Geodynamo regimes dependence on the amplitude of CMB heat flux heterogeneity

Filipe Terra-Nova, Hagay Amit and Gaël Choblet

Laboratoire de Planétologie et Géosciences
Nantes Université

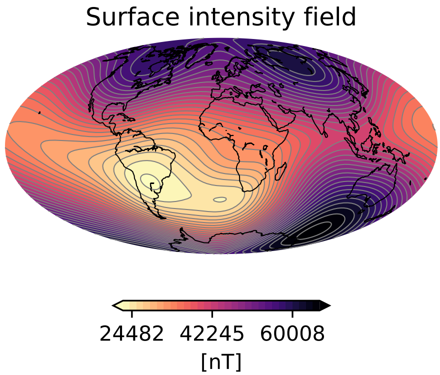
July 7, 2023

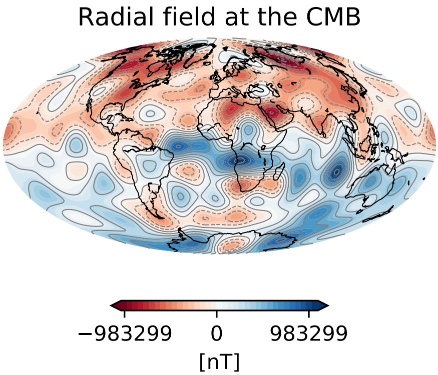
Contents

Contents

Dipole dominance

The Earth's magnetic field is dominated by an axial dipole.

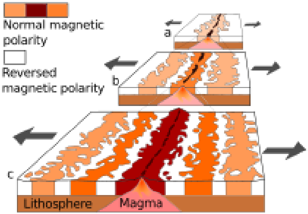


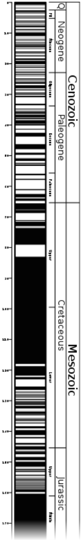


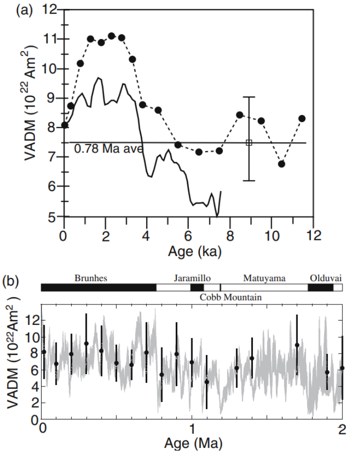
Observations at the surface -> Downward continuation until the CMB.

(Built from COV-OBS.x1 geomagnetic field model (Gillet et al., 2015) in 2019)

Observed (seafloor stripes, left) paleomagnetic reversals (middle) accompanied by weak field (right).







(Paleomagnetic record from e.g. Gradstein et al. (2012); VADM from Olson and Amit (2006))

MHD equations

Numerical dynamo simulations are self-consistent solutions to the full set of magnetohydrodynamic (MHD) equations:

$$E\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} - \nabla^2\mathbf{u}\right) + 2\hat{z}\times\mathbf{u} + \nabla P' = Ra^*\frac{\mathbf{r}}{r_o}C + \frac{1}{Pm}(\nabla\times\mathbf{B})\times\mathbf{B}, \tag{1}$$

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

$$\frac{\partial C}{\partial t} + \mathbf{u}\cdot\nabla C = \frac{1}{Pr}\nabla^2 C, \tag{3}$$

$$\nabla\cdot\mathbf{u} = 0, \tag{4}$$

$$\nabla\cdot\mathbf{B} = 0. \tag{5}$$

Control parameters

The Ekman number (Viscous vs. Coriolis forces):

$$E = \frac{\nu}{\Omega D^2}. \tag{6}$$

Rayleigh number (Convection vs. retarding effects):

$$Ra = \frac{\alpha g_0 q_o D^4}{\kappa \nu k}. \tag{7}$$

The Prandtl number and the magnetic Prandtl number are ratios of diffusivities:

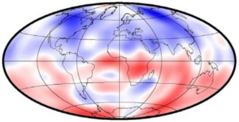
$$Pr = \frac{\nu}{\kappa}, \tag{8}$$

$$Pm = \frac{\nu}{\eta}. \tag{9}$$

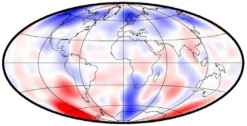
Control parameters are far from Earth's values but output, notably the magnetic Reynolds number (*Rm*) close to 1000 like Earth.

Dipole dominated dynamos: High-latitude patches at the TC; Columnar convection in agreement with QG; Antisymmetric helicity.

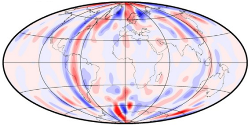
Observed radial field



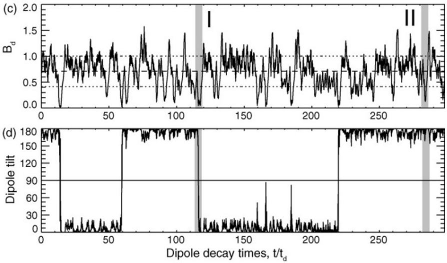
Modeled radial field



Modeled flow



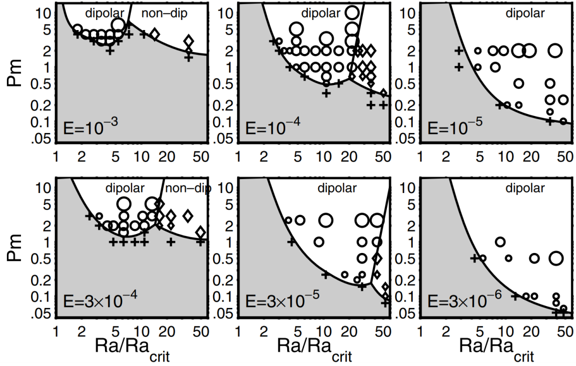
Reversing Dynamos: Long-chrons and rapid polarity transitions when the dipole drops.

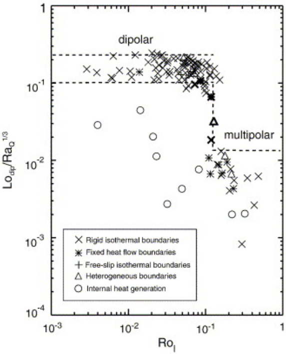


(Geomagentic field (Jackson et al., 2000) in 1980 (top left); Dynamo results from Terra-Nova et al. (2019): Radial field at CMB (top middle) and tangential divergence (top right); Dipole intensity B_d and tilt from Olson et al. (2009))

Dynamo regimes

Parameter study on the dependence of dynamos regimes: failed dynamo, dipole dominated or reversing dynamos.





Transition from dipole dominated to reversing at a critical local Rossby number

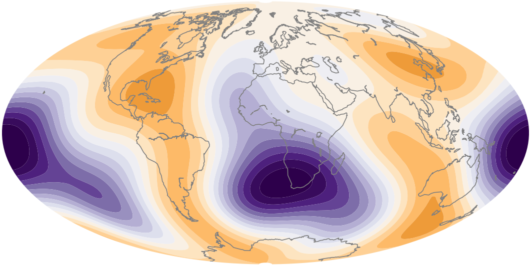
$Ro_\ell = Ro\frac{\bar{\ell}_u}{\pi}$ where $\bar{\ell}_u = \frac{\sum \ell \langle u_\ell \cdot u_\ell \rangle}{2E_{kin}}$

(Figures from Christensen and Aubert, 2006 and Olson and Christensen 2006)

Outer Boundary condition

Prescribe the outer boundary heat flux using inferences from tomographic seismic studies assuming that differences in density are directly proportional to changes in temperature.

(a) δq at the CMB



The amplitude of the imposed anomaly:

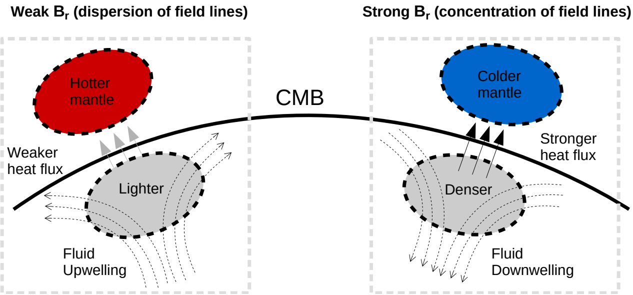
$$q^* = \frac{q_{max} - qmin}{\langle q_o \rangle} \tag{10}$$

Built using the tomographic seismic model for the lowermost mantle from Masters et al. (2000)

Main question: how does the boundary condition affect dynamo regime?

The structure and dynamics of Earth's core are determined by the heat flux across the core-mantle boundary (CMB).

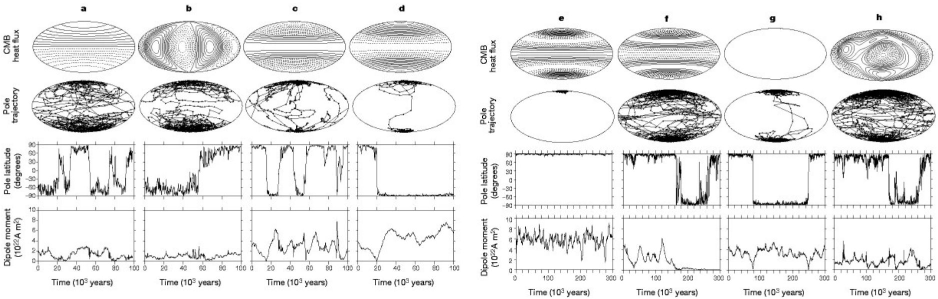
- Gives the maximum heat budget going out of the core.
- Mantle sees CMB as isotherm; Core sees CMB as prescribed heat flux.



(e.g. Gubbins et al, 2007; Lay et al., 2008; Terra-Nova et al., 2019; Mound and Davies, 2023)

Main question: how does the boundary condition affect dynamo regime?

The role of the Earth's mantle in controlling the frequency of geomagnetic reversals.



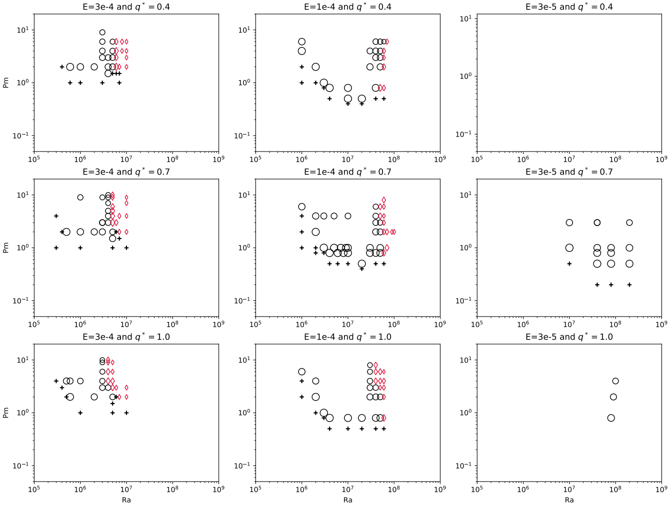
- The pattern of CMB heat flux strongly affects reversibility.
- Equatorial cooling (c,f) favors reversals, polar cooling stabilizes the axial dipole (d,e)

(Glatzmaier et al., 1999)

Contents

Dynamo regimes vs control parameters including q^*

Black circles are dipole dominated, red diamonds reversing and black crosses failed dynamos.

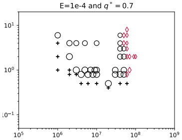


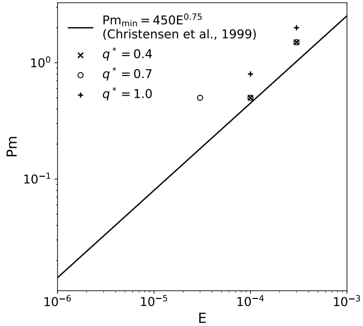
- Increasing convection/rotation destabilizes/stabilizes the dipole (as in Christensen and Aubert, 2006).
- Increasing CMB heat flux heterogeneity amplitude inverses the slope of reversals transition in Ra/Pm space.

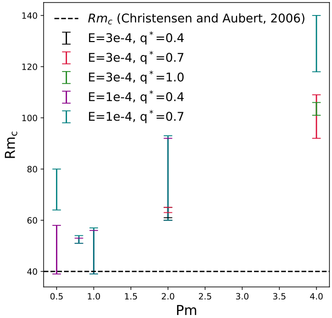
(All runs of numerical dynamos simulations using MAGIC code with prescribed tomographic outer boundary heat flux)

Dynamo onset limit

Similar to the critical Rayleigh number (Ra_c) for the onset of convection, the critical magnetic Reynolds number (Rm_c) gives the onset of dynamo.



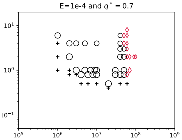


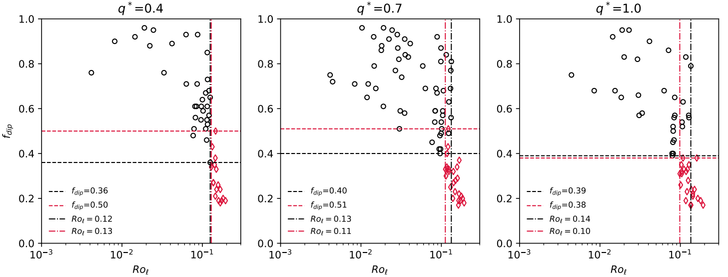


- Weak dependence on q^* suggestive of heterogeneity unfavorable for dynamo (destruction of columnar convection (Helicity)).
- Rm_c controlled by Pm more than by Ra. Effect of q^* not clear yet.

Reversing limit

The amount of **inertia** as a **proxy** to the **reversing limit**.



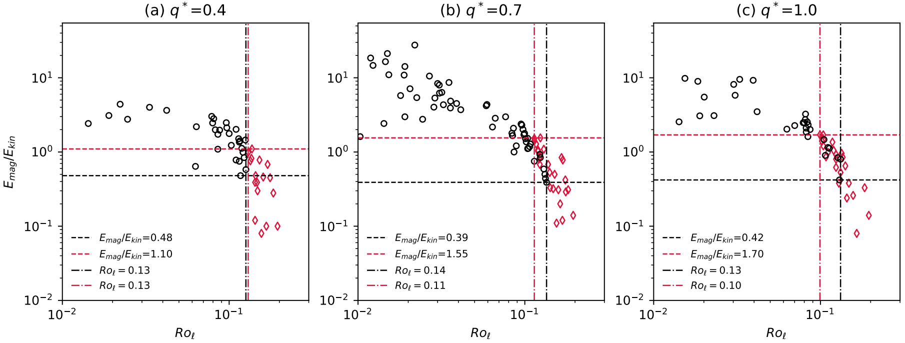


The relative dipole field strength on the outer boundary is defined by:

$$f_{dip} = \left(\frac{\left(\frac{r_e}{r_c}\right)^6 \frac{4}{3}\left((g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2\right)}{\left(\frac{r_e}{r_c}\right)^{2n+4} \sum_{n=1}^{12} \sum_{m=0}^{n} \frac{(n+1)^2}{2n+1} \left((g_n^m)^2 + (h_n^m)^2\right)} \right)^{1/2}$$

- CMB heat flux heterogeneity produces reversals with lower Ro_ℓ.
- Separation of dipole dominance between reversing and non-reversing.

Ratio between magnetic and kinetic energies as a proxy to the MAC balance (≈ 1).

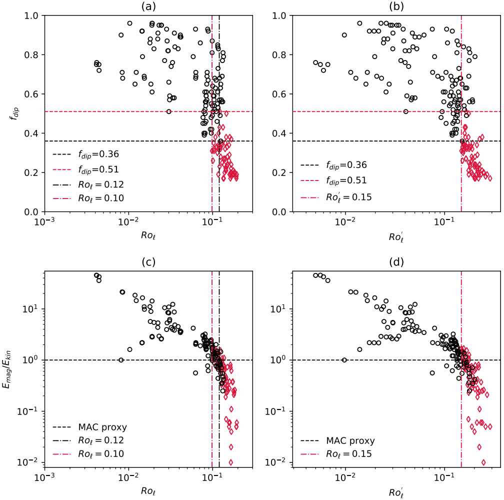


- Reversing numerical dynamos with homogeneous boundary are in CIA balance.
- Increasing CMB heat flux heterogeneity gives reversing dynamos in the MAC (Earth-like) balance.

(For force balance references see Aubert et al., (2017); Schwaiger et al., (2019))

Reversing limit

Heterogeneity corrected local Rossby number: $Ro_\ell' = Ro_\ell(1 + \frac{q^*}{2})$

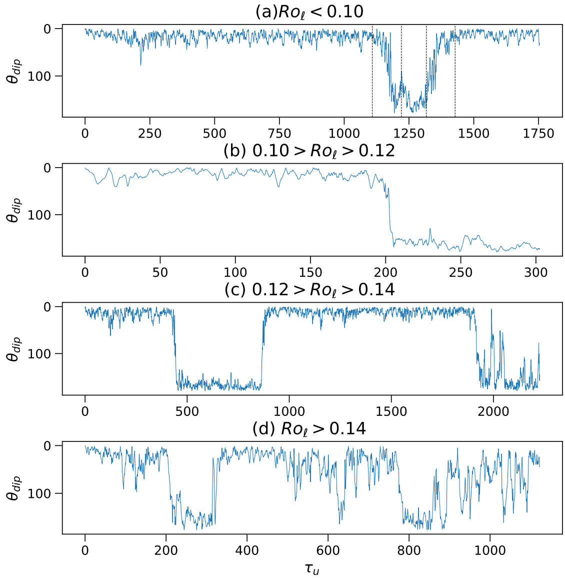


- Better marks the reversing transition.

(For Ro_ℓ' see Olson and Amit, (2014)).

Reversibility for different Ro_ℓ

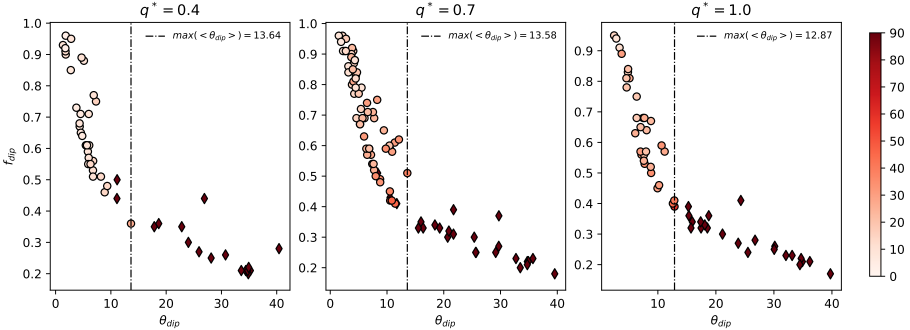
Same q^* for all models.



- Largest Ro_ℓ produces frequent reversals (not Earth-like).
- Smaller Ro_ℓ gives rare Earth-like reversals.

Certainty about non-reversing dynamos?

Mean (x-axis) and maximum (colors) dipole tilt may indicate if a non-reversing dynamo may reverse.



- Larger $\langle\theta_{dip}\rangle$ values result in reversals.
- Non-reversing dynamos: smaller maximal $\langle\theta_{dip}\rangle$ (vertical line) with increasing q^* => heterogeneity promotes reversals.
- Increasing maximum θ_{dip} with increasing q^* => heterogeneity promotes dipole tilt stronger time dependence.

Thank You