Understanding geomagnetic reversals

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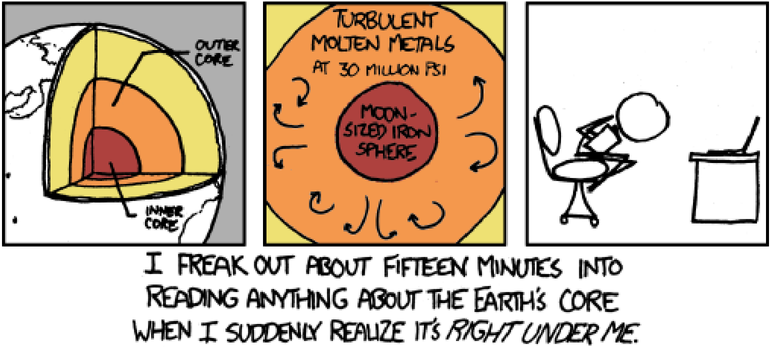
Outline

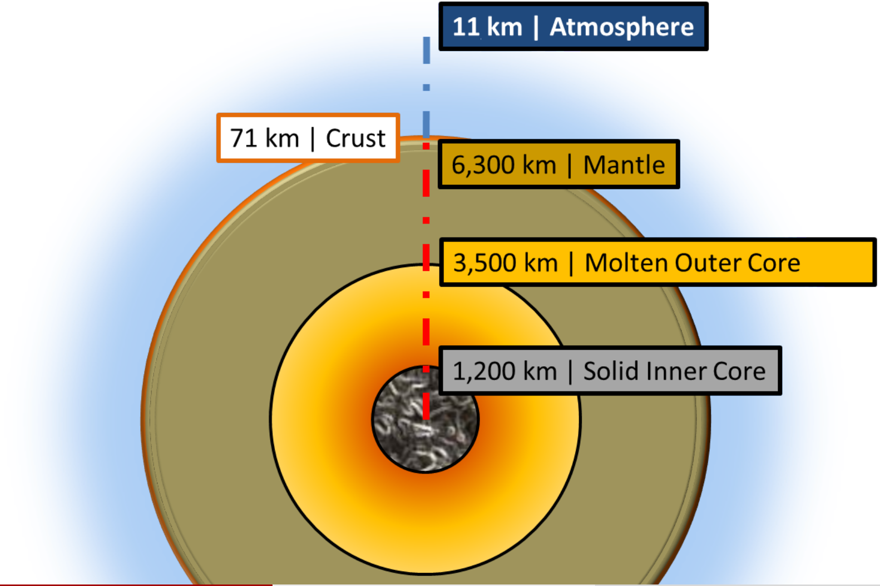
1. Objectives of this Grand Challenge
   - The core and magnetic field of the Earth
   - Numerical simulations of the geodynamo
2. Results
3. About the Irene machine
4. Outlook for future machines

Structure of the Earth



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

Structure of the Earth



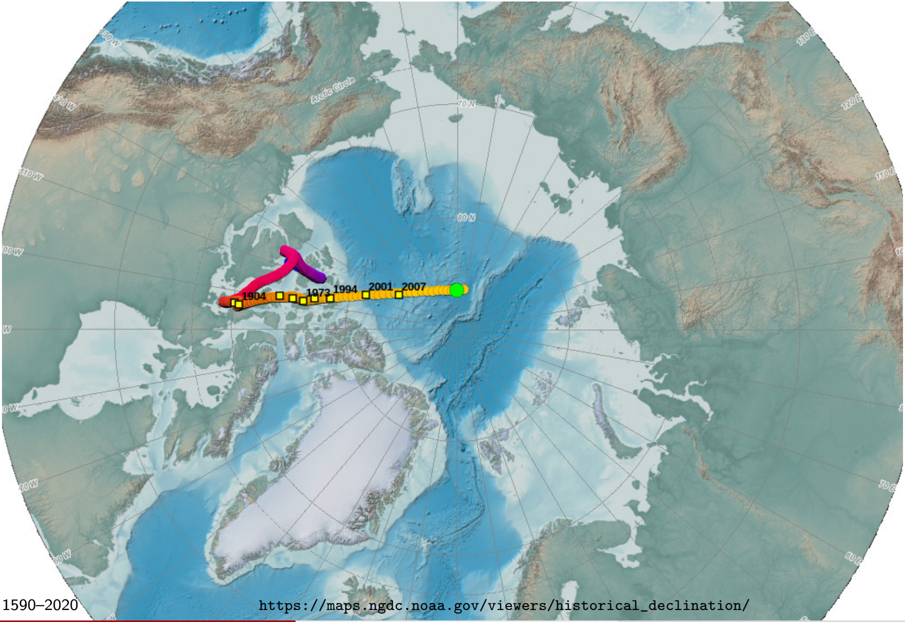
Cool facts about the Earth's core

- 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, 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 – See also poster S5-P29 by Christensen).
  - **A (thermo-chemical) convection-driven dynamo produces the Earth's magnetic field.**

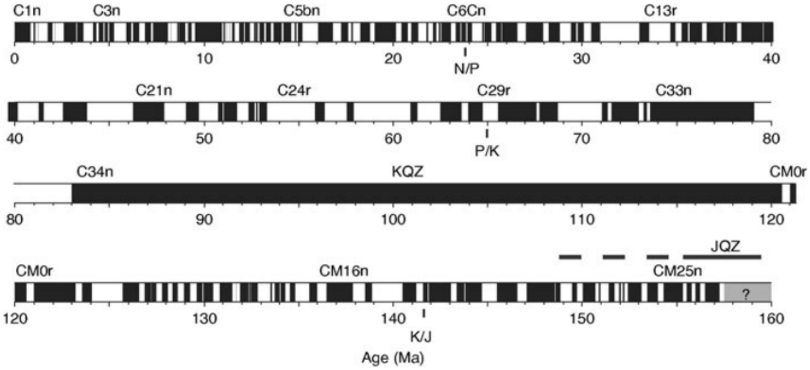
The magnetic north pole is moving



1590–2020

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

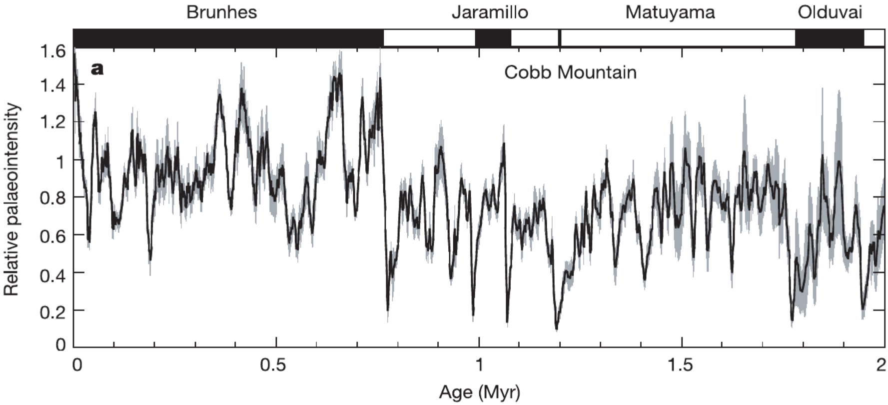
Polarity reversals



- **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 et al., 2005.

20+ years of geodynamo simulations: toward the Earth

1995 : first geodynamo simulation by Glatzmaier & Roberts

- 64 x 32 x 49
- hyperviscosity
- Earth-like, reversals

Non-reversing simulations

- high resolution (up to 5 billion points, 16384 cores);
- short time-scales (few thousand years);
- correct dynamical regime (force balance);
- dominated by magnetic energy;
- do not reverse.

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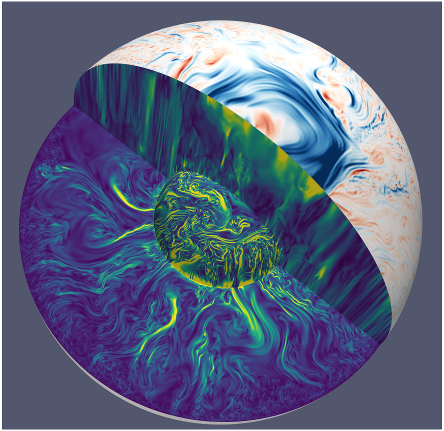
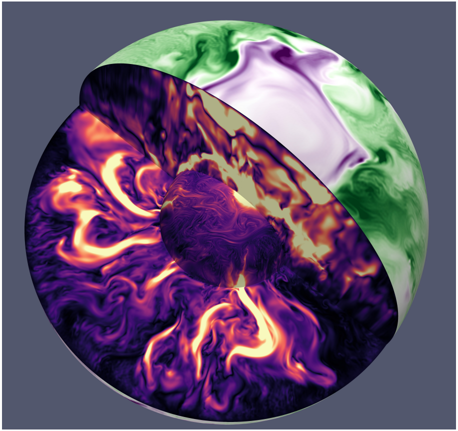
Reversing simulations

- low resolution (the lower, the longer);
- long time-scales (tens of millions of years);
- wrong dynamical regime (too viscous!);
- dominated by magnetic energy;
- reversals observed.

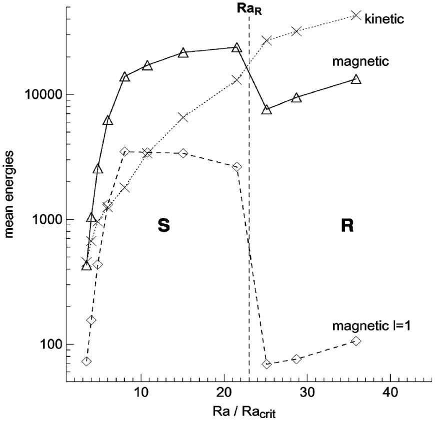
Recent advances in non-reversing simulations

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





When do geodynamo models reverse?



Kutzner and Christensen, 2002

This regime diagram cannot represent Earth's core. Because

- Magnetic energy in Earth's core is 10000 times larger than kinetic energy.
- The reversals are observed for more than 200 million years; it is unlikely the Ra/Ra_{crit} stayed stable for such a long time.

Earth-like reversals?

Glatzmaier & Coe, chapter 8.11 of the Treatise on geophysics (2015) :

[...] it is unlikely that the large-scale convection cells seen in [laminar] studies produce a reversal mechanism representative of that in the Earth's turbulent outer core.

Objectives of this Grand Challenge

Produce geodynamo reversals which are closer to Earth's core.

- Strong magnetic field
- Turbulent flow

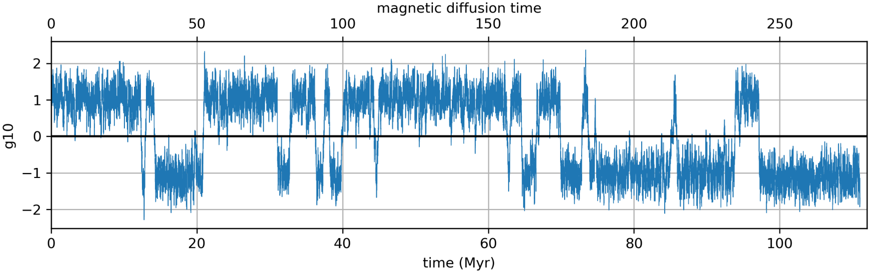
metrics

- Ratio of magnetic over kinetic energy as high as possible (10^4 in the core);
- Pm and E (viscosity) as low as possible ($Pm = 10^{-5}$, $E = 10^{-15}$ for the core);
- Re (Reynolds number) as large as possible ($Re \simeq 10^8$ in the core).

Many rather small but very long jobs.

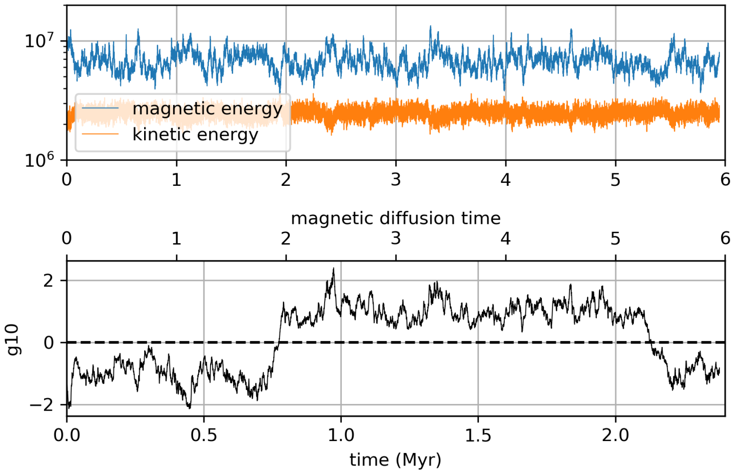
Outline

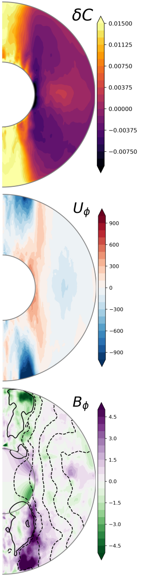
Examples of reversing dynamos



- 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)
- 3.3M points, 3 KNL nodes (17k points/core).

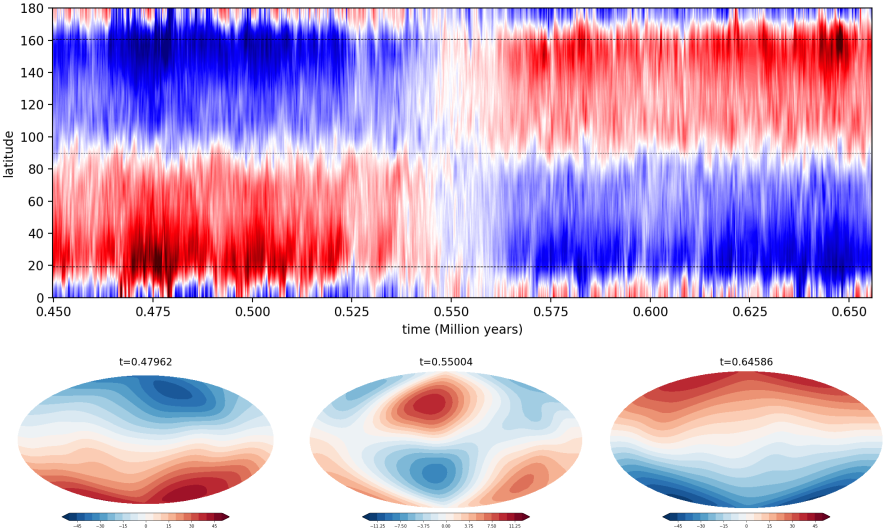
Magnetically-driven reversals?





$Re = 491,\ Pm = 2,\ E_{mag}/E_{kin} = 2.8,$
50M points, 7 KNL (110k points/core).

Zooming on a reversal



Conclusion

This Grand Challenge (16M core.hours on KNL, 7M core.hours on SKL) allowed us:

- to produce the most realistic reversing geodynamo simulations to date, including turbulence.
- to get a reversing regime that resembles that of Earth's core in many aspects.
- to invalidate the previous theory based on viscosity-dominated simulations.

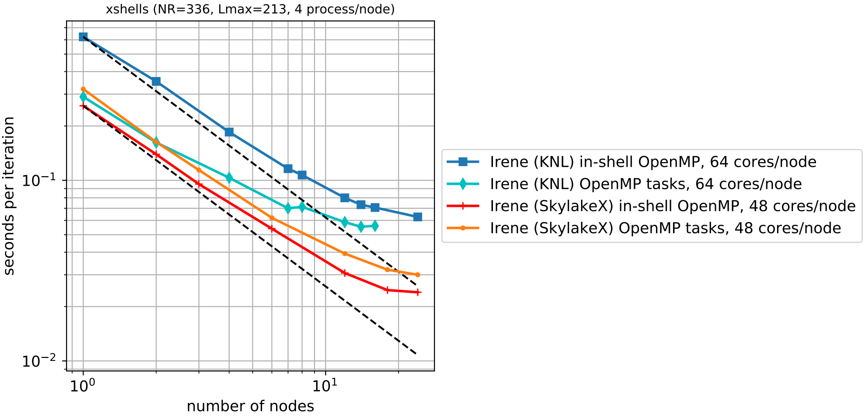
Outline

the XSHELLS code

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

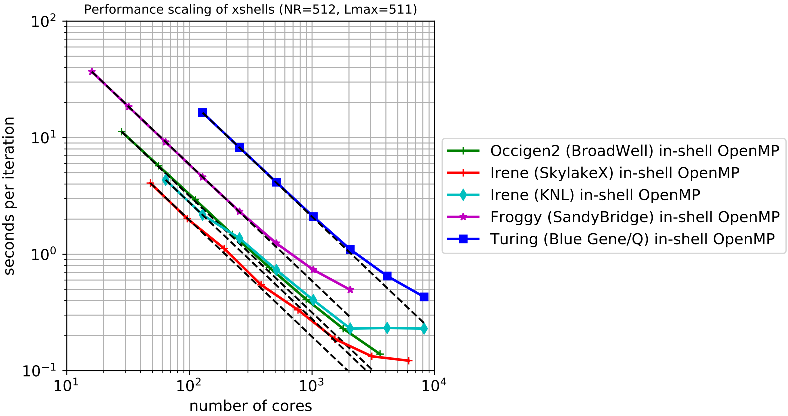
- written in **C++**
- Free & Open-source software
  `https://nschaeff.bitbucket.io/xshells`
- Compilers: **gnu** or **intel** (OpenMP 4 support needed)
- Dependencies: FFTW (or MKL) and SHTns
  `https://bitbucket.org/nschaeff/shtns/`
- Parallelization: domain decomposition with MPI + OpenMP.
- The SHTns library is hand-vectorized for AVX and AVX-512.

Strong scaling on Irene: 50M points



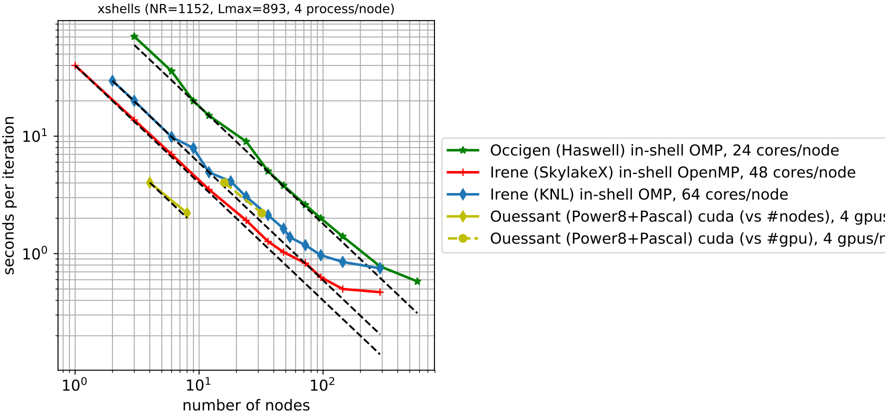
- KNL scaling is not so good for this small case (50M points). But starts competitive with SKL !
- OpenMP tasks were needed to get decent performance on KNL.

Strong scaling on Irene: 600M points



Seemingly bad network performance on KNL...

Strong scaling on Irene: >4G points



What worked for me

on SKL

- for hand-vectorized code: gcc is best
- icc for auto-vectorization, with `-qopt-zmm-usage=high` to use avx512 as much as possible.
- remark: important speedup with avx512 only in computation intensive parts.

on KNL

- gcc does not work well on KNL (too slow init ?).
- **avx512 vectorization is key** (KNL fp latency is about 3x SKL; avx512 needed to leverage high-speed memory).
- remark: higher fp latency means 12 independent operations are needed to reach peak performance (8 on SKL).
- remark: on Frioul, the ability to put everything in HBM helped.

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Outlook for future machines

To go further, we need to use techniques to accelerate the obtention of reversals.

- rare-events algorithms (our next ANR proposal).
- turbulence models to avoid computing the small scales (not available yet).

This implies:

- Run MANY small to medium cases (parametric study) for possibly very long times (several months).
- MPI needs to have high performance for small messages (low latency).
- a few large cases, but probably not much larger than 4G points.