An introduction to the Geodynamo

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ISTerre
Institut des Sciences de la Terre

Outline

1. Observations
2. How to generate a magnetic field?
   - Dynamo effect
   - Where on Earth can we generate a magnetic field?
   - Experimental dynamos
   - Numerical dynamos
   - Throughout Earth's history
3. Convective geodynamo models
   - Turbulence and strong magnetic fields
   - Numerical modeling of polarity reversals

What's the role of Earth's magnetic field?

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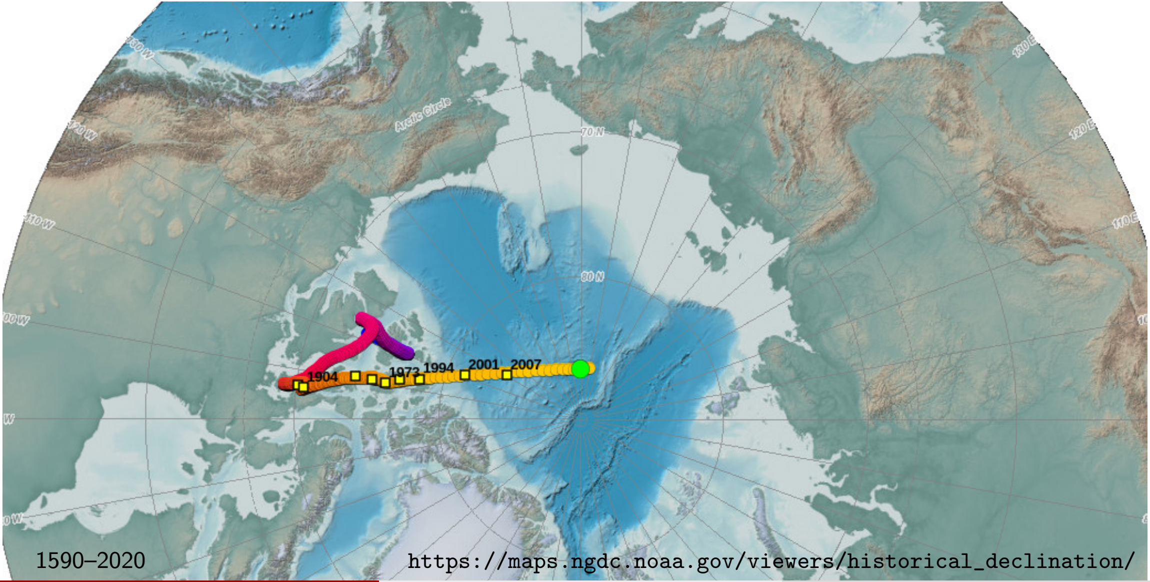
- Mars has no life and no magnetic field.
- But a magnetic field does NOT shield from cosmic rays, the atmosphere does.
- A magnetic field **may** be important to keep an atmosphere from being eroded by solar/stellar wind, at least in case the surface gravity is not enough.

Lammer+ 2008, Space Science Reviews, *Atmospheric escape and evolution of terrestrial planets and satellites*.

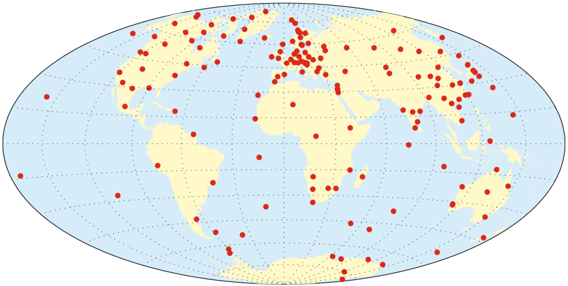
Earth's magnetic field moves



1590–2020 https://maps.ngdc.noaa.gov/viewers/historical_declination/

Geomagnetic field measurements

Started by Gauss (and others) in 1836, today we have many magnetic ground observatories



(from Finlay+ 2016)

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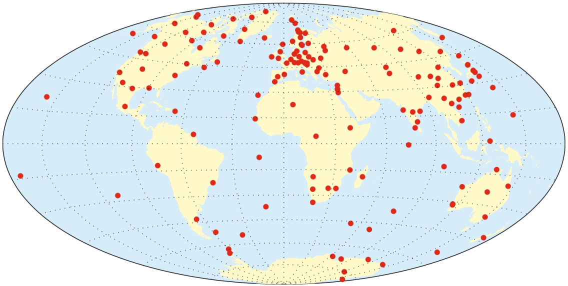

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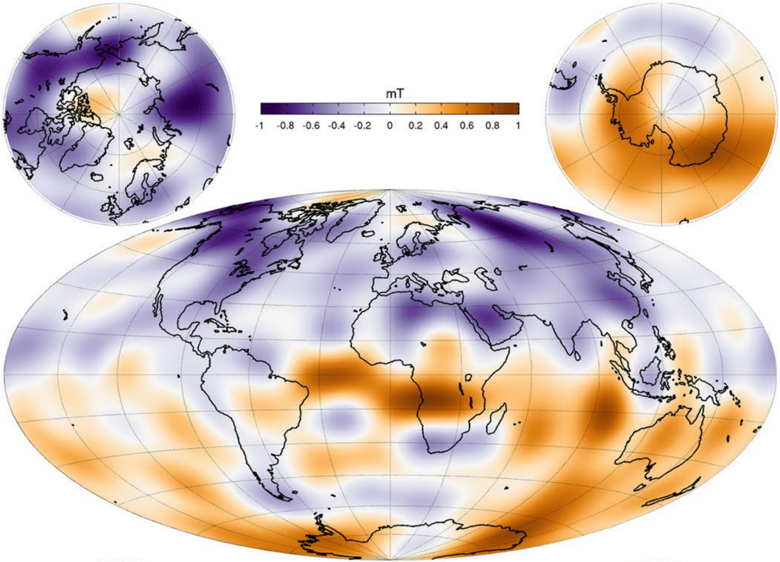
Measures from satellites since 1979. Currently 3 dedicated satellites (SWARM).

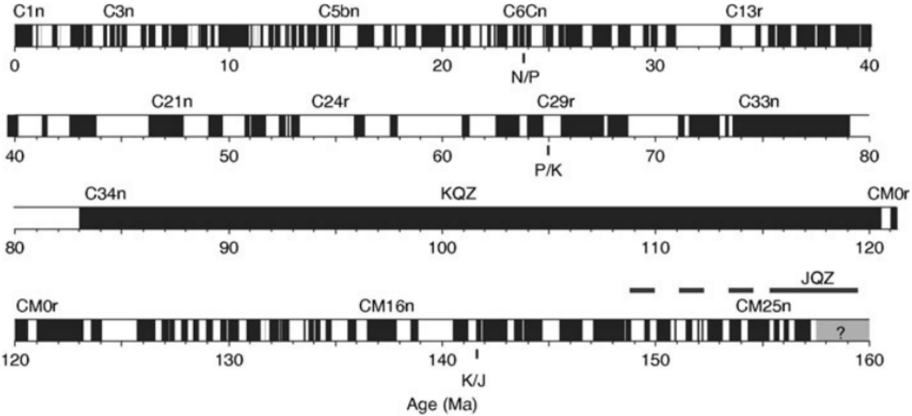
Geomagnetic field models



Magnetic field at the Core-Mantle Boundary (CMB) in 2015.

(CHAOS-6 model, from Finlay+ 2016).

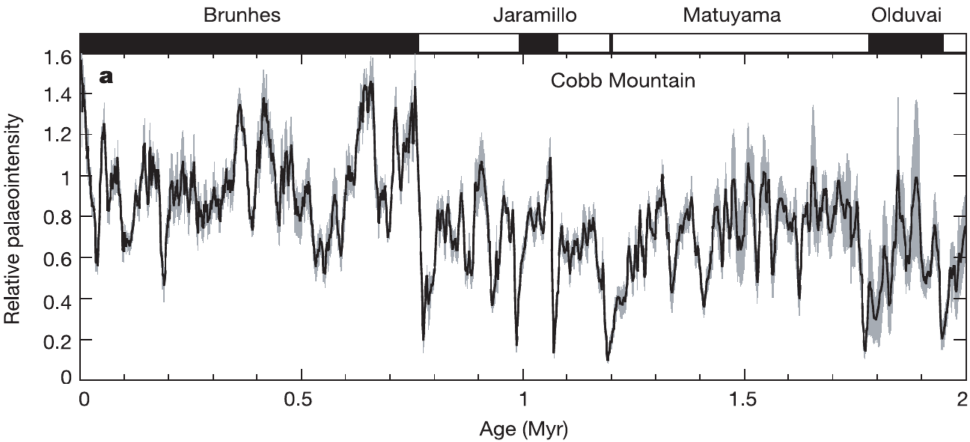
Polarity reversals



- **A superchron** with the same polarity for almost 40 Millions years.
- **Frequently reversing** periods, where a given polarity stays for 1 Million year or less.

from Hulot+ (2010).

Paleointensity models: sint2000



- Typical intensity variations from 0.5 to 1.5 times the mean – factor 3 between min and max outside reversals.

from Valet+ (2000).

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Issues:

- How to maintain electric charge?
- Geomagnetic reversals $\mathbf{B} \to -\mathbf{B}$ would require to reverse $\mathbf{v}$ too...

Dynamo effect

Induction: moving a (neutral) electric conductor in a magnetic field produces electric currents

Induction equation

$$\partial_t \mathbf{B} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma} \Delta \mathbf{B}$$

- $\mathbf{B} = 0$ is always solution.
- But **sometimes** there is also a $\mathbf{B} \neq 0$ solution: dynamo action
- if $\mathbf{B}$ is solution, $-\mathbf{B}$ is also a solution.

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magnetic field variations = Induction + ohmic losses

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When is the induction term capable of surpassing ohmic losses?

Requirements to generate a magnetic field (I)

The velocity should be large enough.

Necessary condition: large enough velocities

$$Rm \gg 1 \quad \Leftrightarrow \quad \sigma VL \gg 10^6\ [SI]$$

- electrically conducting (σ) fluid layer (e.g. liquid iron core, $\sigma \sim 10^6$ [SI])
- large scale L (e.g. 3500 km for the Earth)
- fast fluid motions V (e.g. > 10 km/yr $= 3 \times 10^{-4}$ m/s in the Earth's core)

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$\Rightarrow \quad Rm \gtrsim 1000$ in the core today. OK

Requirements to generate a magnetic field (II)

The flow should not be too simple.

No matter how fast, you will never get a dynamo from:

- a solid-body rotation
- a purely "toroidal" flow.
- a two-dimensional flow.

Thermal convection is OK, precession not straightforward.

Requirements to generate a magnetic field (III)

Enough power should be available to overcome (ohmic) dissipation.
Depends on:

- the strength of the magnetic field you want to sustain.
- the details of turbulent flow (dissipation length-scale).

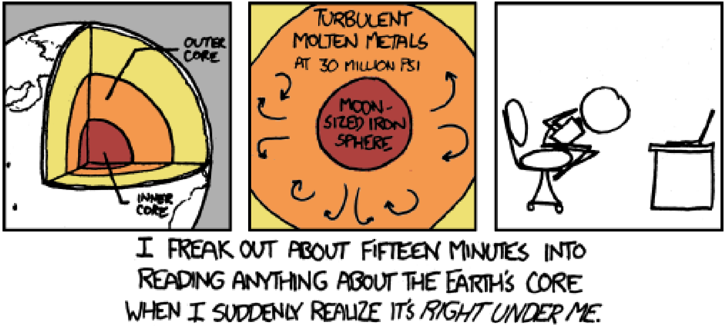
Numerical and experimental studies suggest 0.1 – 1 TW is needed for the geodynamo.

Christensen & Tilgner, Nature 2004
Christensen, Space Sci Rev 2010.

Back to Earth

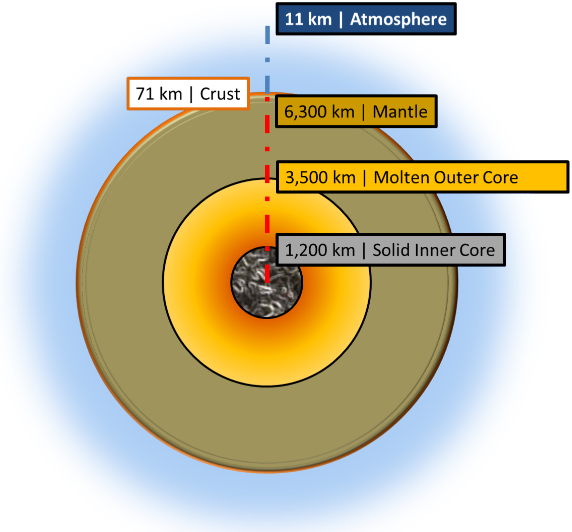
Where can we reach all these requirements?

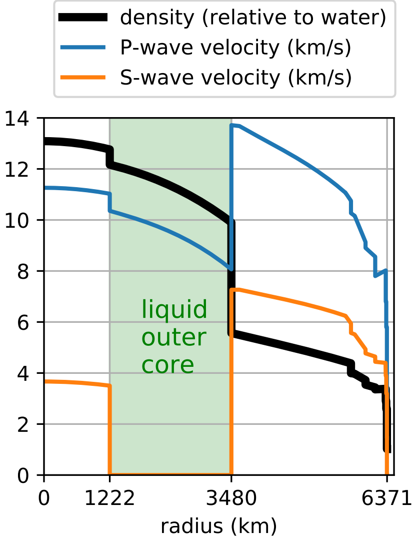
Structure of the Earth



http://www.xkcd.com/913/

Structure of the Earth





Cool facts about the Earth's core

- Viscosity of water
- **Earth's spin (Coriolis force) dominates the dynamics.**
- Large scale motions at the top of the core have speeds around 10 km/year (0.3 mm/sec, turnover time is about 200 years, $\sim 10^6$ times faster than plate tectonics)
- Turbulent motion (very high Reynolds number $Re \gtrsim 10^8$).
- Magnetic field is dominated by a tilted dipole.
- Heat flux extracted by the mantle ($\sim$ 10TW, $<$ 100mW/m^2).
  - Strong convection (very high Rayleigh number $Ra \gg 10^{20}$? Probably many times critical).
- The magnetic energy is 10000 times larger than the kinetic energy!

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1. Liquid metal motion within ambient magnetic field produce electric currents (like your favorite wind turbine or nuclear power plant)
2. Electric currents produce magnetic field (like the magnetic locks on doors)
3. If your flow is adequate and motions are fast enough, you may amplify the ambient field.

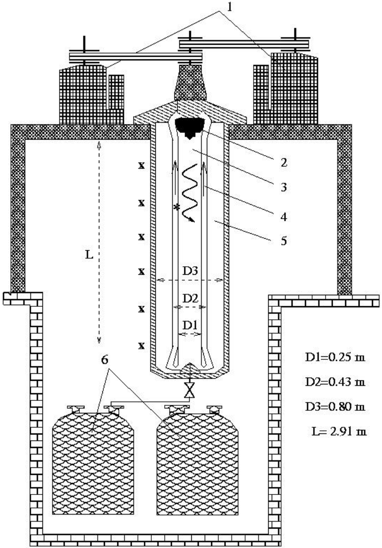
Some dynamo attempts in the lab

Constrained flows: dynamo action osberved

- Riga experiment (1999):
  2 m^3 Na, 200 kW, dynamo
- Karlsruhe experiment (1999):
  3 m^3 Na, 500 kW, dynamo

Unconstrained (turbulent) flows: no (real) dynamo action

- VKS2 (2006): 0.15 m^3 Na, 300 kW, dynamo only with ferromagnetic parts
- Maryland 3 meter sphere (ongoing):
  13.5 m^3 Na, 500 kW, no dynamo (yet)



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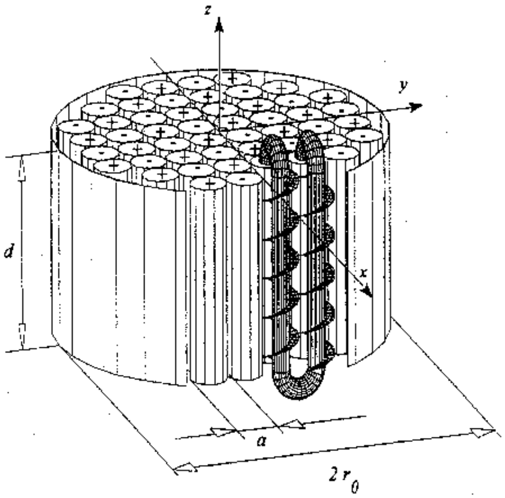

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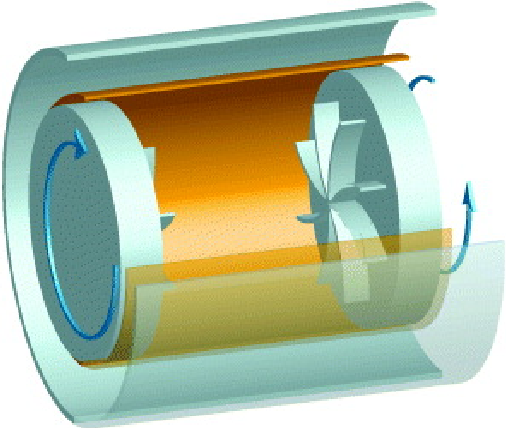

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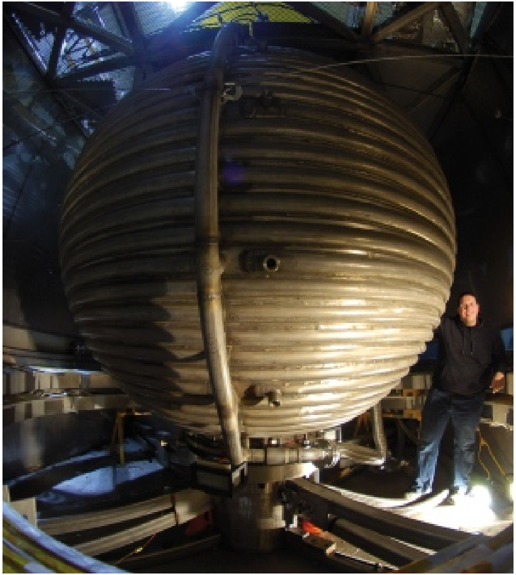
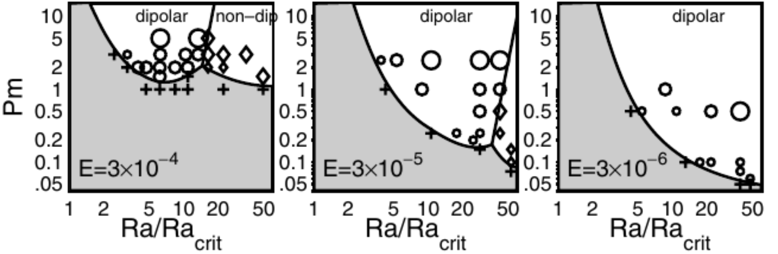


Numerical dynamos: convection

Buoyancy driven (convection) in rotating spheres

- dynamos since 1995
- work amazingly well for $Rm > 50$.
- columnar flows (due to planet spin) seem to be the key.
- scaling laws available since 2006, although viscosity is still very important in the numerics.

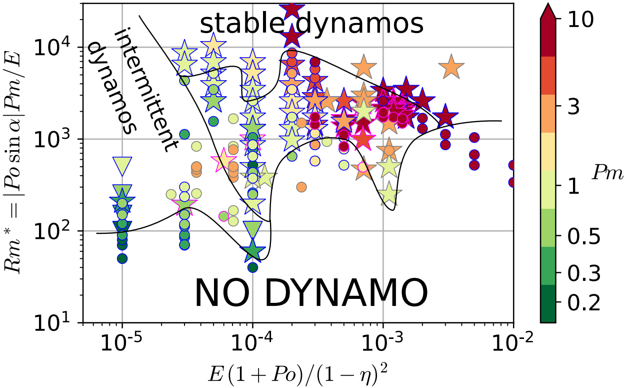


from Christensen & Aubert 2006

Numerical dynamos: precession

Precession in spheres

- dynamo possible, but not ubiquitous (Cebron+ 2019)
- NO scaling law available.
- low-viscosity dynamos with large-scale vortices
- does deformation (ellipsoid) help?



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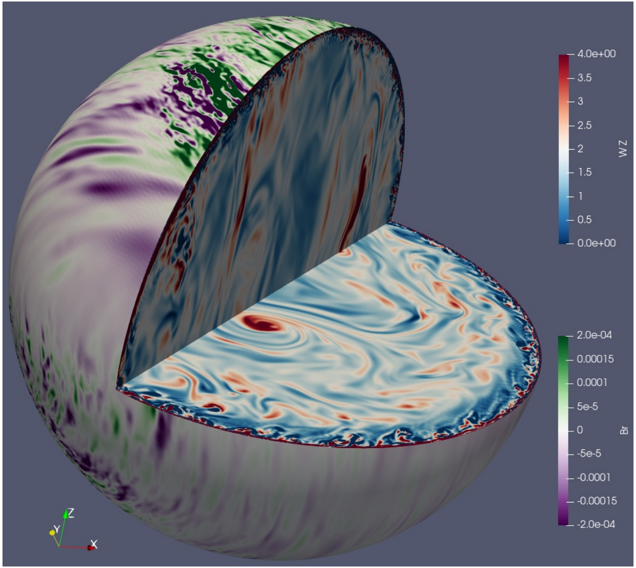
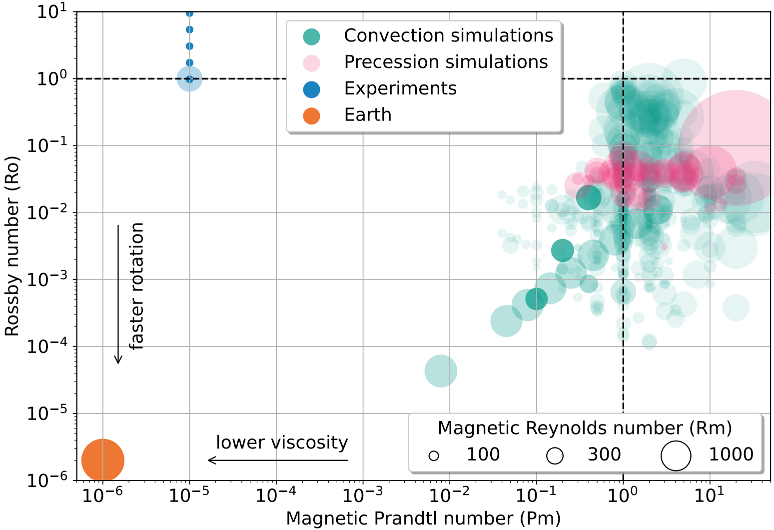
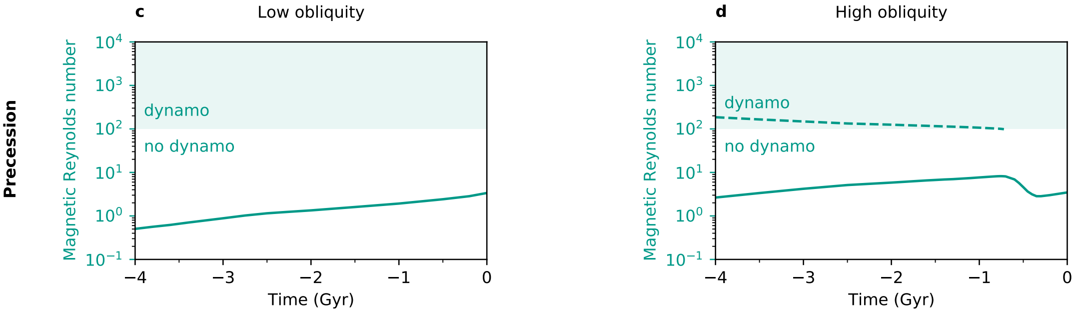


A parameter space comparison



A precession geodynamo throughout Earth history?

We cannot estimate the power provided by precession, but we can estimate the fluid velocities and thus *Rm*:

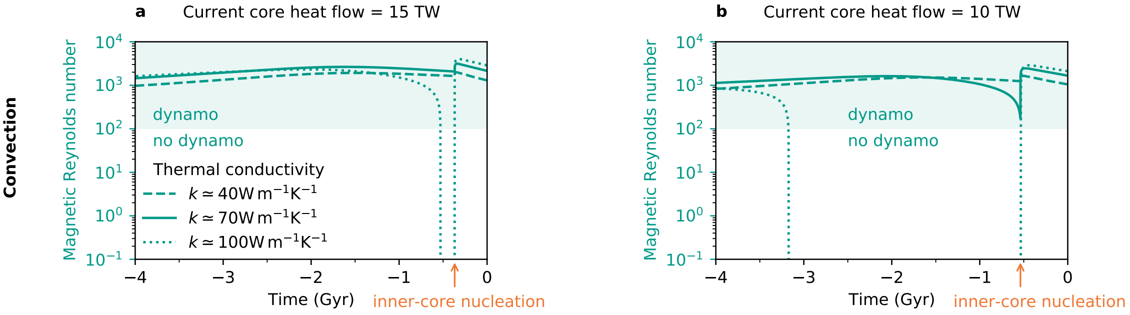


Precession alone is very unlikely to explain the geodynamo.

from D. Cébron and M. Landeau (work in progress)

A convection geodynamo throughout Earth history?

Expected *Rm* accross Earth history.



Convection is likely to explain the geodynamo, ruling out too high thermal conductivity.

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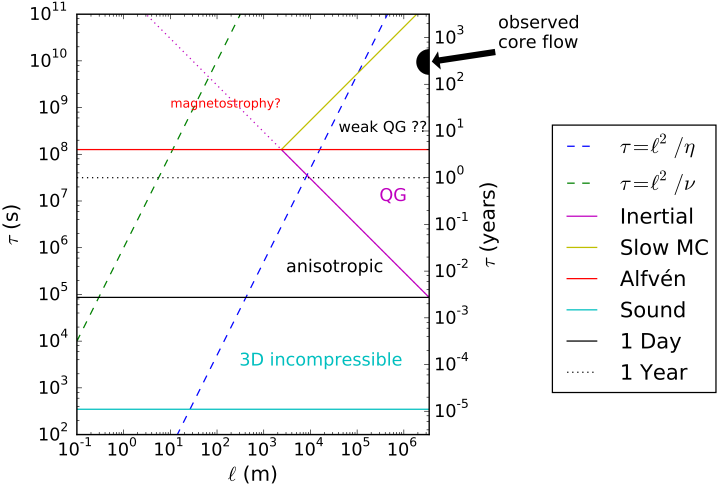
Regime diagram of the Core



$$\tau = \Omega^{-1} L/\ell$$

$$\tau = \ell\, L\Omega/V_A^2$$

$$\tau = L/V_A$$

Nataf & Schaeffer (2015) *Turbulence in the Core*, in "Treatise on Geophysics"

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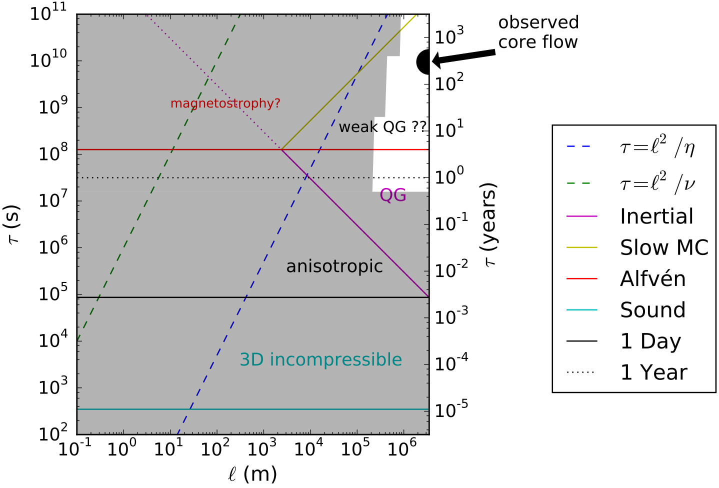

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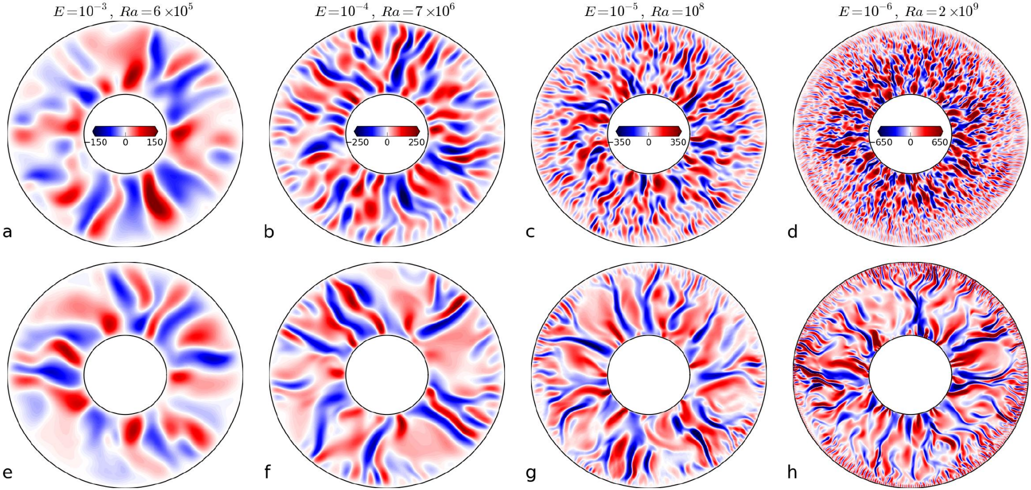
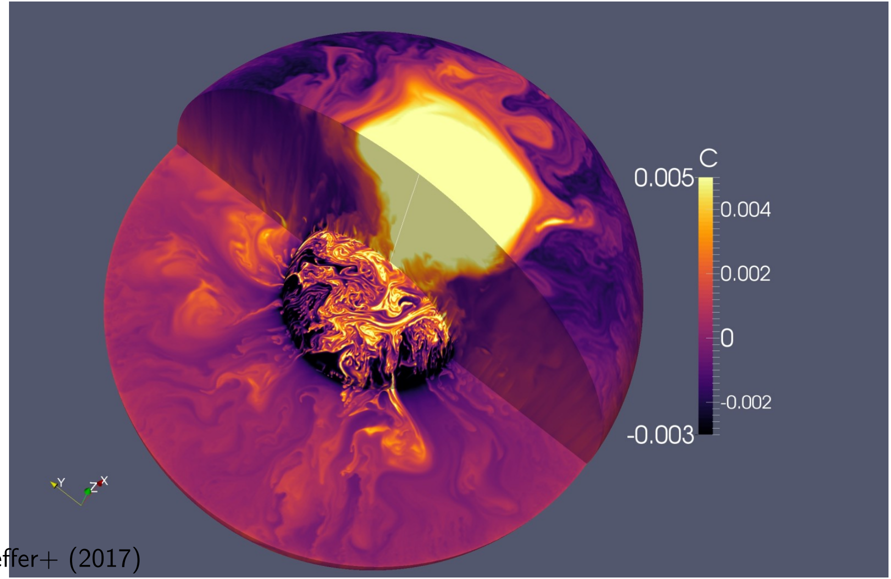
The influence of the magnetic field



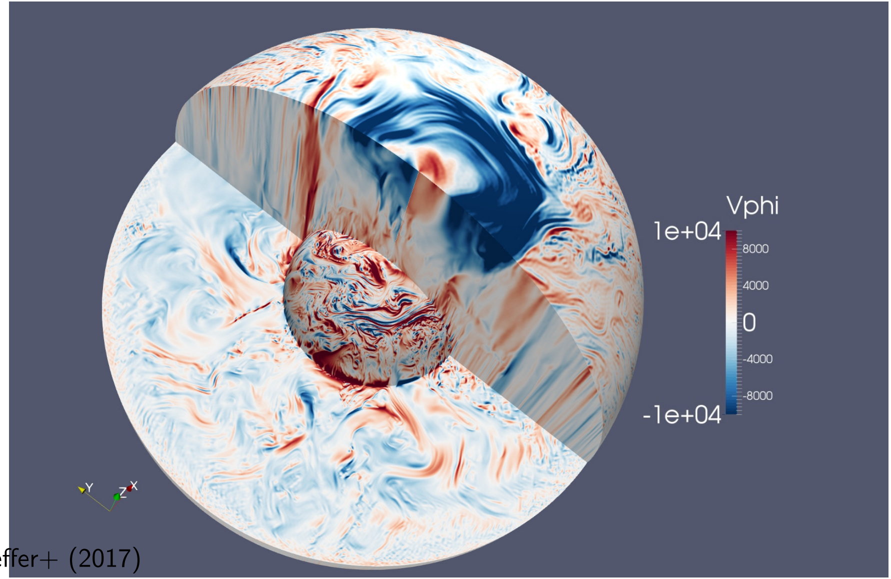
Top/Bottom: Without/With magnetic field. From left to Right: decreasing viscosity (and increasing B).
From Yadav+ (2016)

3D views: temperature field



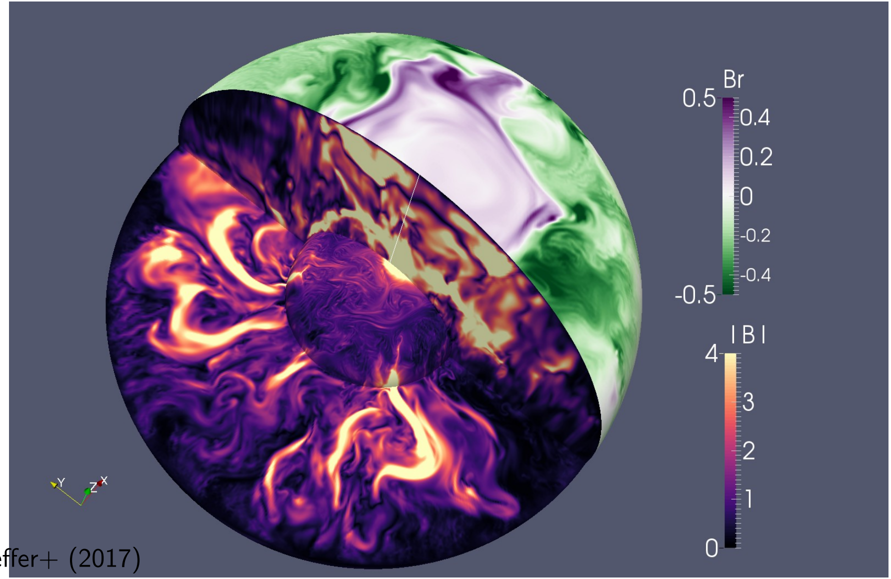
From Schaeffer+ (2017)

3D views: velocity field



From Schaeffer+ (2017)

3D views: magnetic field



From Schaeffer+ (2017)

What about polarity reversals?

These high-resolution simulations do not reverse.

- Simulated time < 5000 years.
- To run for longer times requires to reduce resolution and hence cheat on the viscosity...

25+ years of geodynamo simulations: reversals

- 1995 : Glatzmaier & Roberts
  - hyperviscosity
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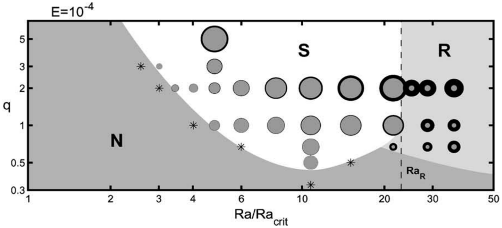

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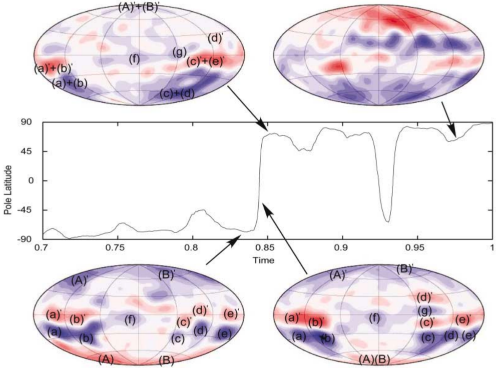

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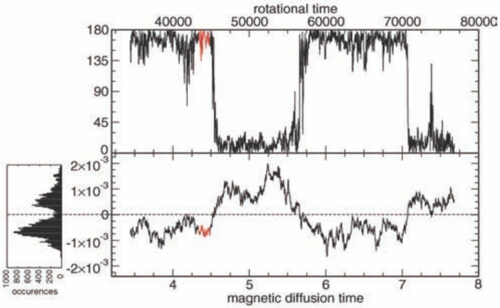

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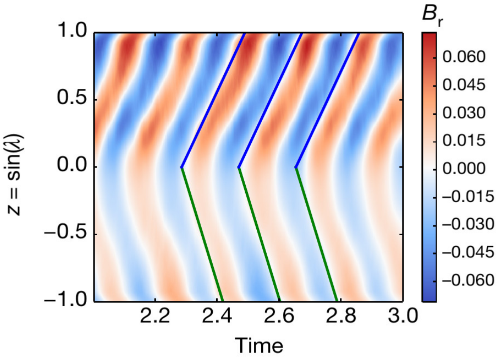
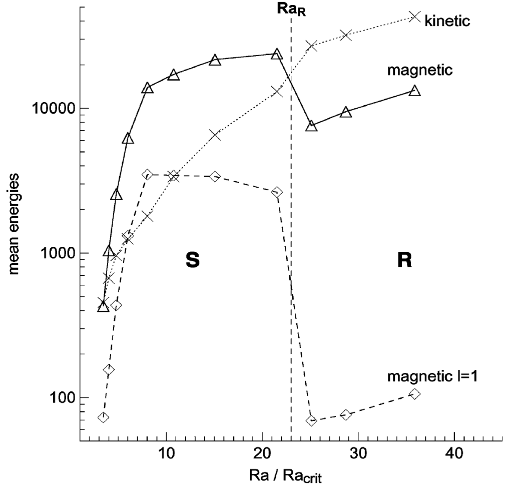
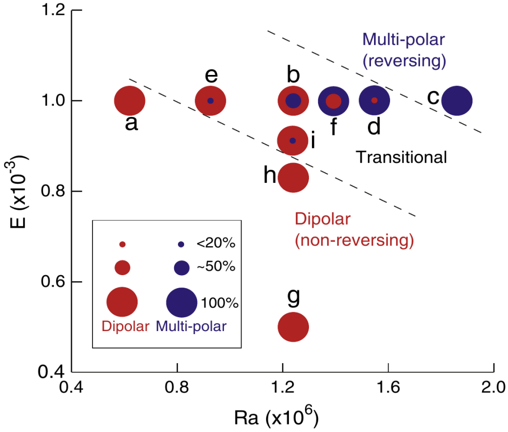
- 2016 : Sheyko+
  - $E = 2.4 \times 10^{-6}$, $Pm = 0.04$
  - Parker waves, quasi-periodic, low field



When do geodynamo models reverse?



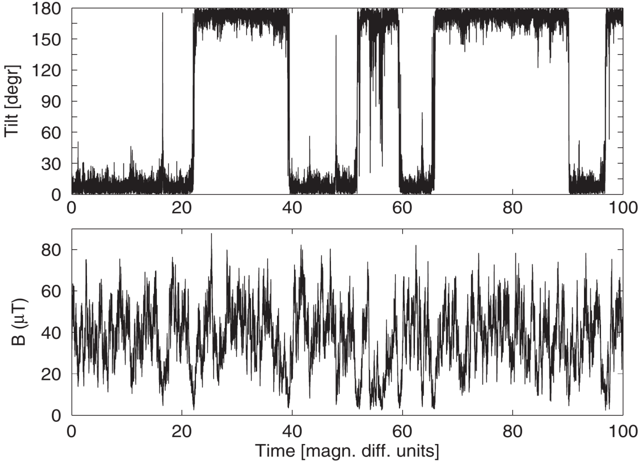
Kutzner & Christensen (2002)



Olson+ (2011)

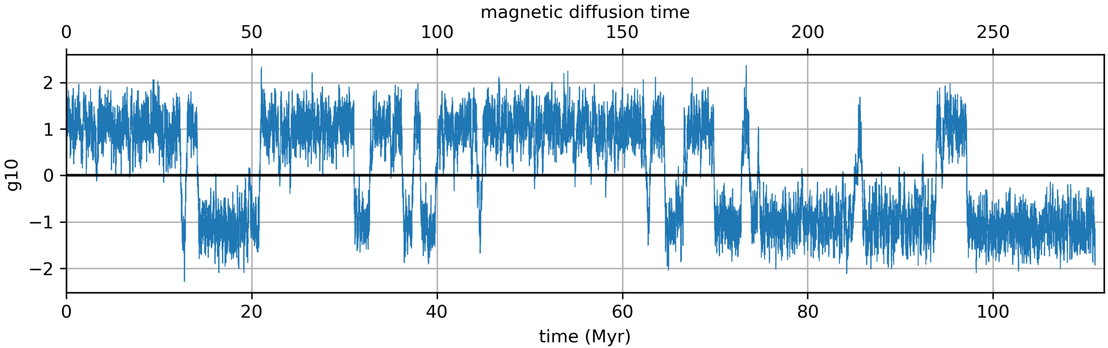
Examples of reversing dynamos

U.R. Christensen / Physics of the Earth and Planetary Interiors 187 (2011) 157–169



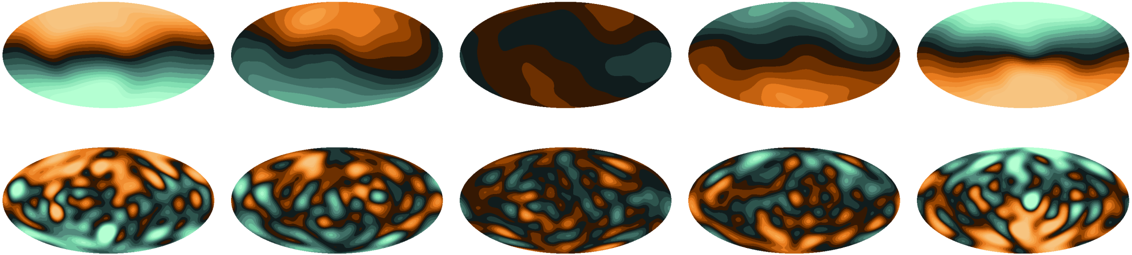
From Christensen (2011): $E = 3 \times 10^{-4}$, $Pm = 3$; large fluctuations of intensity.

Our reference case: $E = 10^{-4}$, $Pm = 3$, $Rm = 650$



- Conducting inner-core
- NR=100 (in the fluid), Lmax=79, Mmax=63
- Hyper-diffusivity beyond degree 55.
- local Rossby: $Ro_l = 0.098$
- Elsasser: $\Lambda = 12$
- Magnetic energy $= 0.85$ Kinetic energy

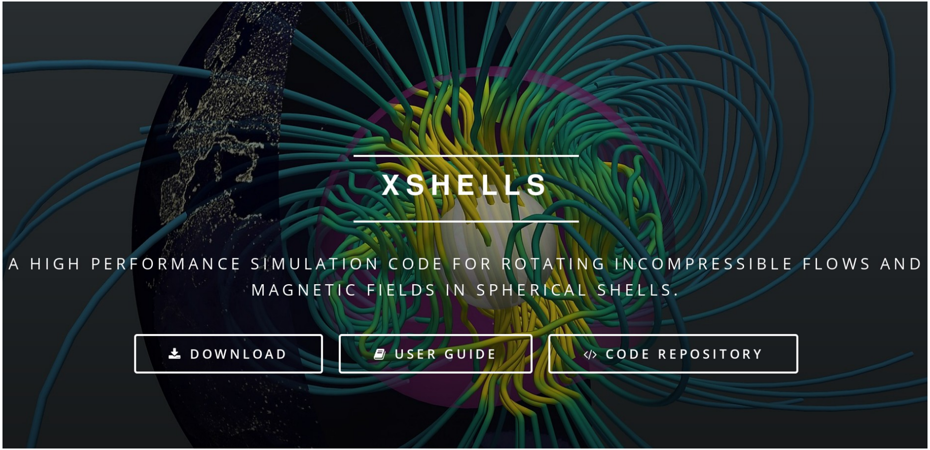
A reversal example



Radial magnetic field up to degree 13 at Earth's surface (top) and at the core surface (bottom)

At Earth's surface, the field strength is reduced by a factor 10

Thank you for your attention



Core simulations made with XSHELLS code: `https://nschaeff.bitbucket.io/xshells`