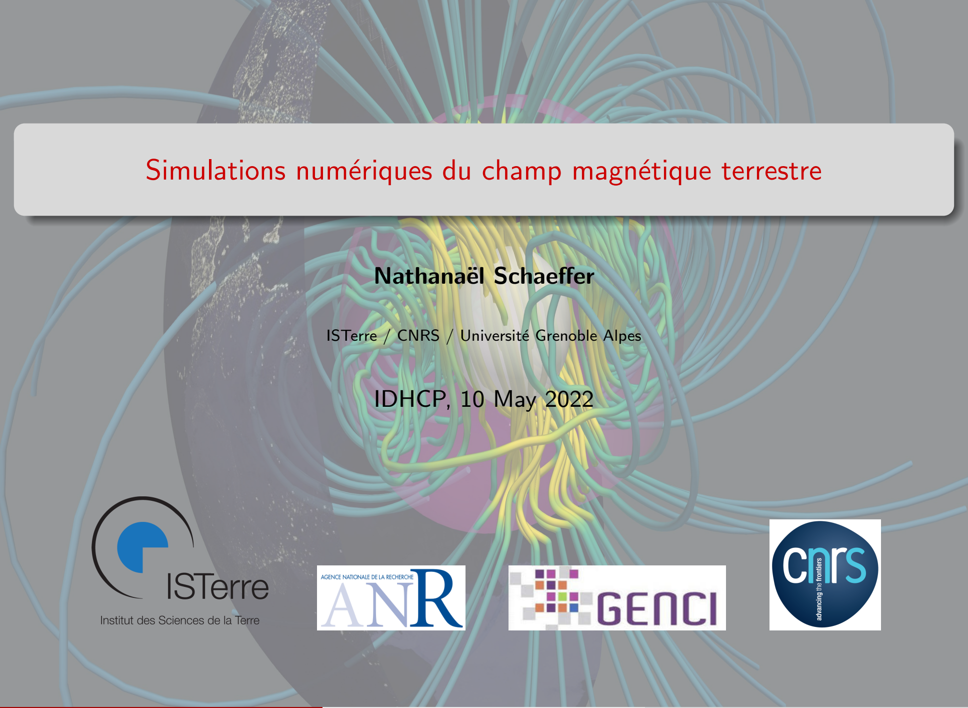

Simulations numériques du champ magnétique terrestre

Nathanaël Schaeffer

ISTerre / CNRS / Université Grenoble Alpes

IDHCP, 10 May 2022

Foreword: Are planetary magnetic fields useful?

- Earth has life and a magnetic field.

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Foreword: Are planetary magnetic fields useful?

- Earth has life and a magnetic field.
- 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*.

Outline

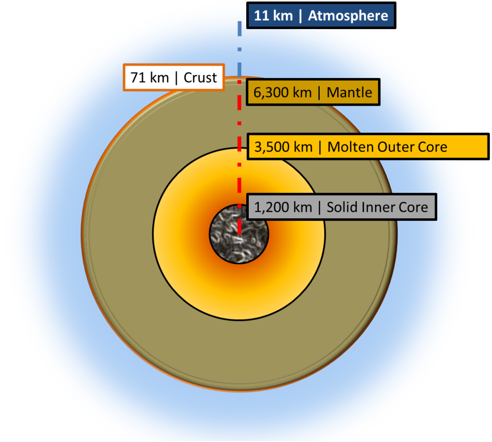
1. The core and magnetic field of the Earth
    - Observations and facts
    - The geomagnetic field
    - A dynamic magnetic field

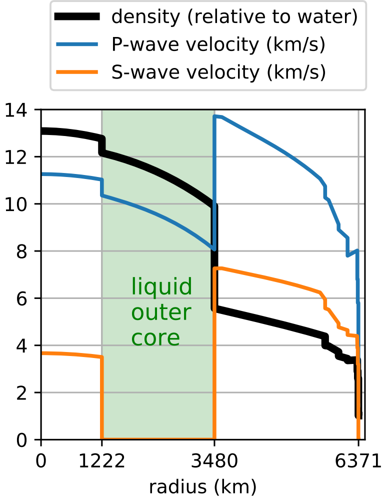
2. Numerical models
    - 20+ years of simulations
    - Recent advances

3. Numerical method

4. Reversals
    - 20+ years of reversing simulations
    - Geodynamo models vs Earth
    - Reversals elsewhere
    - Discussion & Outlook

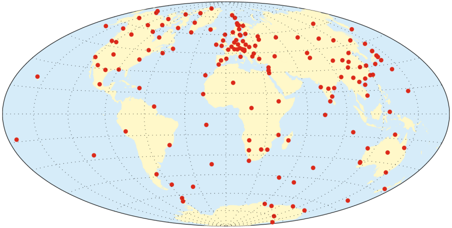
Structure of the Earth





Geomagnetic field measurements

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



(from Finlay+ 2016)

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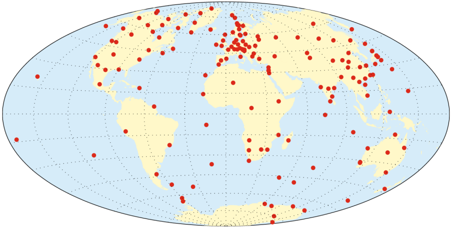
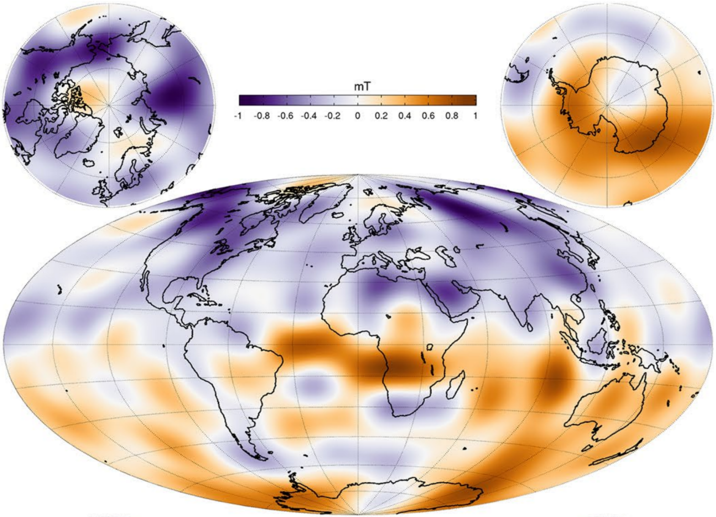


(from Finlay+ 2016)

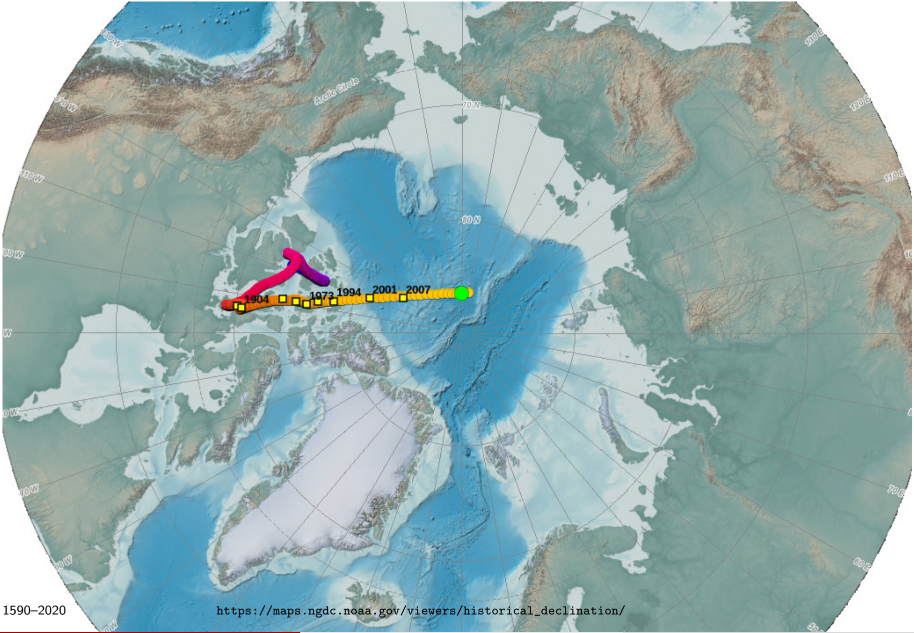
Measures from satellites since 1979.
Currently 3 dedicated satellites (SWARM).

Geomagnetic field models



Magnetic field at the Core-Mantle Boundary (CMB) in 2015.
(CHAOS-6 model, from Finlay+ 2016).

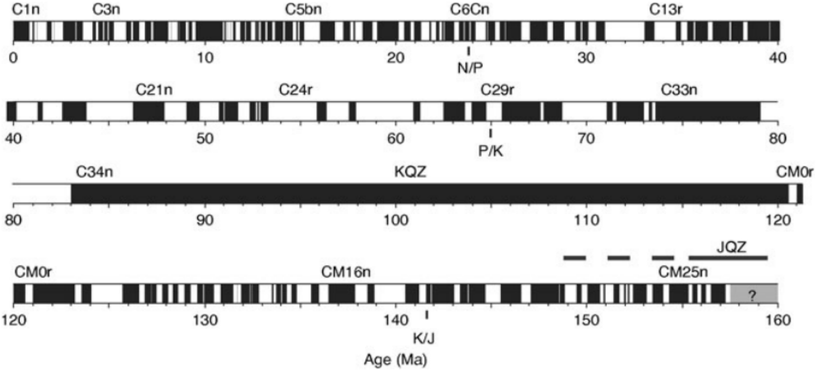
The magnetic north pole is moving



1590–2020

https://maps.ngdc.noaa.gov/viewers/historical_declination/

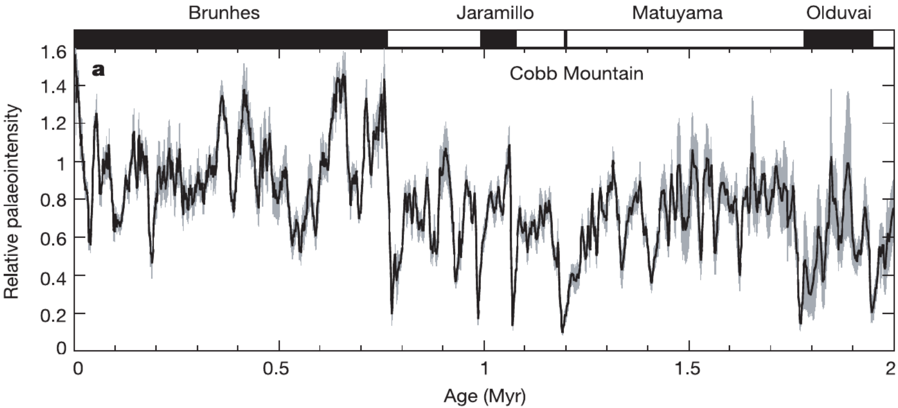
Polarity reversals



- **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 et al., 2010

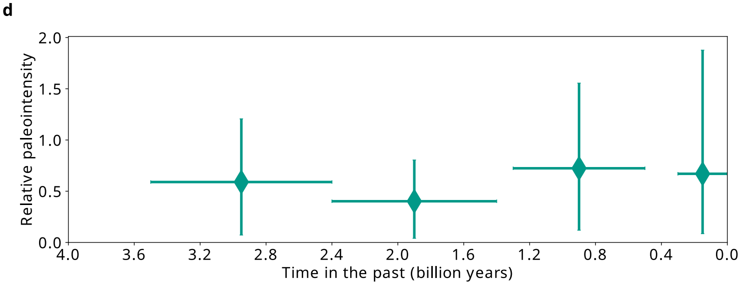
Paleointensity models: sint2000



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

from Valet, Meynadier, and Guyodo, 2005.

A very old magnetic field



from Landeau et al., 2022, *Sustaining Earth's magnetic dynamo*, Nature Review Earth & Environment.

Cool facts about the Earth's core

- A broad range of time-scales
  - from months (SV) to million years (reversals)
- Viscosity of water
  - **Earth's spin (Coriolis force) dominates the dynamics** $\Leftrightarrow E \sim 10^{-15}$
  - **Momentum diffuses much slower than magnetic field** $\Leftrightarrow Pm \sim 10^{-5}$
- 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)
  - Turbulent motion (very high Reynolds number $Re \gtrsim 10^8$).
  - Magnetic Reynolds number $Rm \gtrsim 1000$ (moderate compared to astrophysical objects)
  - Earth's spin (Coriolis force) dominates the dynamics $\Leftrightarrow Ro \sim 3 \times 10^{-6}$.

Cool facts about the Earth's magnetic field

- Magnetic field at the surface is dominated by a tilted dipole.
- Magnetic energy dominates kinetic energy by a factor 10^4 (4 mT estimated in the core – Gillet+ 2010, 0.5 mT or 5 gauss at the surface).
  - Earth's spin (Coriolis force) still dominates the fast dynamics $\Leftrightarrow Le \sim 10^{-4}$ (e.g. Jault 2008).
  - The magnetic field and the Coriolis force influence long-term dynamics $\Leftrightarrow \Lambda \gtrsim 10$.
- Heat flux extracted by the mantle (~ 10TW, < 100mW/m^2).
  - Strong convection (very high Rayleigh number $Ra \gg 10^{20}$? Probably many times critical.
  - **A (thermo-chemical) convection-driven dynamo produces the Earth's magnetic field.**

Outline

20+ years of geodynamo simulations: toward the Earth

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    - Chebychev, 64 x 32 x 49
    - hyperviscosity
    - Earth-like, reversals, and all the hype.

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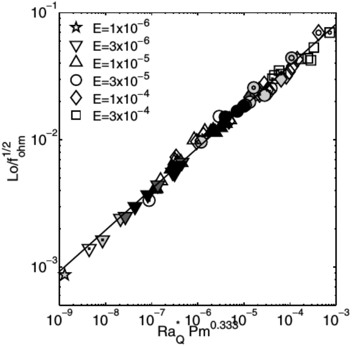

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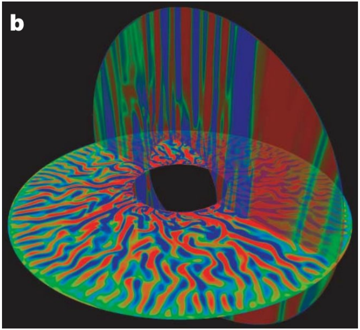
  - $E = 10^{-6}$, Re=700, Pm=1
  - convection sheets, zonal jets.



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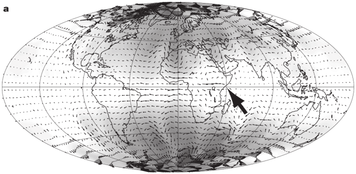
- 2013 : Aubert+
  - Chebychev, 768 x 384 x 160
  - $E = 2.5 \times 10^{-5}$, Re=1000, Pm=0.2
  - Coupled Earth, westward drift got right.



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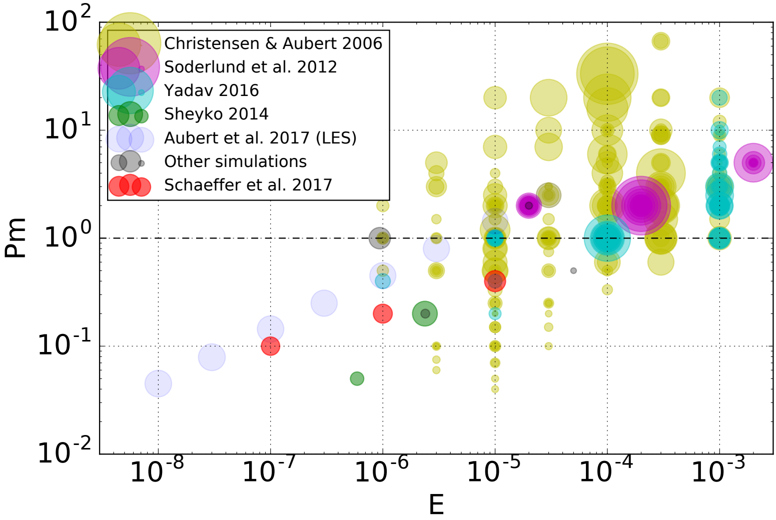
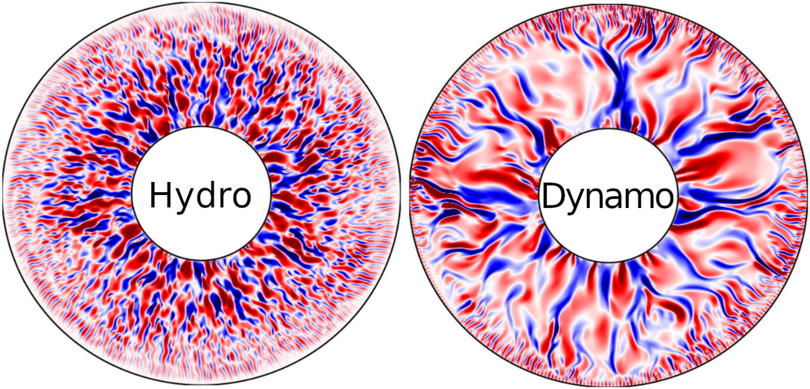


Earth: $E = 10^{-15}$, $Pm = 10^{-6}$. From Schaeffer et al., 2017.

Recent advances (I)

A series of recent studies at lower viscosities ($E \leq 10^{-6}$, Yadav et al., 2016; Aubert, Gastine, and Fournier, 2017; Schaeffer et al., 2017) all point in the same direction:

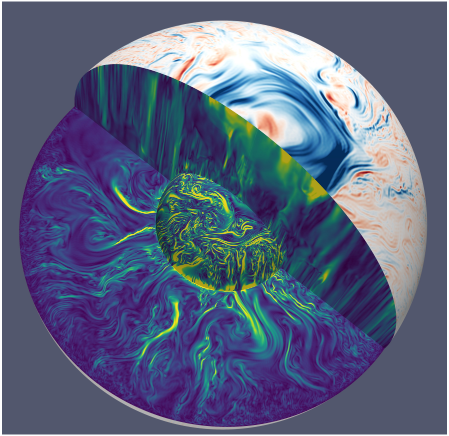
- Stronger magnetic field, a Magneto-Buoyancy-Coriolis force balance replaces the inertia-driven regimes.
- The magnetic field changes the scale of convection to larger scales.

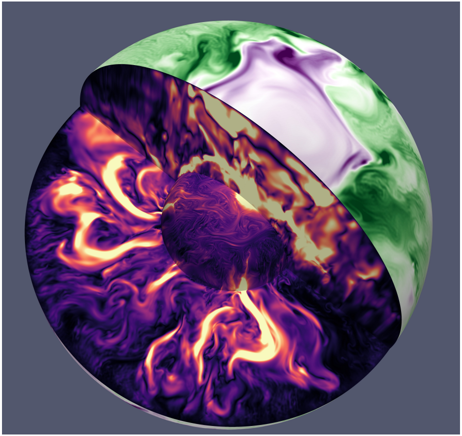


from Yadav et al., 2016

Recent advances (II)

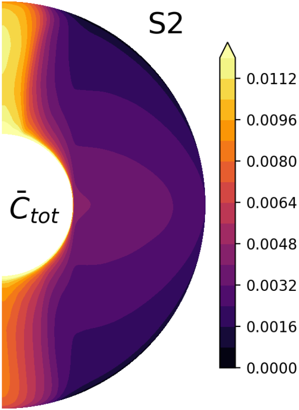
- Schaeffer et al., 2017 highlights the very large spatial and temporal fluctuations of the magnetic field.
- Intense polar vortices: thermal winds, magnetically shaped.

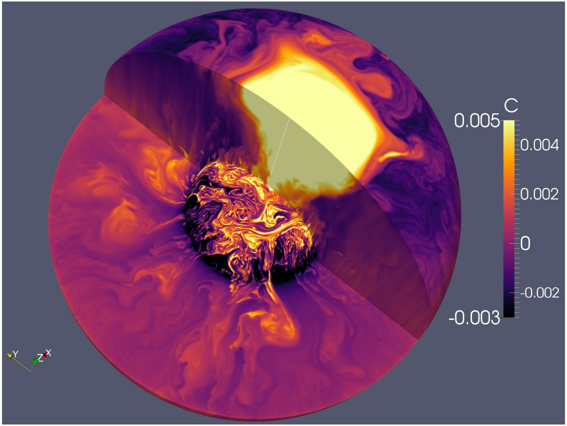




Recent advances (III)

- Schaeffer et al., 2017 highlights the density segregation between polar and equatorial regions.
- Looking at the numbers, the density contrast is too low for being seen by seismology, except if composition variations contribute too.





Hot topics

Ostensibly lacking in these models are:

- slow MAC waves – difficult to sort out?
- stably stratified layer & possible double-diffusive effects.
- reversals – simulations are too short...

Outline

1. The core and magnetic field of the Earth
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Equations of rotating MHD in planetary cores

Navier-Stokes equation

$$\partial_t \mathbf{u} + (2\Omega\,\mathbf{e_z} + \nabla \times \mathbf{u}) \times \mathbf{u} = -\nabla p + \nu\Delta\mathbf{u} + (\nabla \times \mathbf{b}) \times \mathbf{b} - \alpha g\, T\, \vec{r}$$

Induction equation

$$\partial_t \mathbf{b} = \nabla \times (\mathbf{u} \times \mathbf{b}) + \eta\Delta\mathbf{b}$$

Temperature equation

$$\partial_t T + \mathbf{u}.\nabla T = \kappa\Delta T$$

$E = \nu/D^2\Omega \sim 10^{-15}$
$Pm = \nu\mu_0\sigma \sim 10^{-5}$

$Ra = \Delta T \alpha g D^3/\kappa\nu \gg 1 \quad (?)$
$Pr = \nu/\kappa \sim 1$

Equations of rotating MHD in planetary cores

Navier-Stokes equation

acceleration = advection

Pressure gradient + Coriolis force

+ Magnetic force + Archimedes force + viscous drag

Induction equation

magnetic field variations = Induction + ohmic losses

Temperature equation

temperature variations = Advection + thermal conduction

$$E = \nu / D^2 \Omega \sim 10^{-15}$$
$$Pm = \nu \mu_0 \sigma \sim 10^{-5}$$

$$Ra = \Delta T \alpha g D^3 / \kappa \nu \gg 1 \quad (?)$$
$$Pr = \nu / \kappa \sim 1$$

the standard framework to solve the problem

- Divergence-free vector fields are represented with two scalar fields

$$\mathbf{u} = \nabla \times (\mathbf{r}T) + \nabla \times \nabla \times (\mathbf{r}P)$$

- Spherical harmonic decomposition:

$$P(r,\theta,\phi) = \sum_{\ell} \sum_{m} P_{\ell,m}(r) Y_m^{\ell}(\theta,\phi)$$

- Finite difference discretization of $P_{\ell,m}(r)$.

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Pros:

- Two scalars instead of 3 components and zero-divergence constrain enforced.
- Spherical harmonics make the magnetic boundary condition easy;
- Spherical harmonics are concise: less data to describe the field;
- No problem at the poles.
- At least **one order of magnitude faster** than local methods

Cons:

- It is a spectral method: more difficult to parallelize.

Discretized equations

$$Mu_{t+dt} = Lu_t + NL(u_t)$$

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- Evaluate linear term Lu
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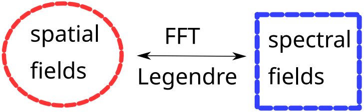
- Evaluate non-linear term $NL(u)$
  - in spatial space using spherical harmonic transforms → costly, coupling in θ, ϕ
  - FFT $O(n^3 \log n)$ is bandwidth limited, Legendre transform $O(n^4)$ not so much
- Solve for u_{t+dt} by "inverting" matrix M.
  - sparse matrix M, band-diagonal
  - Thomas algorithm (Gauss substitution) → cheap, coupling in r, sequential in r
  - bandwidth limited

the SHTns library: efficient spherical harmonic transforms

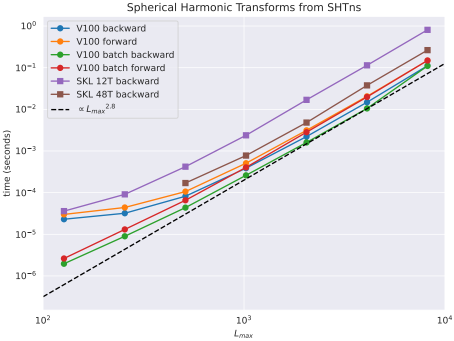
- blazingly fast.
- on-the-fly transforms (do not store matrix coefficients, compute them as needed).
- on-the-fly rotations (do not store Wigner-d matrices).
- use FFTW library for the Fourier transform, or VkFFT on GPU.
- hand vectorized routines (support AVX & AVX-512, VSX, Neon).
- Tested up to degree 65000+.


spatial fields

FFT

Legendre

spectral fields



SHTns library is freely available

`https://gricad-gitlab.univ-grenoble-alpes.fr/schaeffn/shtns`

the XSHELLS code: resistive MHD in the sphere

A high performance simulation code for rotating incompressible flows and magnetic fields in spherical shells.

- written in **C++**
- Free & Open-source software `https://nschaeff.bitbucket.io/xshells`
- Compilers: **gnu** or **intel** (OpenMP 4 support needed)
- Dependencies: FFTW (or MKL) and SHTns
- Parallelization: domain decomposition with MPI + OpenMP.
- ongoing port to GPU (cuda).

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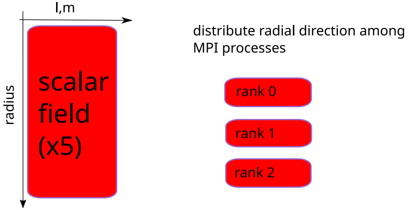

limit communications as much as possible

- domain decomposition favors the SH transform: radial decomposition
- do not use "transpose" data (no `MPI_Alltoall`)
- linear solve phase is tricky to parallelize efficiently

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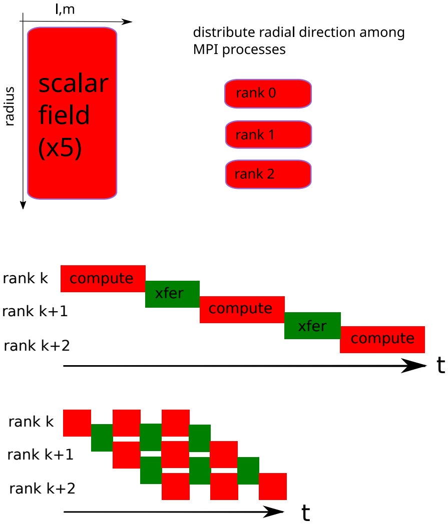
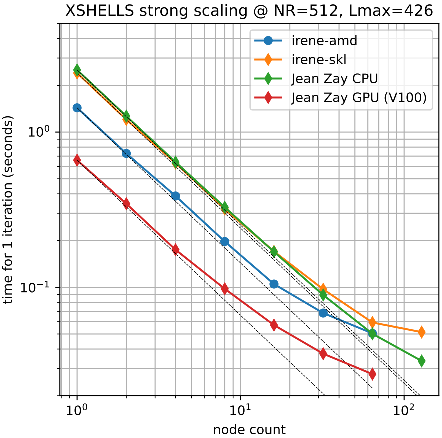


distribute radial direction among MPI processes

Porting of XSHELLS on GPU with CUDA

Except the Legendre transform, everything is "memory bound". **GPU bring a lot more memory bandwidth.**

- Ongoing effort
- About 75% of the computations are ported.
- About 900 lines of additional GPU specific code so far.



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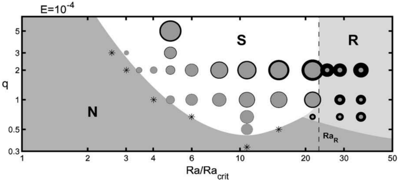

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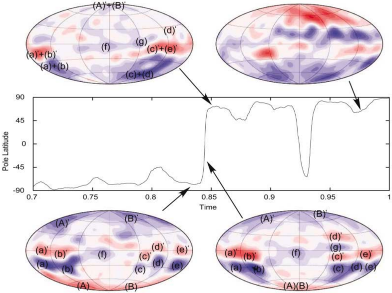

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- 2008 : Aubert+
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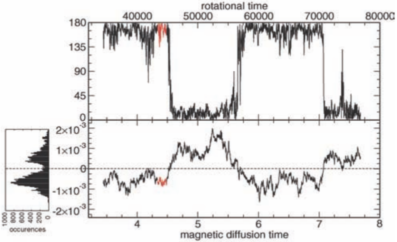

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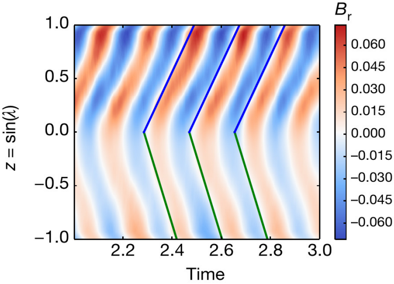
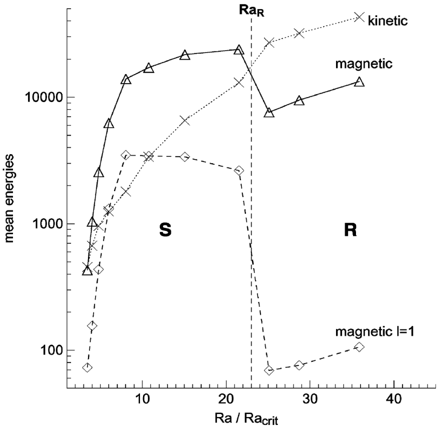
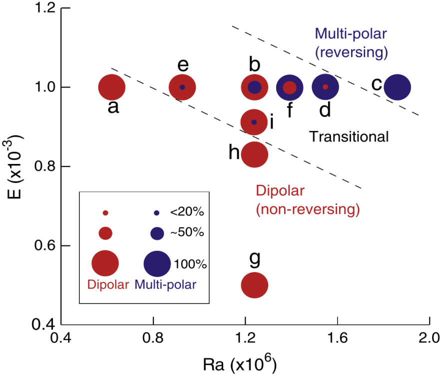
- 2016 : Sheyko+
    - $E = 2.4 \times 10^{-6}$, $Pm = 0.04$
    - Parker waves, quasi-periodic, low field



When do geodynamo models reverse?

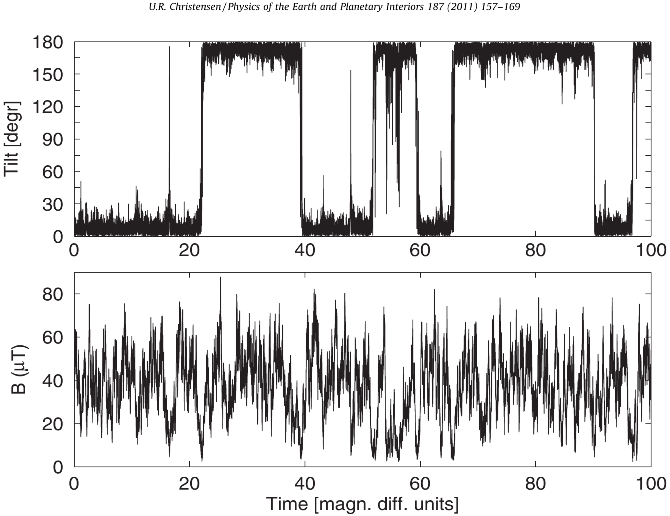


Kutzner and Christensen, 2002



Olson, Glatzmaier, and Coe, 2011

Examples of reversing dynamos



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

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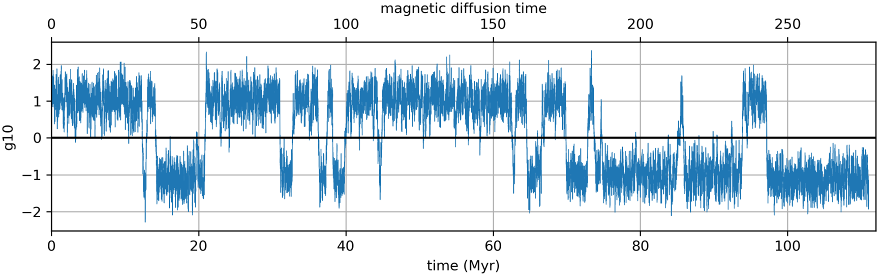

- geodynamo run at $Re = 217$, $Pm = 3$, $E_{mag}/E_{kin} = 0.84$
- 3 reversals within 2 Myr
- same polarity for more than 17 Myr (superchron)

20+ years of geodynamo simulations: reversals

	all	reversing numerics		
	numerics	high viscosity	medium viscosity	Earth's core
E	$\geq 10^{-7}$	$\geq 10^{-4}$	$\geq 2.4 \times 10^{-6}$	$\simeq 10^{-15}$
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20+ years of geodynamo simulations: reversals

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Problems:

- Parker waves: periodic, weak-field: impossible in the Earth's core.
- inertia driven: impossible to happen in the Earth's core.

Inertia-driven reversals are impossible in the Earth's core

Inertia-driven reversing dynamos operate at $Ro_{loc} = 0.1$ (e.g. Olson and Christensen, 2006).
With $Ro_{loc} = Ro\,R/\ell^\star$, where $\ell^\star$ is a typical scale of convection.

If polarity reversals were inertia-driven:

For the Earth, $Ro = 3 \times 10^{-6} \Rightarrow \ell^\star = \mathbf{100m}$.
What do we know about $\ell^\star$ in the core?

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Ooops!

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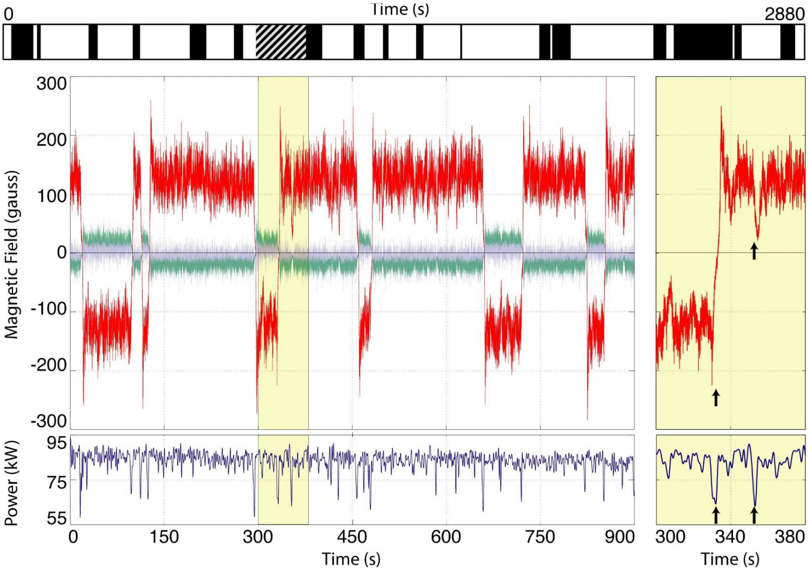
1. The core and magnetic field of the Earth
2. Numerical models
3. Numerical method
4. Reversals
    - 20+ years of reversing simulations
    - Geodynamo models vs Earth
    - Reversals elsewhere
    - Discussion & Outlook

Reversals...

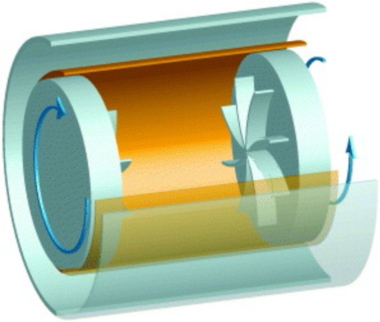


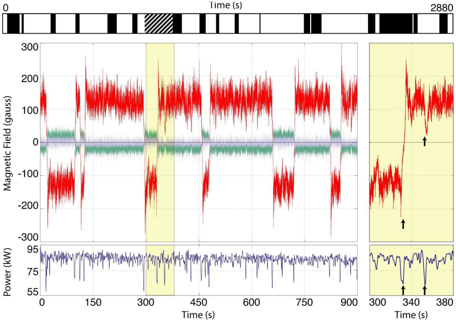
from Berhanu et al., 2007

Reversals in VKS2: a lab fluid dynamo (almost)

VKS2: Turbulent flow between discs

- VKS2 (2006): 0.15 m^3 Na, 300 kW
- dynamo only with soft iron blades (ie magnets)



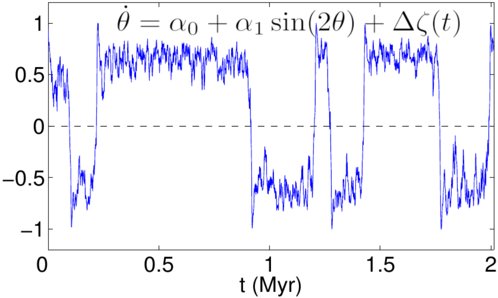


Reversals are captured by a very simple model

A dynamical system below a saddle-node bifurcation can be driven into reversals by fluctuations (noise) $\zeta(t)$.

Right: $\alpha_0 = -185 Myr^{-1}$, $\alpha_0/\alpha_1 = -0.9$, $\Delta/\sqrt{|\alpha_1|} = 0.2$.

from Pétrélis et al., 2009.



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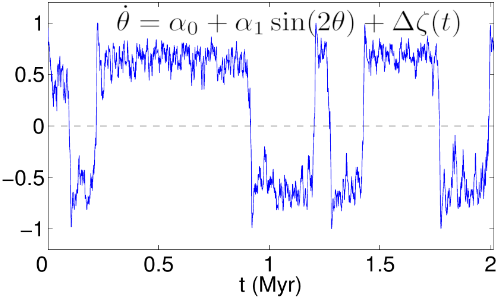

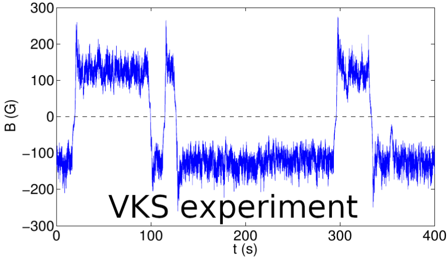

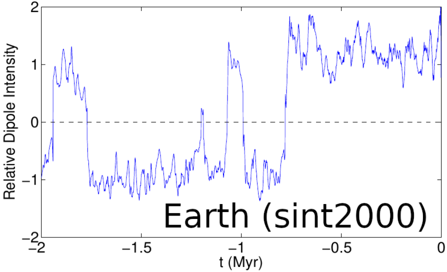

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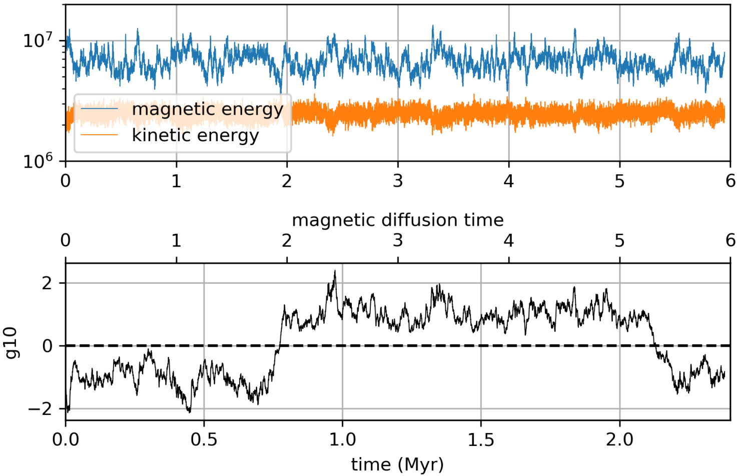
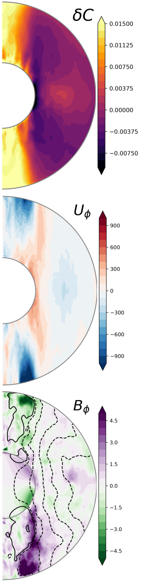
Can we get reversals with strong magnetic fields?

For a hope of obtain strong magnetic fields in reversing simulations:

- we need more realistic simulations (lower viscosity, strong forcing)
- but not too high definition, so we can run them long enough!

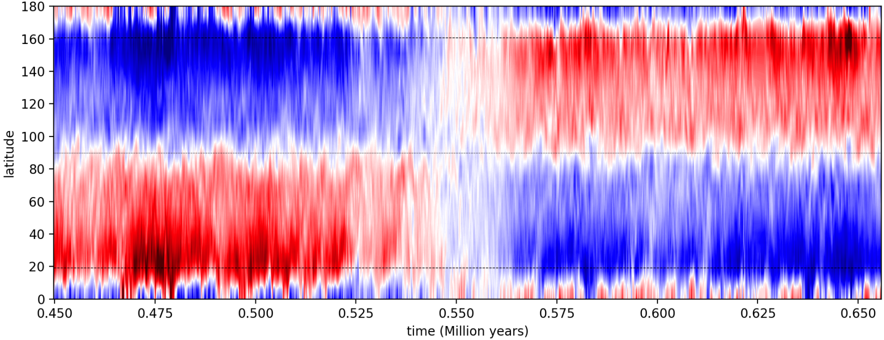
Magnetically-driven reversals?

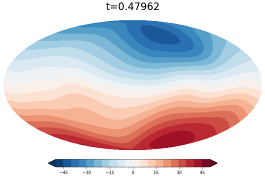


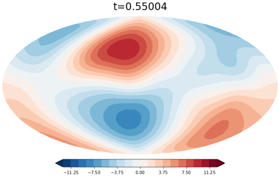


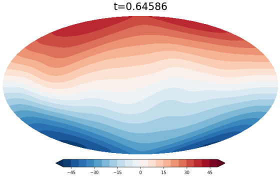
$E = 10^{-5},\ Pm = 2,\ Ro_{loc} = 0.053,\ f_{dip} = 0.33,\ \Lambda = 19,\ E_{mag}\,/\,E_{kin} = 2.8$

Zooming on a reversal



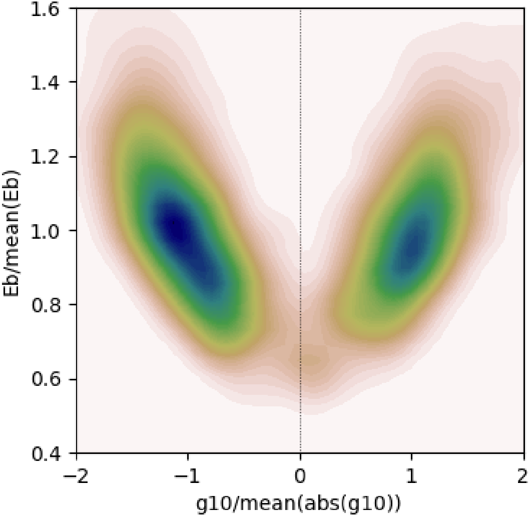






What do we learn from these strong field reversals?

Joint distribution of total magnetic energy and surface axial dipole.



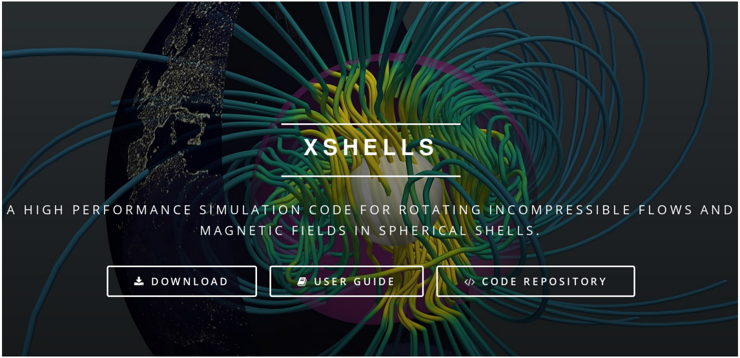
During reversal, magnetic field reduced by 15 to 20% **in the whole core**.

Conclusion & Outlook

Strong field reversals exist in numerics. Study them to learn about Earth's ones.

- Influence of mantle geodynamics on reversals (input from N. Coltice)
- Statistical properties of reversal (need to simulate a lot of events)

Thank you for your attention



XSHELLS

A HIGH PERFORMANCE SIMULATION CODE FOR ROTATING INCOMPRESSIBLE FLOWS AND MAGNETIC FIELDS IN SPHERICAL SHELLS.

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