The Geodynamo from a Whole-Earth Perspective

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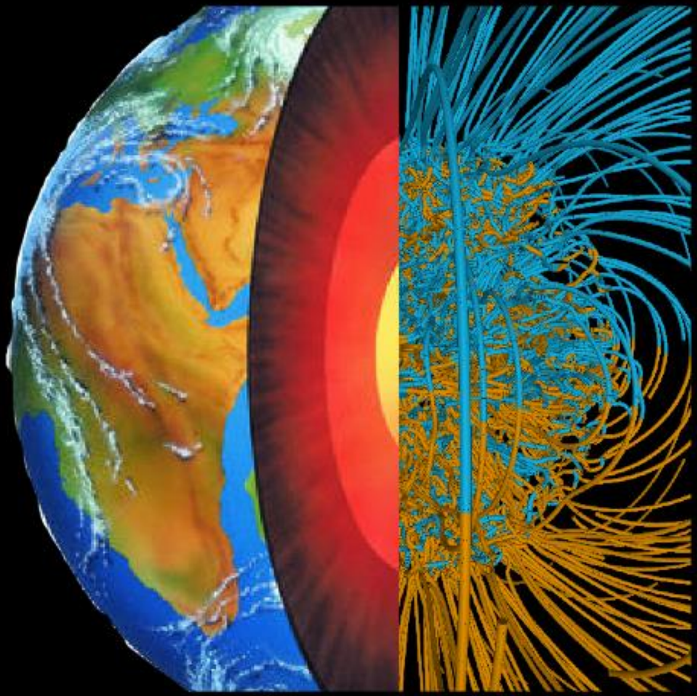
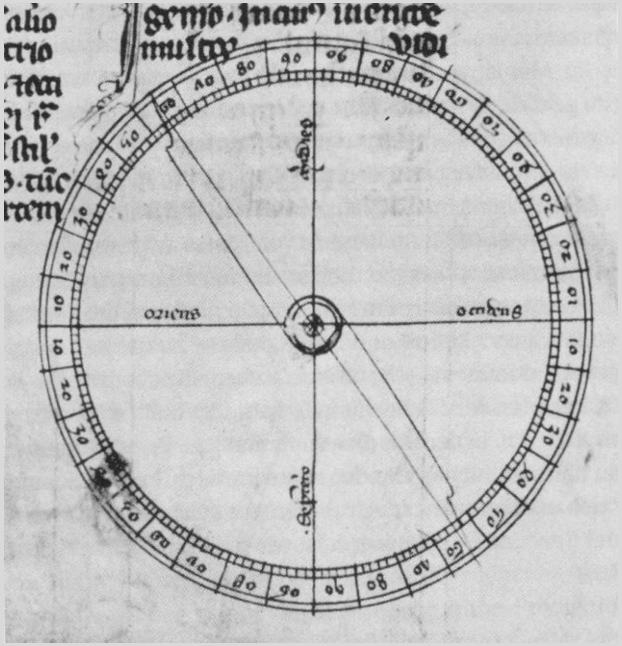


Physics Colloquium

University of Toronto

January 23, 2014



Petreus Peregrinus, ca. 1269

Topics

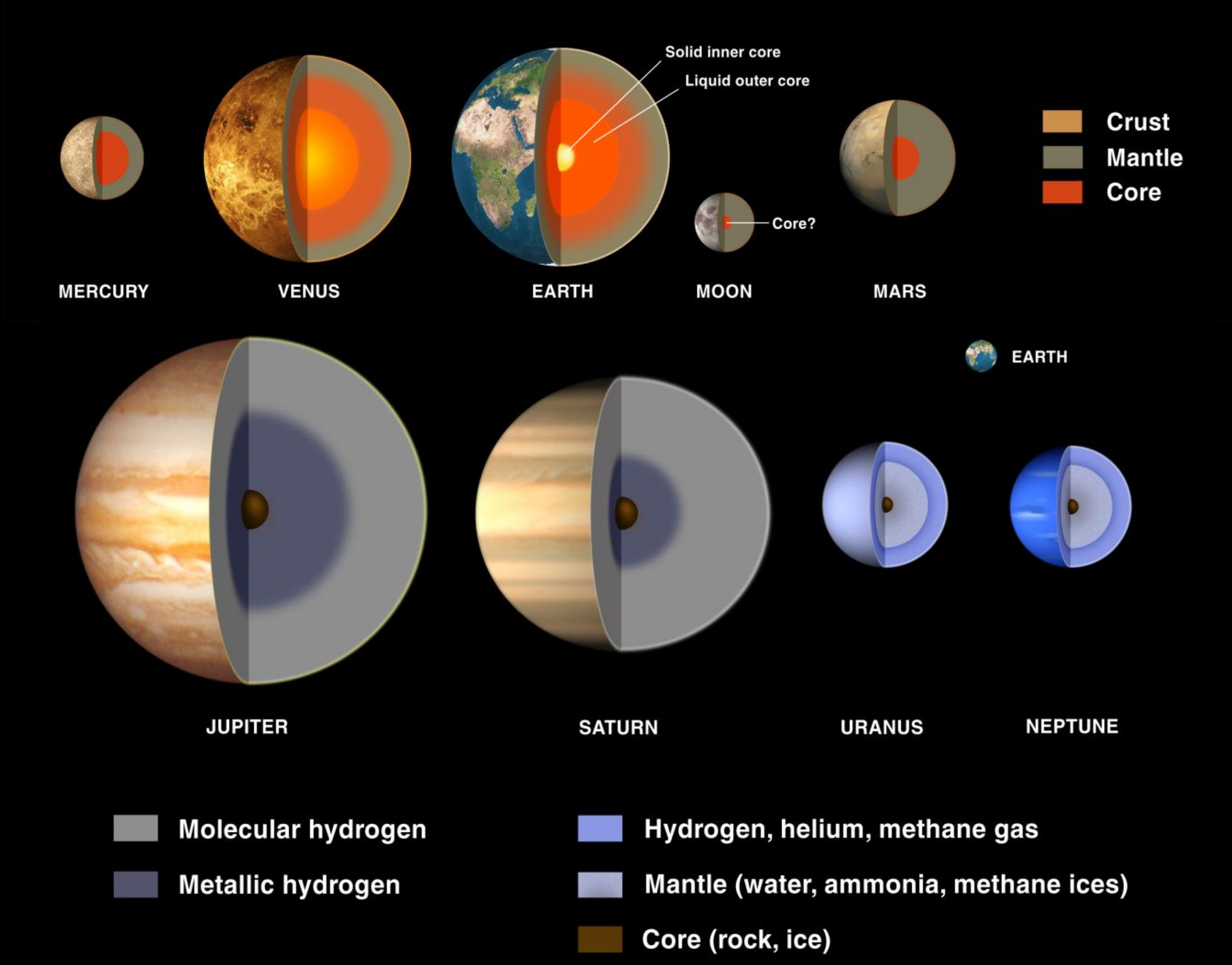
- The geodynamo -- a short tour
- Magnetic polarity reversals and evolution of the mantle-core system
- Where is the frontier?

Requirements for a self-sustaining planetary dynamo:

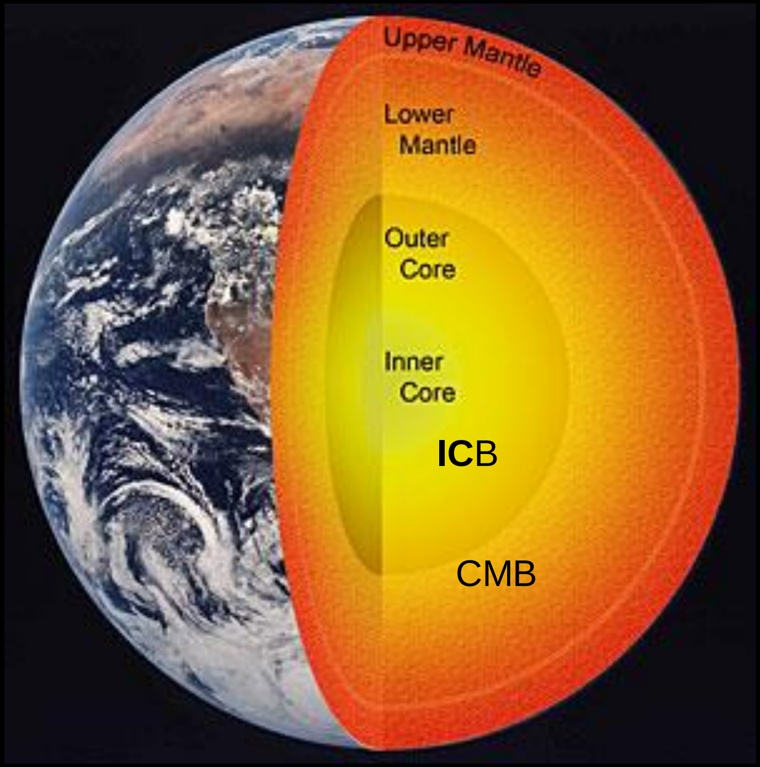
1. Large electrically conducting fluid interior

2. Kinetic energy source (convection or other fluid motions)

3. Planetary rotation (for positive magnetic feedback)



The Geodynamo Process



- Energetics: Heat loss to the mantle (10-16TW), chemical differentiation and inner core solidification (~2×10^6 kg/s) drive thermo-chemical convection in the molten outer core.

- Dynamics: Convection in the outer core induces electric currents and the geomagnetic field.

- Timescales:

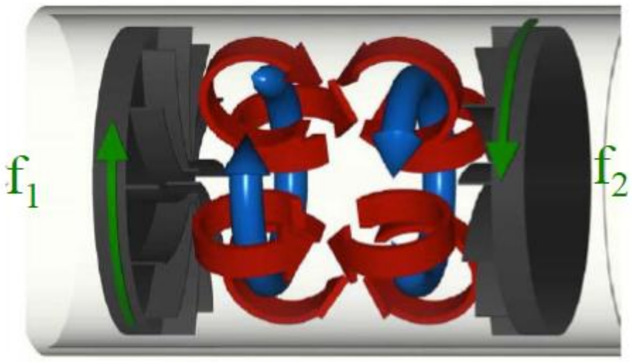
In the core: magnetic decay $\tau_d \sim 200$ kyr; convective turnover time $\tau_c \sim 200$ yr;
$Rm = \tau_d / \tau_c \sim 1000$ ($Rm_{critical} \sim 40$)

In the mantle: Wilson cycle ~ 300 - 400 Myr.

- Geodynamo age > 3.4 Ga

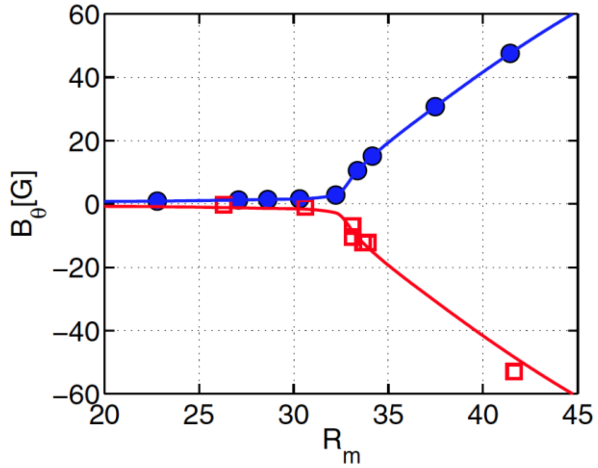
VKS Liquid Sodium Dynamo Experiment

Design

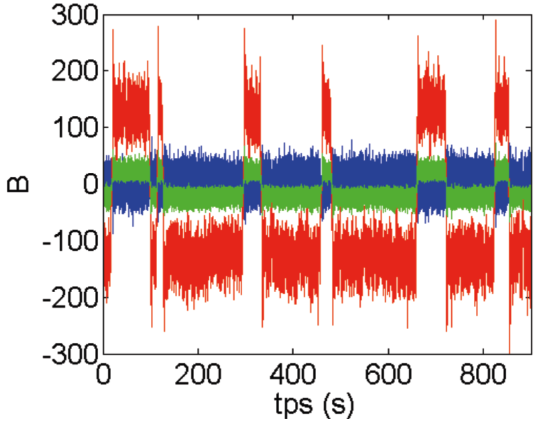


Apparatus

Dynamo Onset



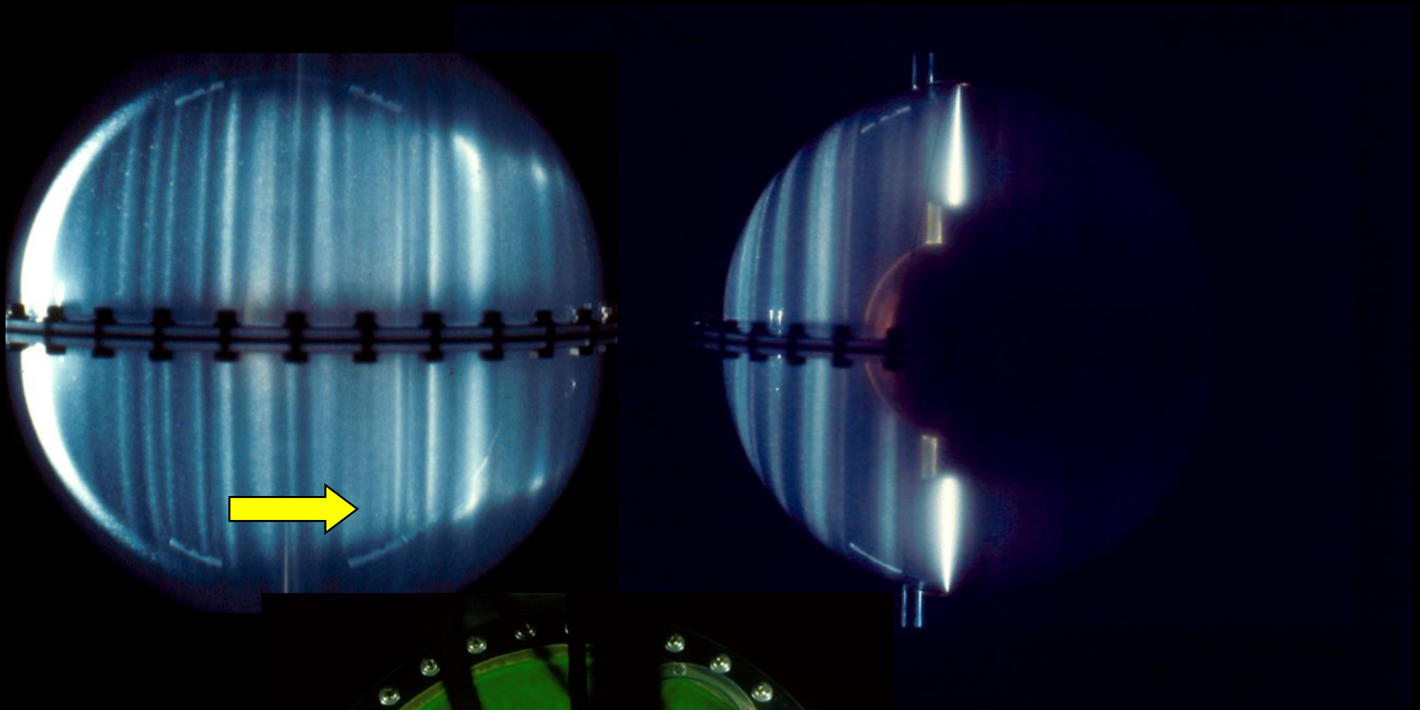
Polarity Reversals @ Large Rm



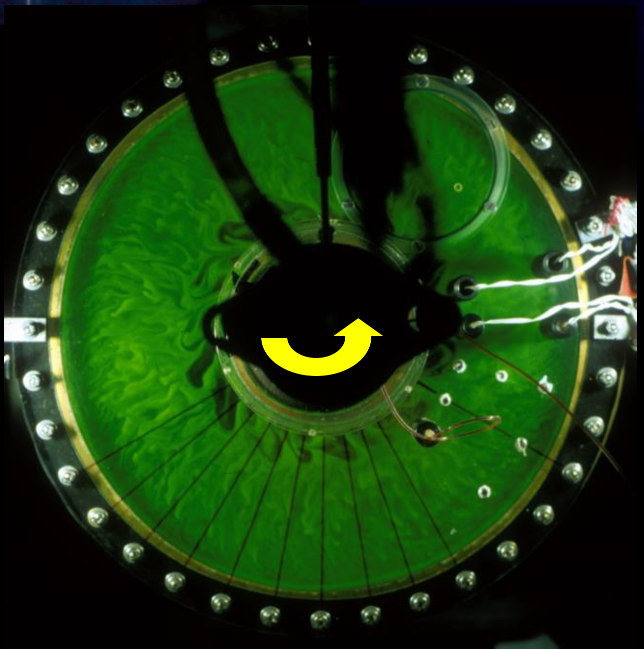
Berhanu et al. (2008, 2010); Moncheaux et al. (2009)

Convection in a Rotating Sphere

Meridional views

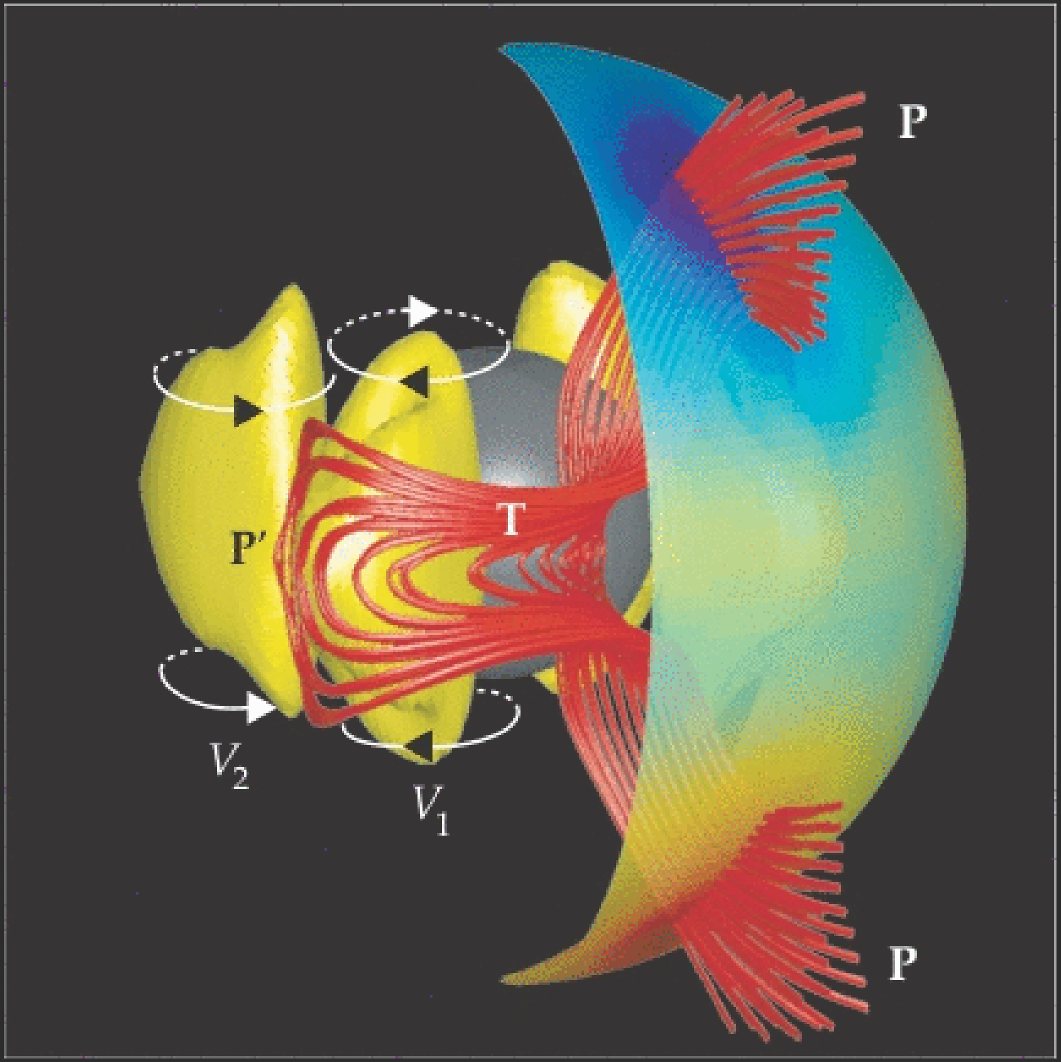


Equatorial view

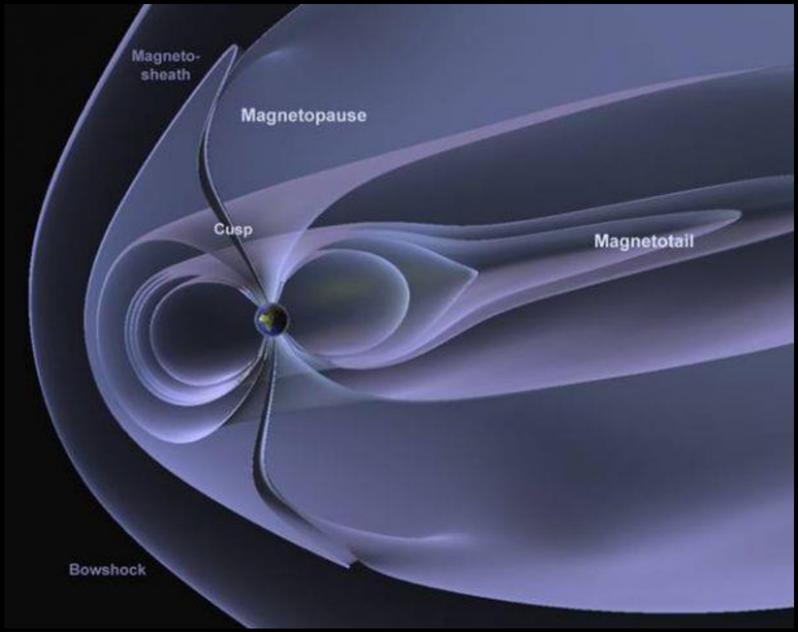


Cardin and Olson (2007)

Dynamo Action via Rotating Convection

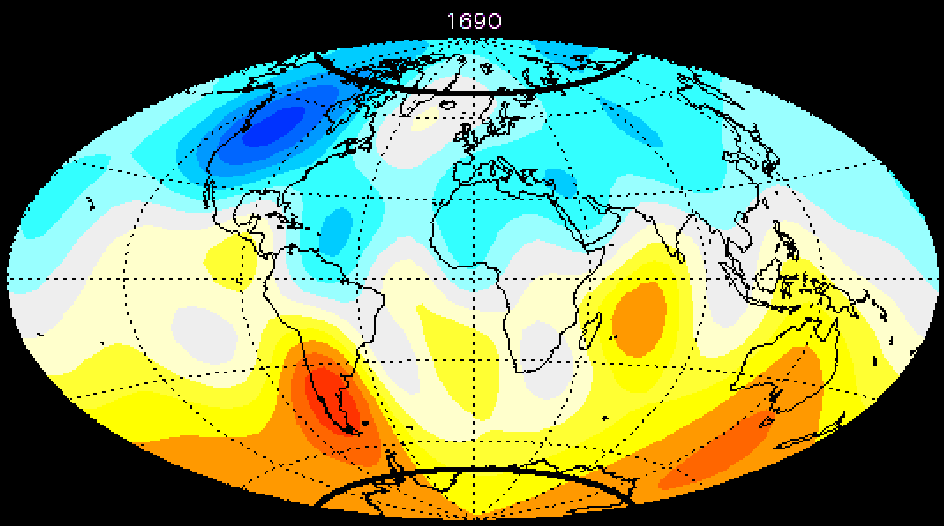


Geomagnetic Field Structure



External: geomagnetic field lines in the solar wind

Internal: geomagnetic field on the core-mantle boundary (CMB)
1690-2010



B_r (1 mT max intensity)

Dynamo Equations

(Simplified for thermo-chemical convection)

Navier-Stokes:

$$E\left(\frac{\partial u}{\partial t} + u\cdot\nabla u - \nabla^2 u\right) + 2\hat{z}\times u + \nabla P = EPr^{-1}Ra\frac{r}{r_o}\chi + Pm^{-1}(\nabla\times B)\times B$$

Induction:

$$\frac{\partial B}{\partial t} = \nabla\times(u\times B) + Pm^{-1}\nabla^2 B$$

Co-density (temperature + light elements):

$$\chi = \alpha T + \beta C$$

Continuity:

$$\nabla\cdot(u,B) = 0$$

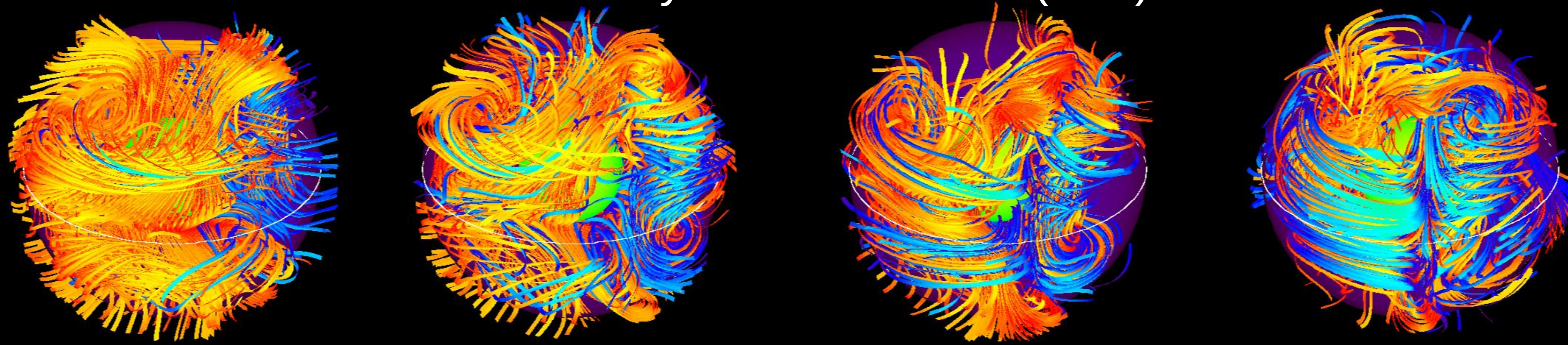
Transport:

$$\frac{\partial \chi}{\partial t} + u\cdot\nabla\chi = Pr^{-1}\nabla^2\chi + \varepsilon$$

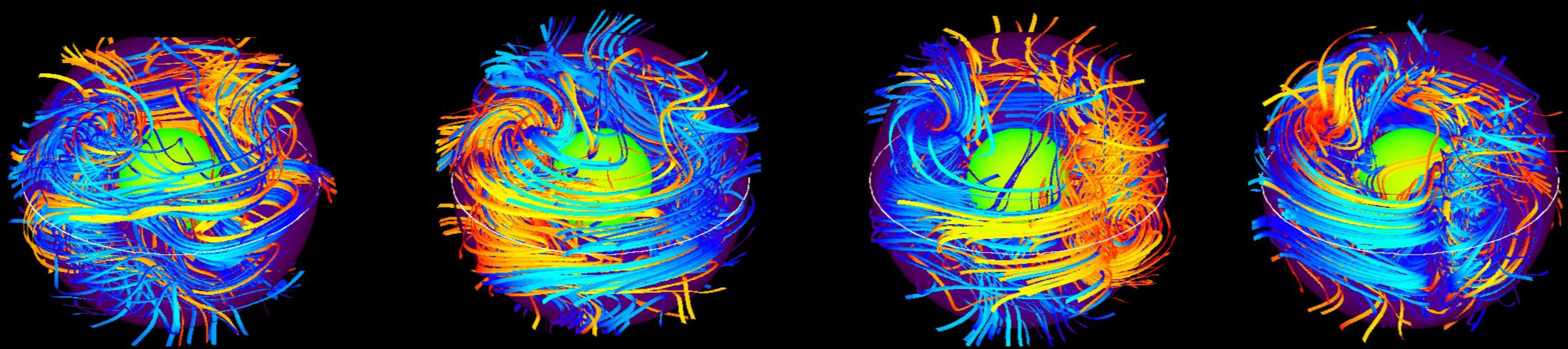
Self-sustaining dynamo: finite magnetic energy w/o external sources

Dynamo Parameters ----- Inputs -------	Earth's Core	Dynamo Models (Numerical, Laboratory)
E (Ekman #) rotational constraint	10^{-9} (turbulent) 10^{-13} (laminar)	10^{-3} - 10^{-7} > 10^{-6}
Ra (Rayleigh #) convective forcing	10^{20} - 10^{30}	10^{4} - 10^{10} mechanical forcing
Pr (Prandtl #) viscous/ thermal diffusion	0.1 - 1	~ 1 ~ 0.1
Pm (magnetic Prandtl #) viscous/magnetic diffusion ----- Outputs ------------	10^{-5} - 10^{-6}	0.1 - 20 ~ 10^{-5}
Rm (magnetic Reynolds #) fluid velocity	1000 - 2000	40(critical) - 1500 < 500
Λ (Elsasser #) magnetic energy density	0.1 - 1	0.1 - 1 0.1 - 1
Ro_l (local Rossby #) turbulence	~ 0.1	0.01 - 0.1 1 - 100

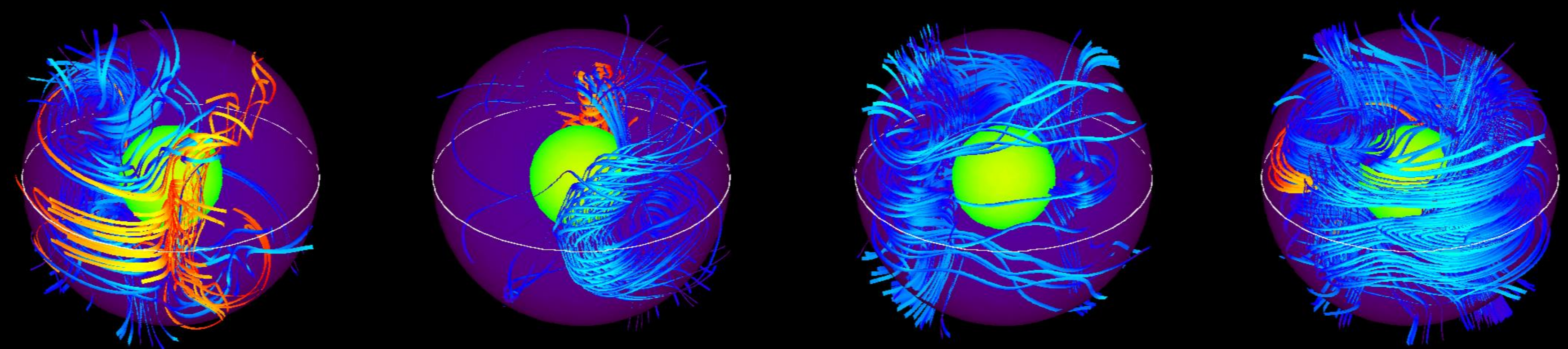
Numerical Dynamo Reversal (R-N)



1. Dipole Collapse Stage



2. Multi-polar Transition Field Stage



3. Dipole Regeneration Stage

Olson, Amit & Driscoll (2009)

Why geomagnetic polarity reversals matter

• Chronology: Geomagnetic Polarity Time Scale (GPTS)

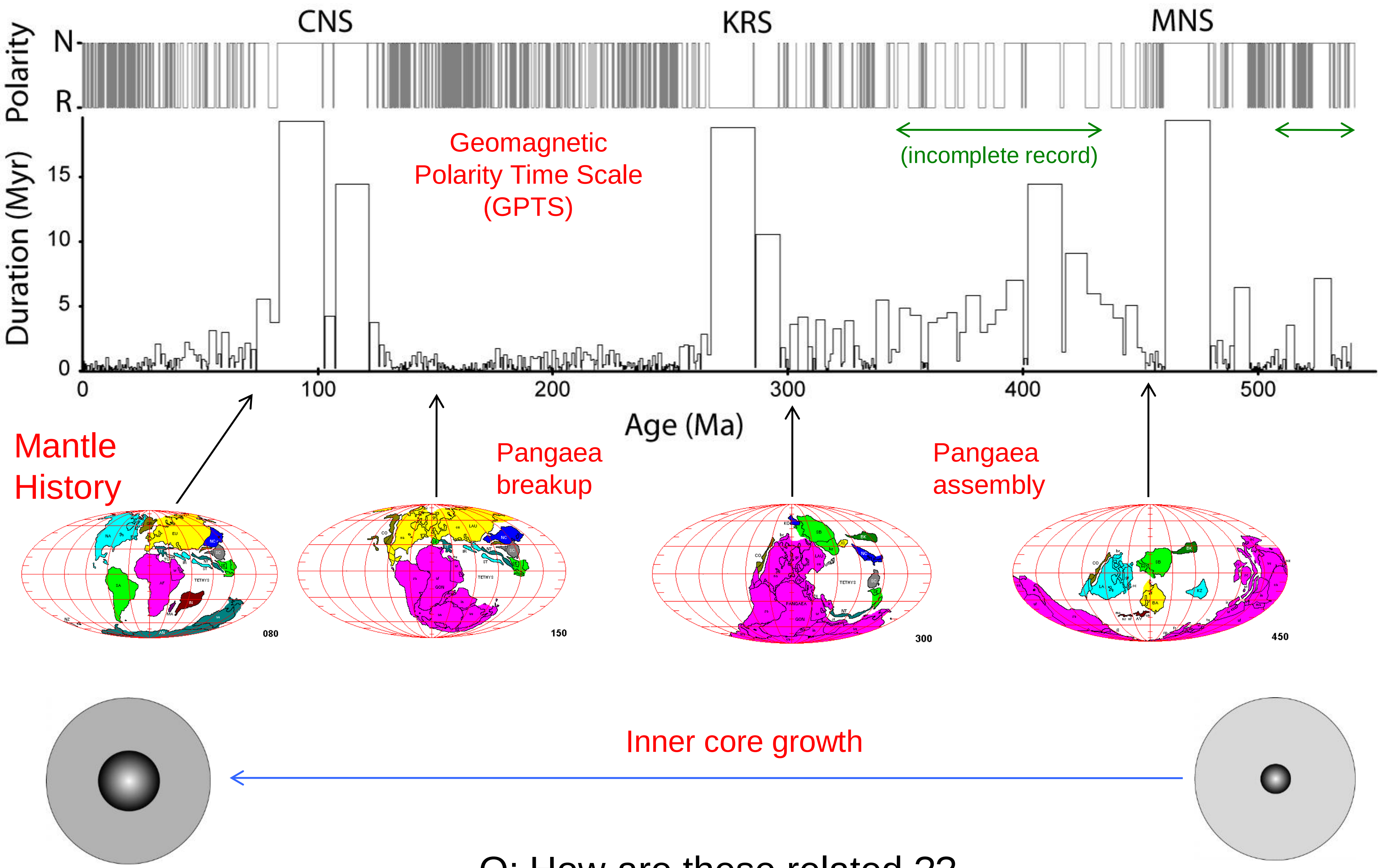
• Environmental perturbations:

1. Magnetosphere contraction during reversals ⇔ increased charged particle flux into the atmosphere.
2. Low field intensity during reversals affects ^{14}C production, ^{10}Be abundance, etc.

• Reversals (and excursions) = extreme forms of geomagnetic variability.

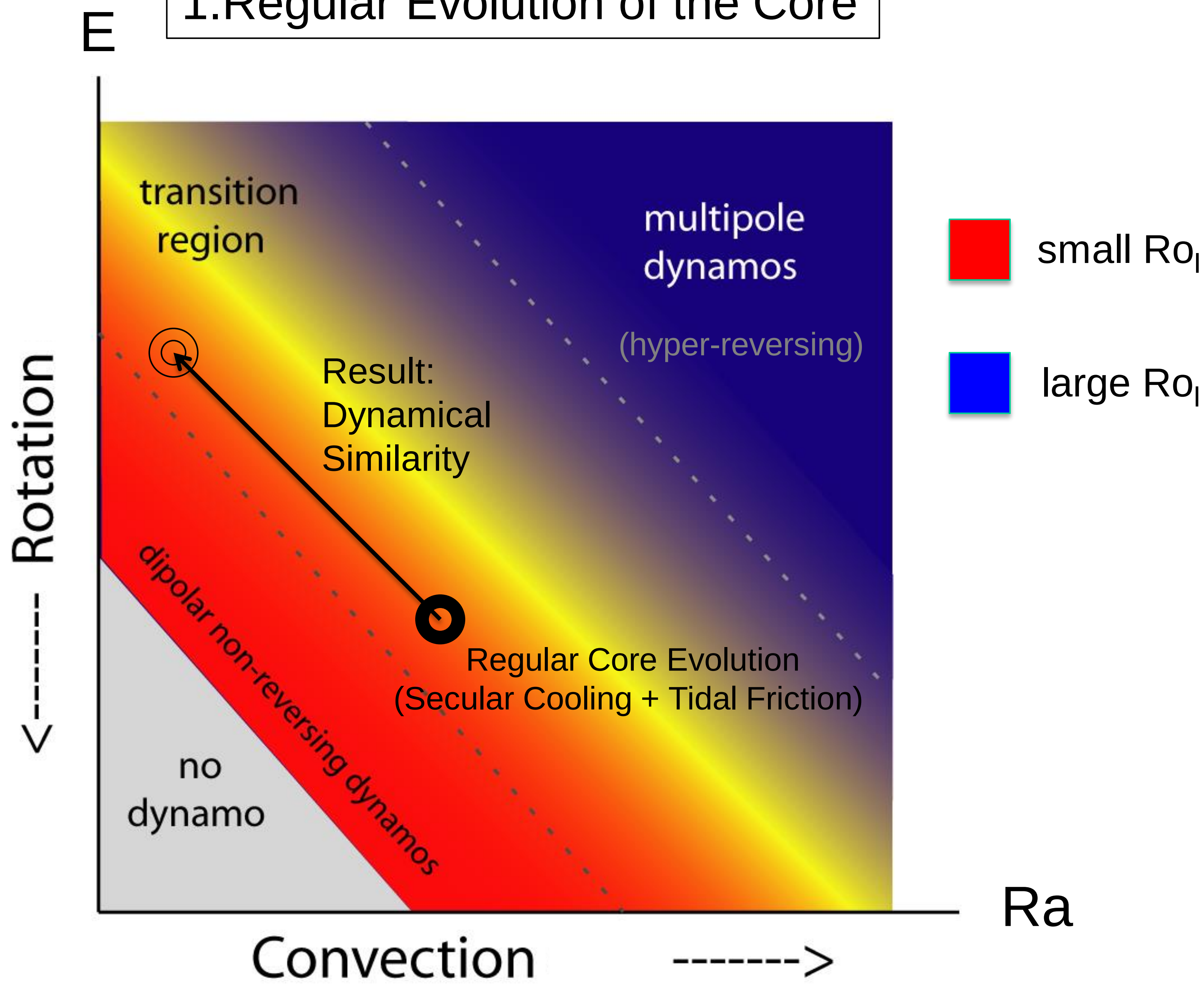
• Geodynamic connection: Reversal frequency depends on energy flow through the core, which is controlled by the mantle.

Core-Mantle Evolution (0-600 Ma)

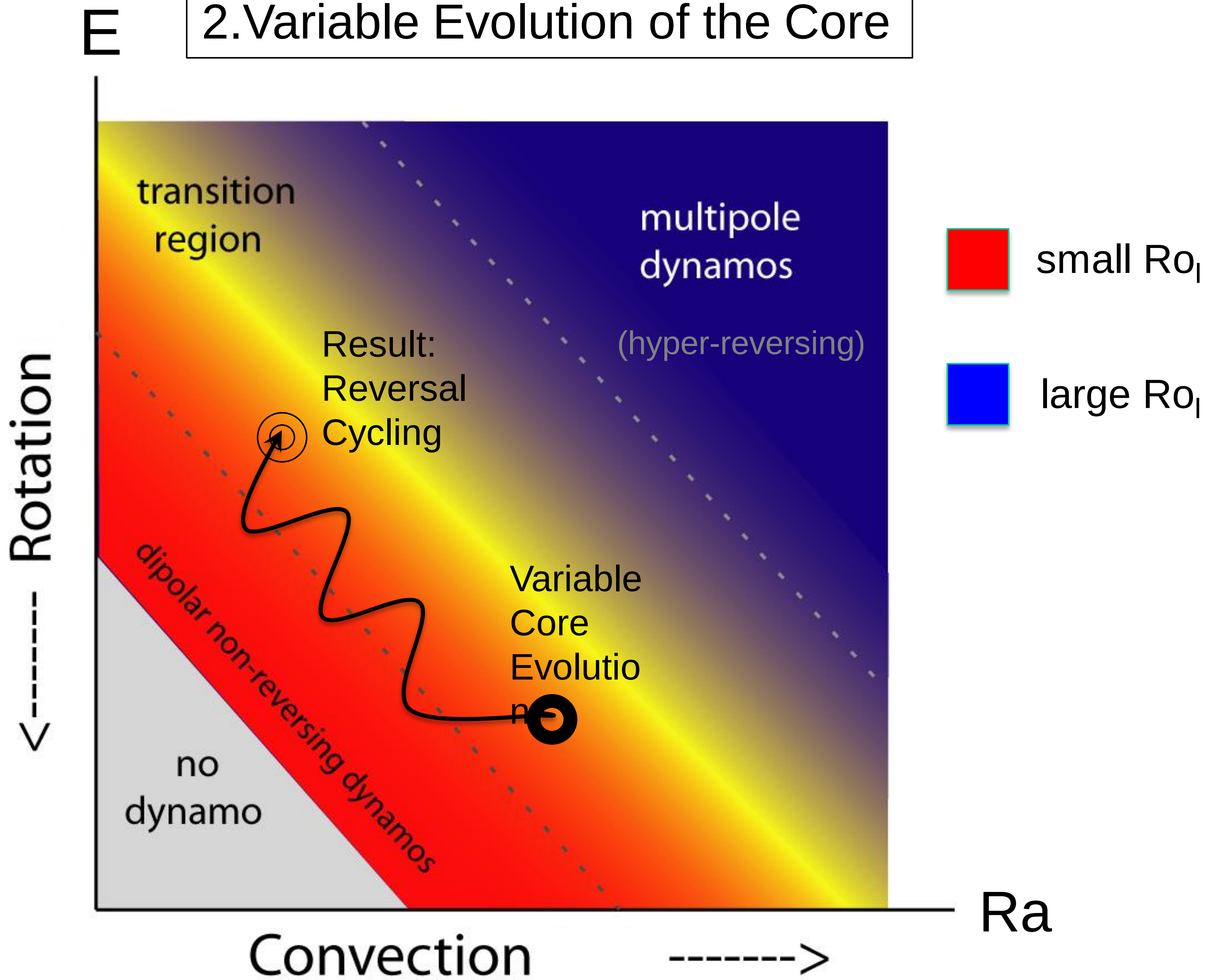


Q: How are these related ??

1.Regular Evolution of the Core



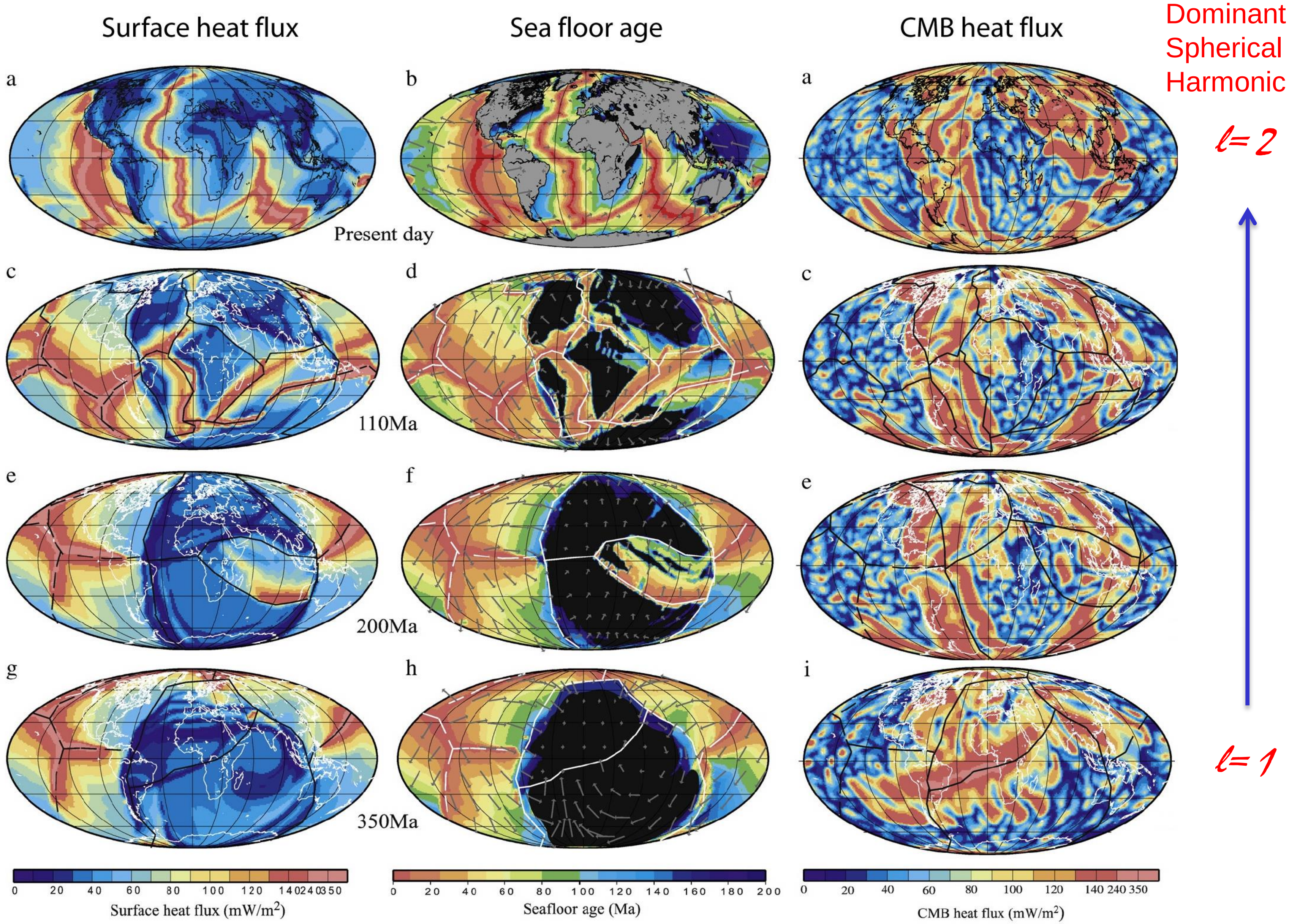
2.Variable Evolution of the Core



A Whole Earth Dynamo

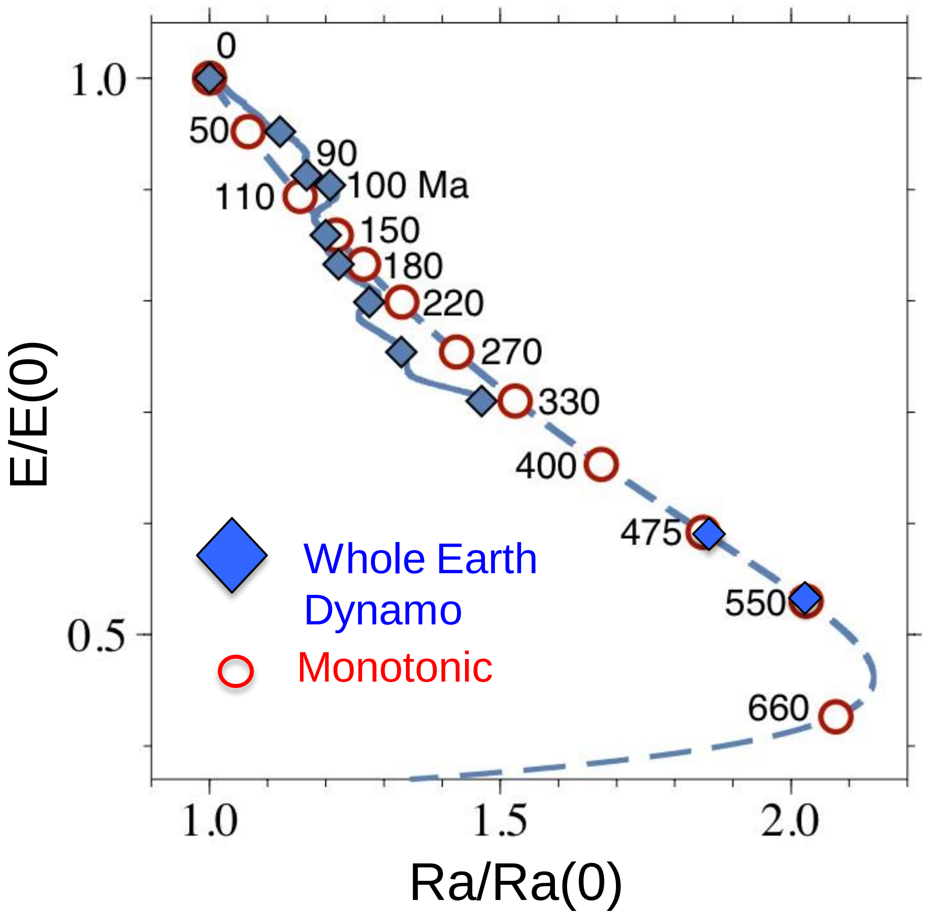
- Driven by CMB heat flux from time-variable mantle history constrained by plate motions (Zhang & Zhong, EPSL 2011)
- Calculate the evolution of the core, including
  - a) Inner core growth
  - b) Chemical differentiation
  - c) Increase in length of day
- Derive time-dependent dynamo control parameters and boundary conditions
- Tune the dynamo to the present-day geomagnetic reversal rate
- Compare dynamo reversals with the GPTS through the Phanerozoic

Mantle History from a Mantle GCM

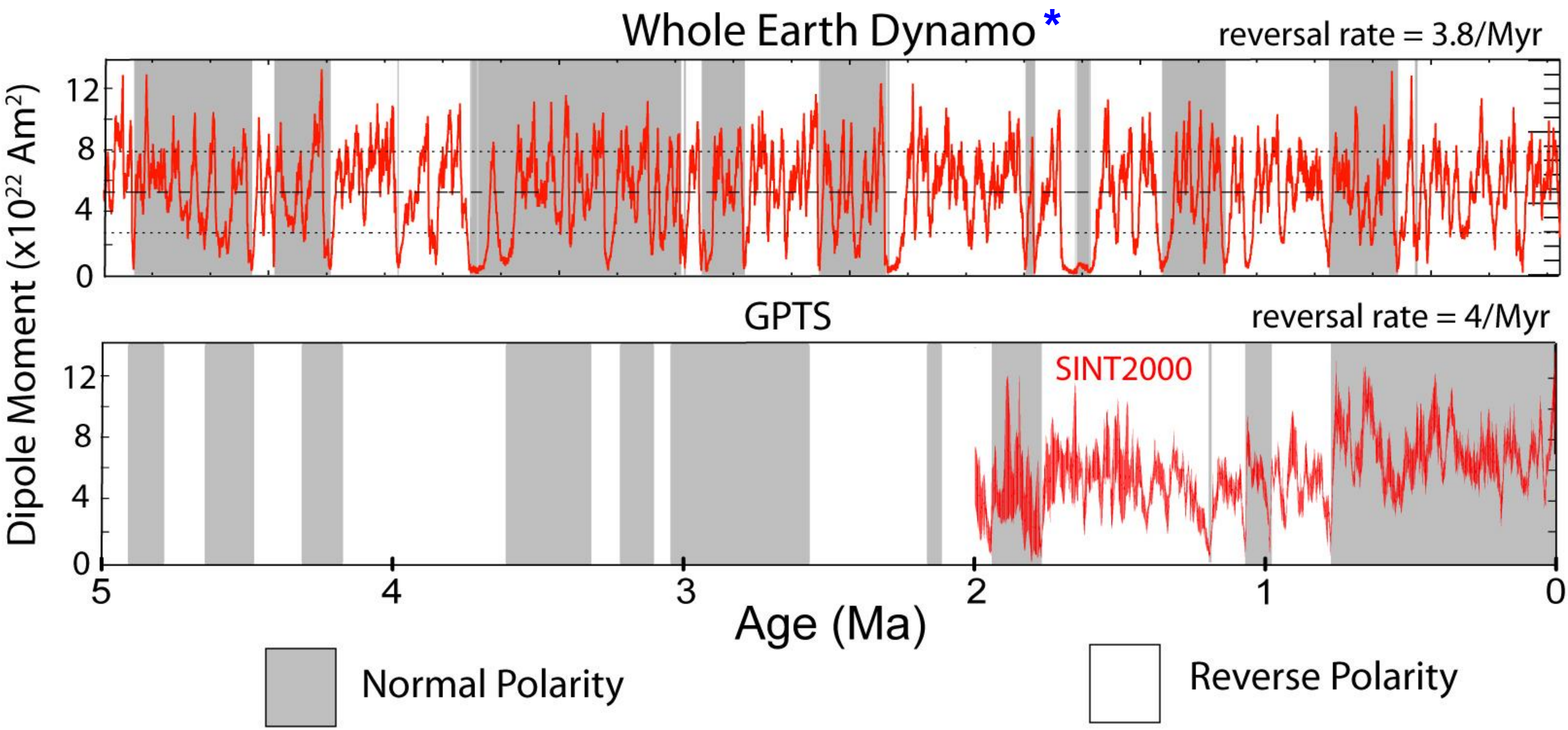


(Zhang & Zhong, EPSL 2011)

Dynamo Control Parameter Evolution



Reversal Rate Tuning: 0-5 Ma

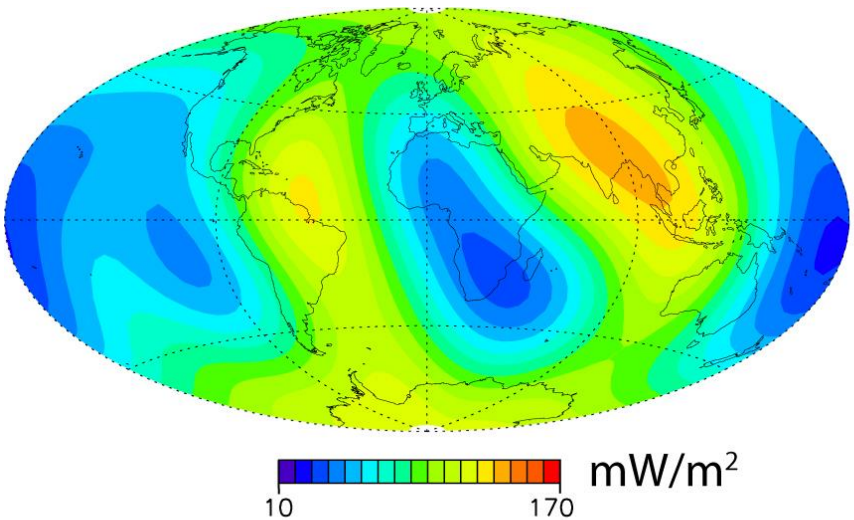


* E(0)=5.7e-3; Ra(0) =3e4; Pr=1; Pm=20; τ_d=200kyr

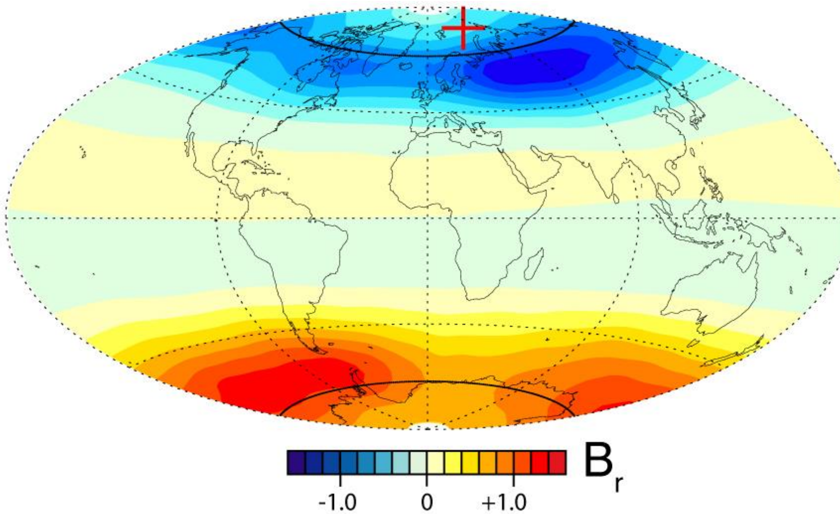
SINT2000: Valet et al. (2005)

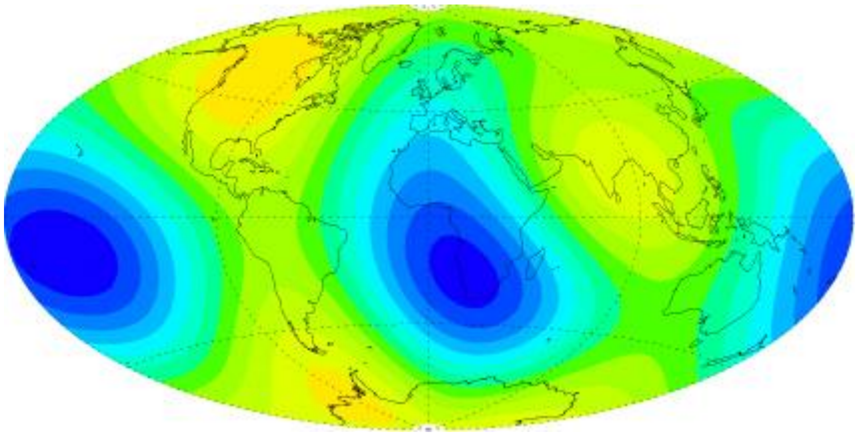
Whole Earth Dynamo: Present-day (0-5 Ma time average) structure

CMB heat flux

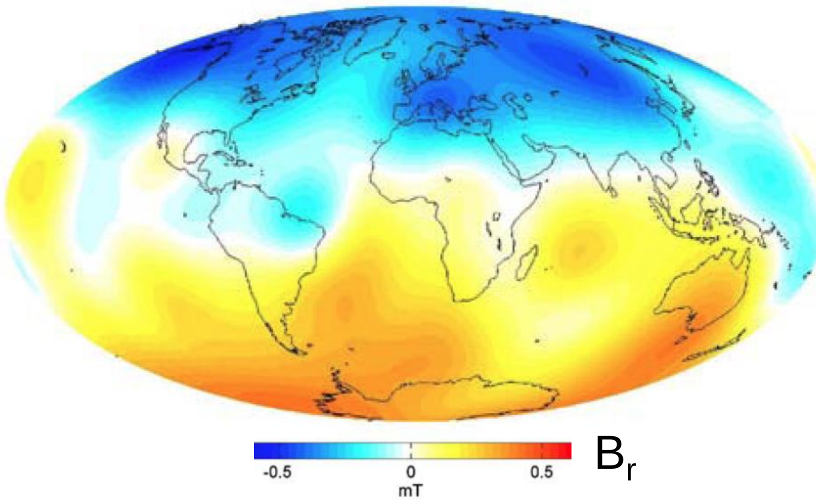


CMB magnetic field





CMB heat flux from seismic tomography

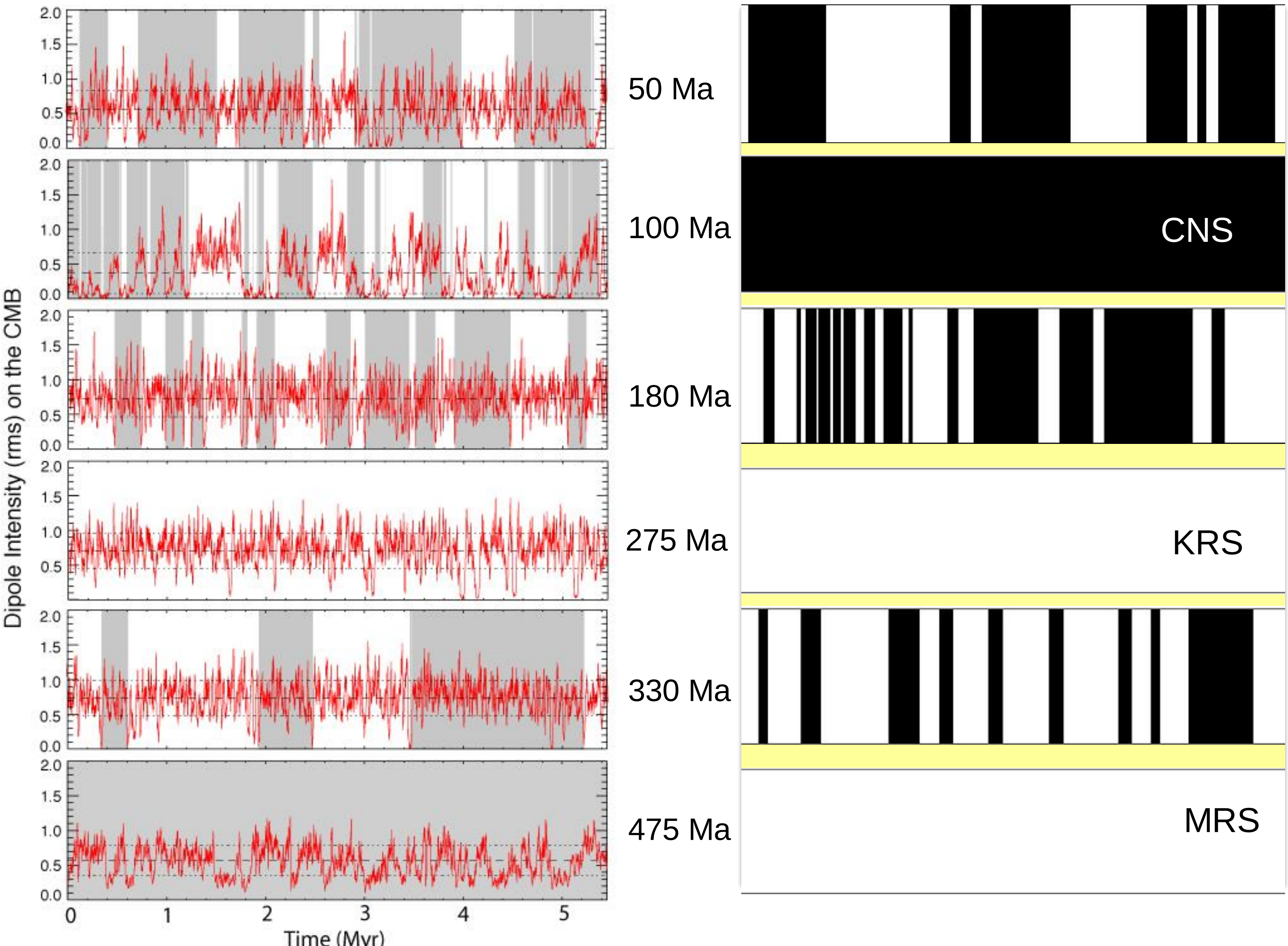


0-5 Ma CMB Paleomagnetic Field

(Johnson & Constable, 1995)

Whole Earth Dynamo Reversals

GPTS (5.4 Myr segments)



Olson, Deguen, Hinnov & Zhong (2013)

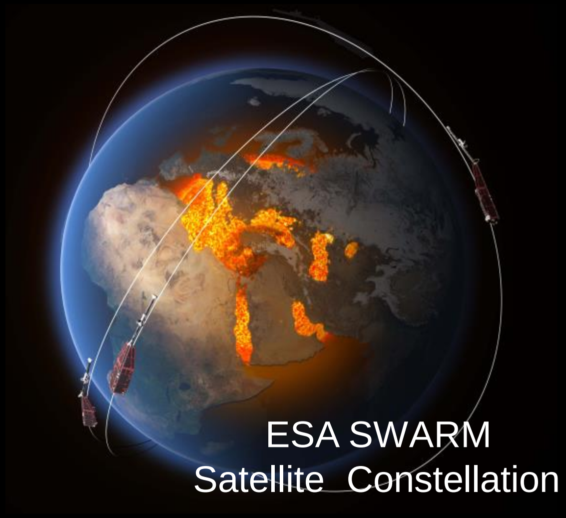
Where is the Frontier?

Planned

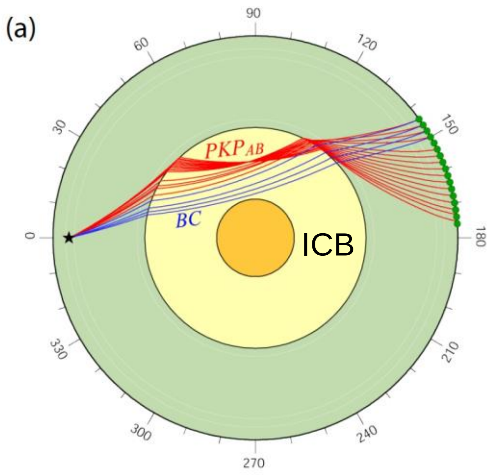
- Advanced numerical dynamos: faster rotation, lower viscosity…
- Improved satellite images of the geomagnetic field
- Spacecraft missions

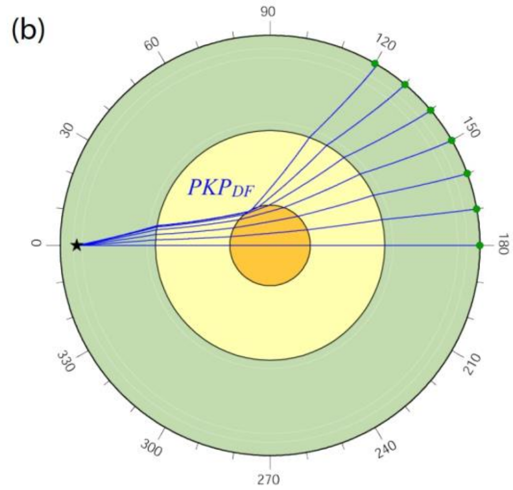
Serendipity

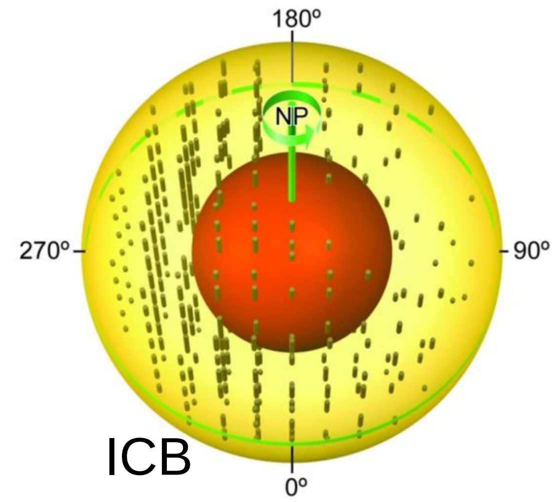
1. Inner core structure and dynamics
2. Geomagnetic Jerks
3. Exo-planet magnetism

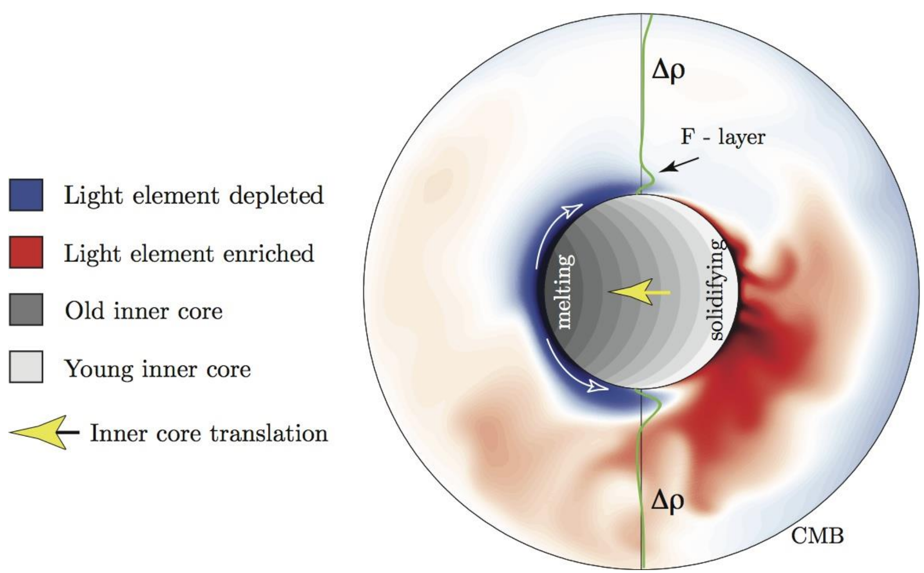


Inner Core Anisotropy: E-W dichotomy



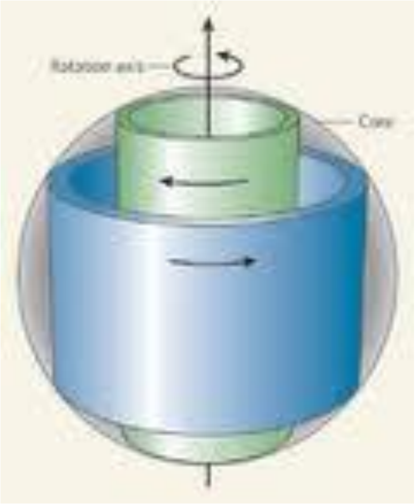






Lopsided Inner Core Growth & Translation

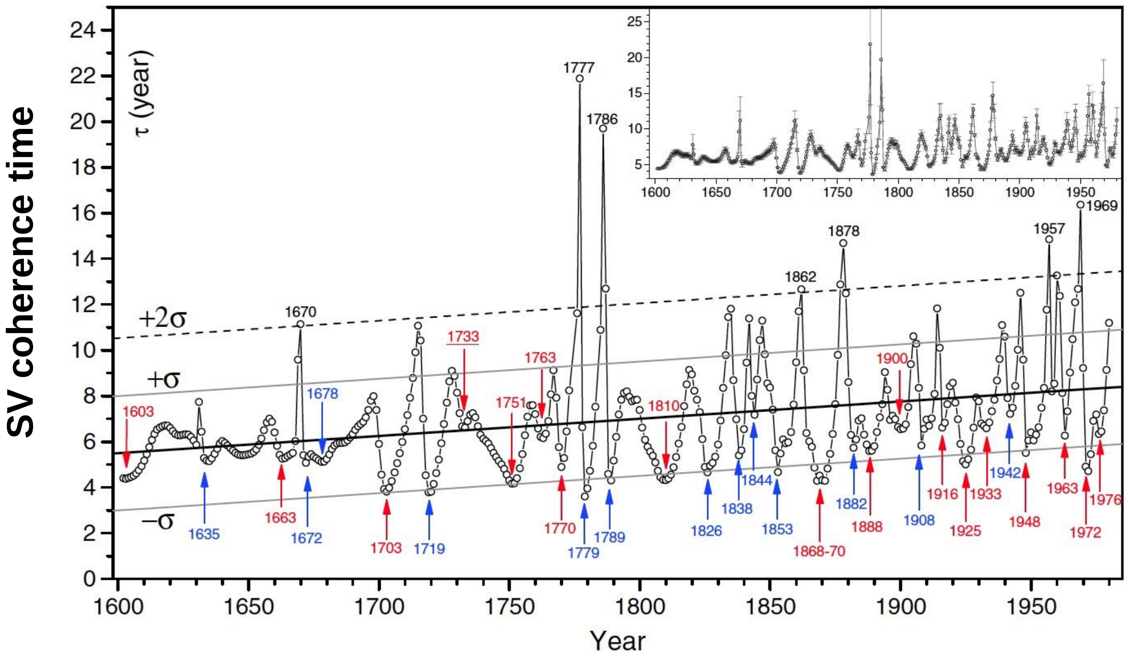
Souriau & Romanowicz, *Phys Earth Planet. Inter*. 101, 33 (1996)
Sun & Song, *Phys. Earth Planet. Inter*. 167, 53 (2008)
Irving et al., *Geophys. J. Int*. 178, 962 (2009)
Monnereau et al. *Science* 328, 1014 (2010)
Alboussiere et al. *Nature* 466, 744 (2010).
Buffett, *Phys Today* (2013)….

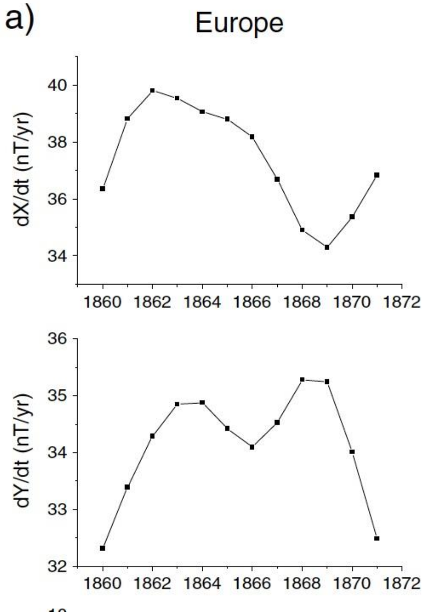


Geomagnetic Jerks and Torsional Oscillations

Q: What is a geomagnetic jerk?

- abrupt change in secular variation (SV)
- come from the core field
- related to TOs?



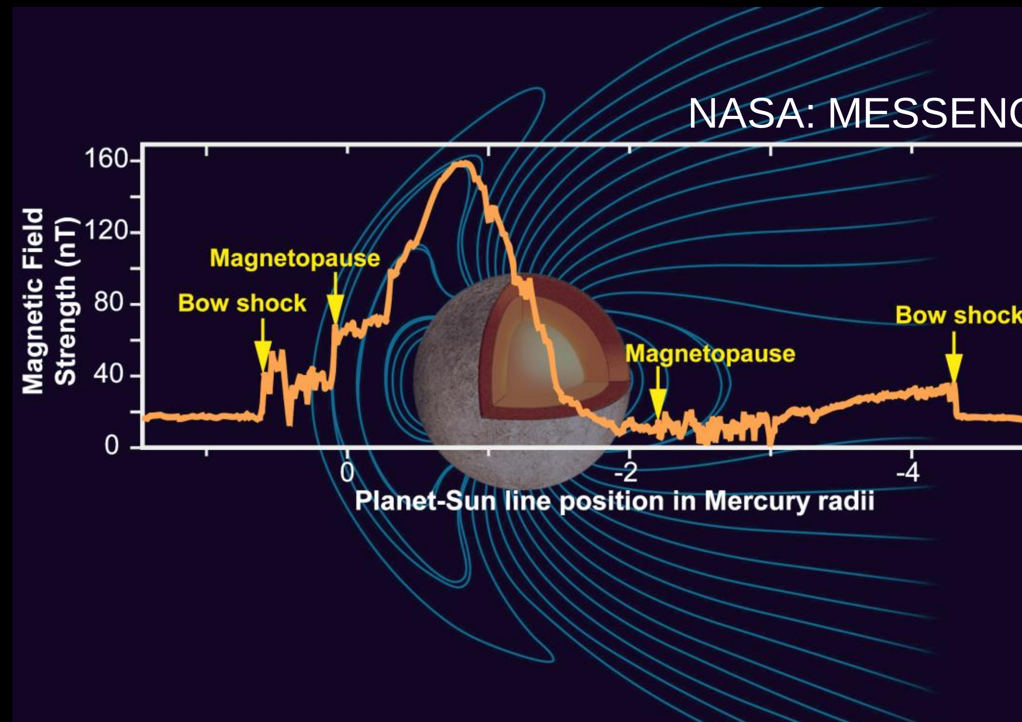


Qamili et al., G-Cubed 14(4), 2013

Burke & Franklin (1955)

Mercury’s Faint Dynamo

NASA: MESSENGER



- 300 nT surface intensity (1% of Earth's)
- 480 km north polar offset dipole < 3^{o} tilt
- Little (or no) observed SV

Anderson et al., Science 333, 1859 (2011)