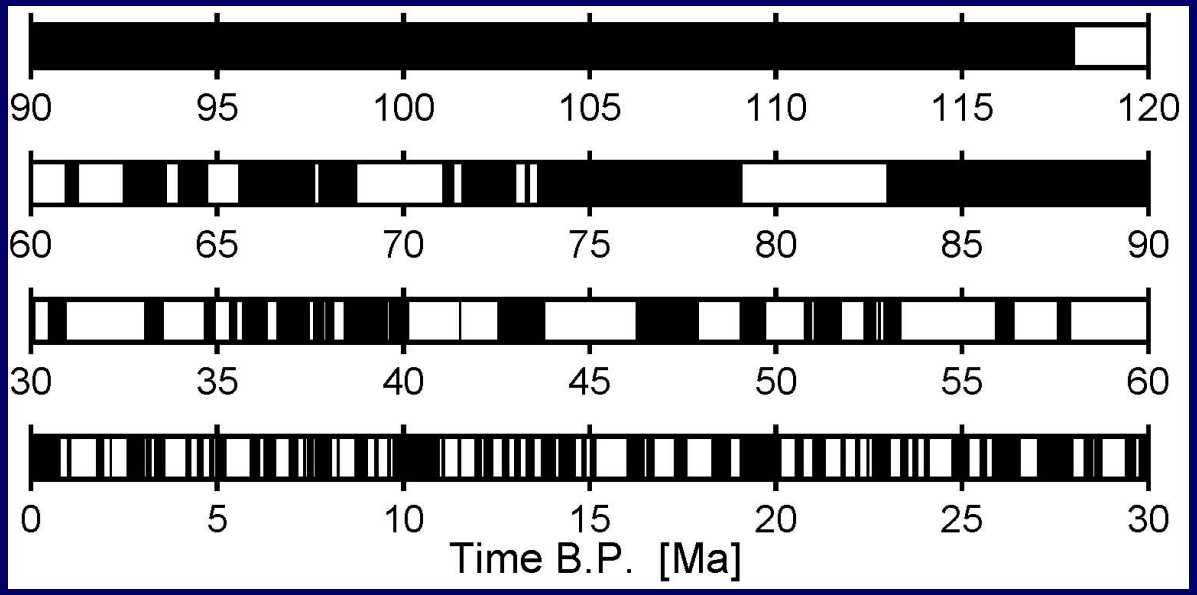


Reversal frequency increased by forcing differential rotation

Reversal frequency decreased by suppressing differential rotation

Change in reversal frequency





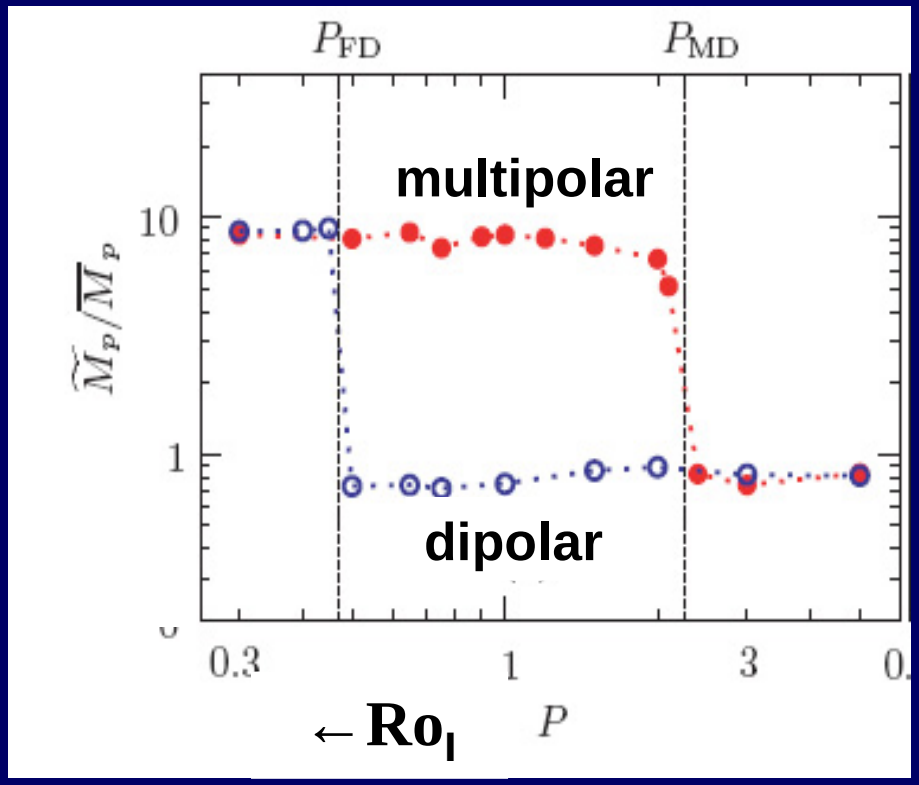
Dynamo models suggest reversals are sensitive to small change in parameters

Is there evidence from geomagnetic field that this is so?

Change of reversal frequency on 100 Mill.year time scale

Possibly change in core heat flow by changes in mantle

Bistability and hysteresis



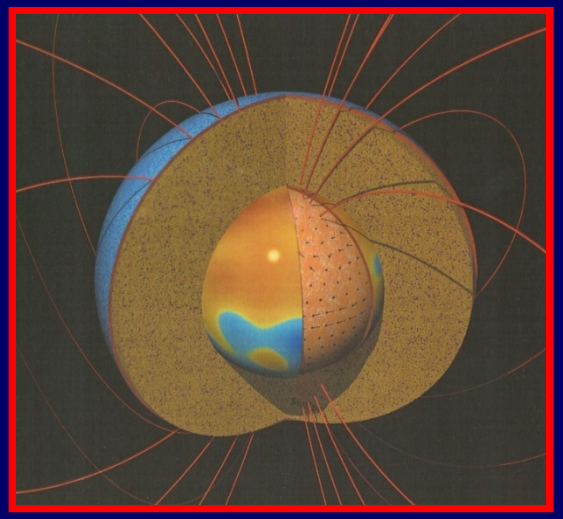
Simitev & Busse, EPL 2009

In other dynamo models, bistability of dipolar and multi-polar solutions found over significant parameter range.

For such dynamos, rapid dipole reversals by an excursion into the multipolar mode would not be possible

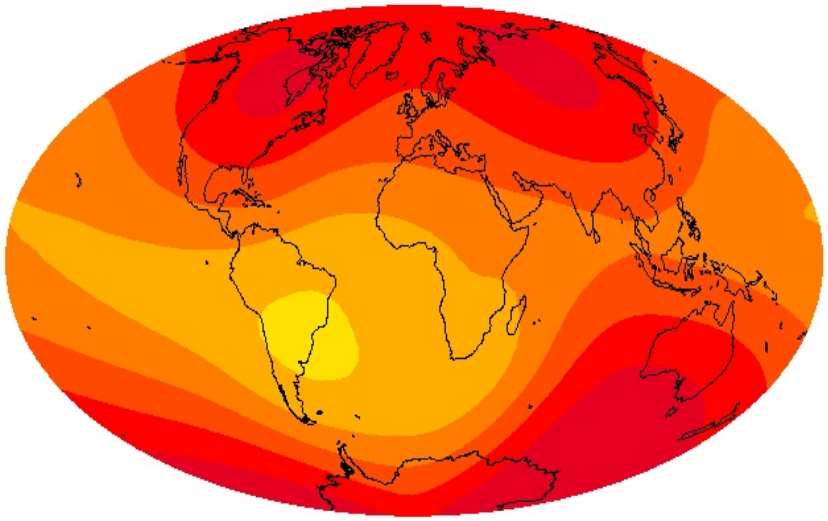
Conclusions

- Geodynamo probably close to phase transition between strongly dipolar and multipolar regime
- Dipole reversals due to instability of dipolar dynamo. Fluctuations lead to brief lapse into multipolar phase.
- Phase transition occurs where inertial force relative to Coriolis force reach a critical limit
- Inverse inertial cascade transfers energy from small eddies to geostrophic differential rotation

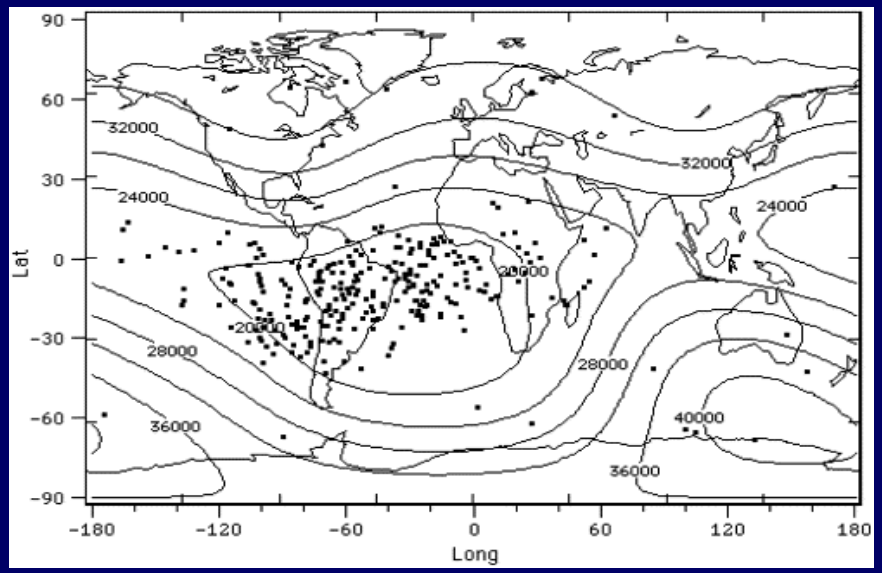


- Anti-Ω-effect eliminates toroidal flux tubes of dipolar dynamo
- Open question: is Earth by chance near critical point, or is it self-organized criticality ?

Hazard for satellites



Geomagnetic field intensity 1990



Radiation damage events Topex/Poseidon

Heirtzler, JASTP, 2002

- Geomagnetic field particularly weak over South Atlantic and South America (South Atlantic Anomaly)
- Disruption of electronics on satellites by MeV protons
- Field intensity in SAA anomaly decreasing by 2% in 10 years