Time changes in the geomagnetic field I: core field, secular variation and the geodynamo

GEOL/PHYS 6650
Geophysics Seminar: Geomagnetism

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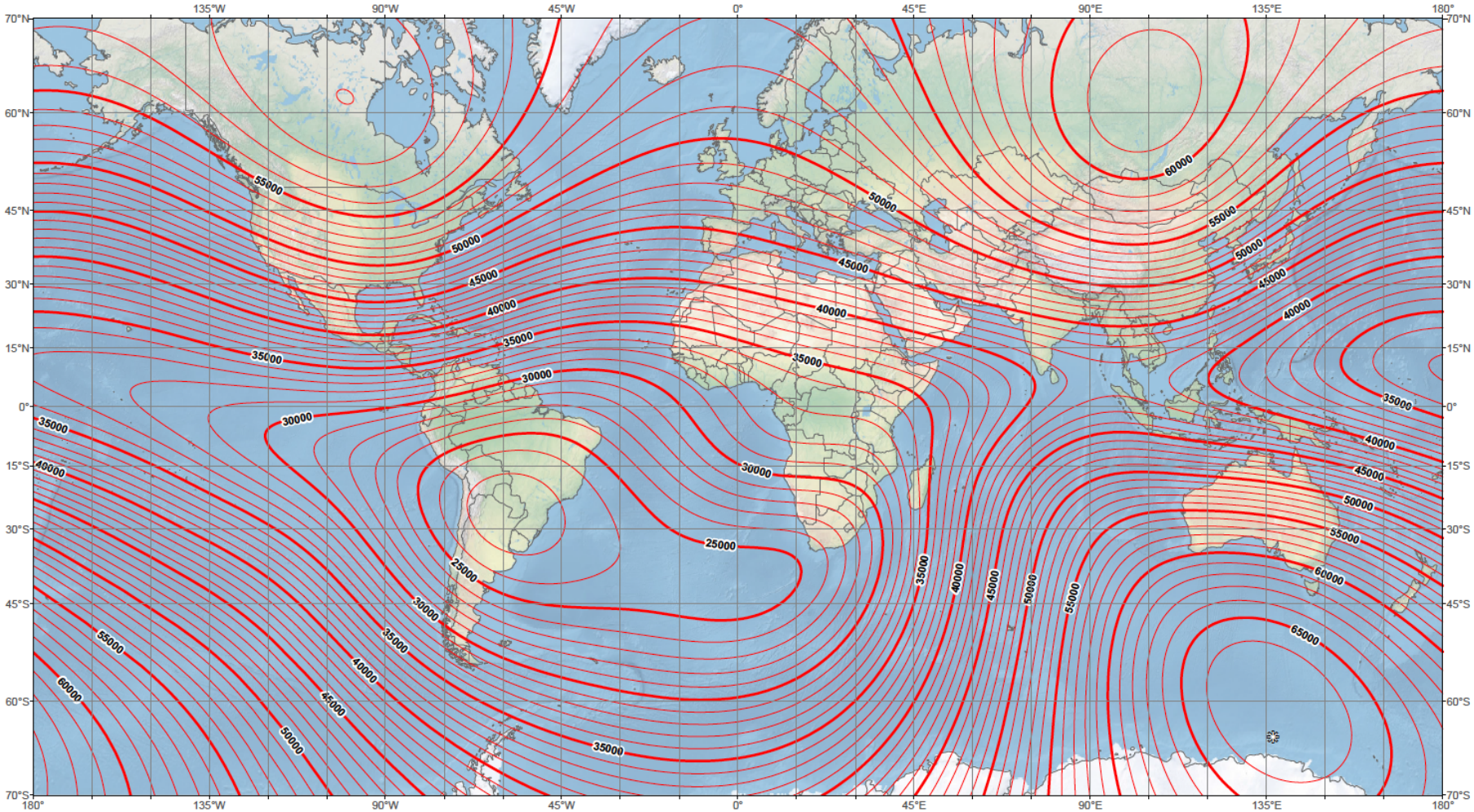
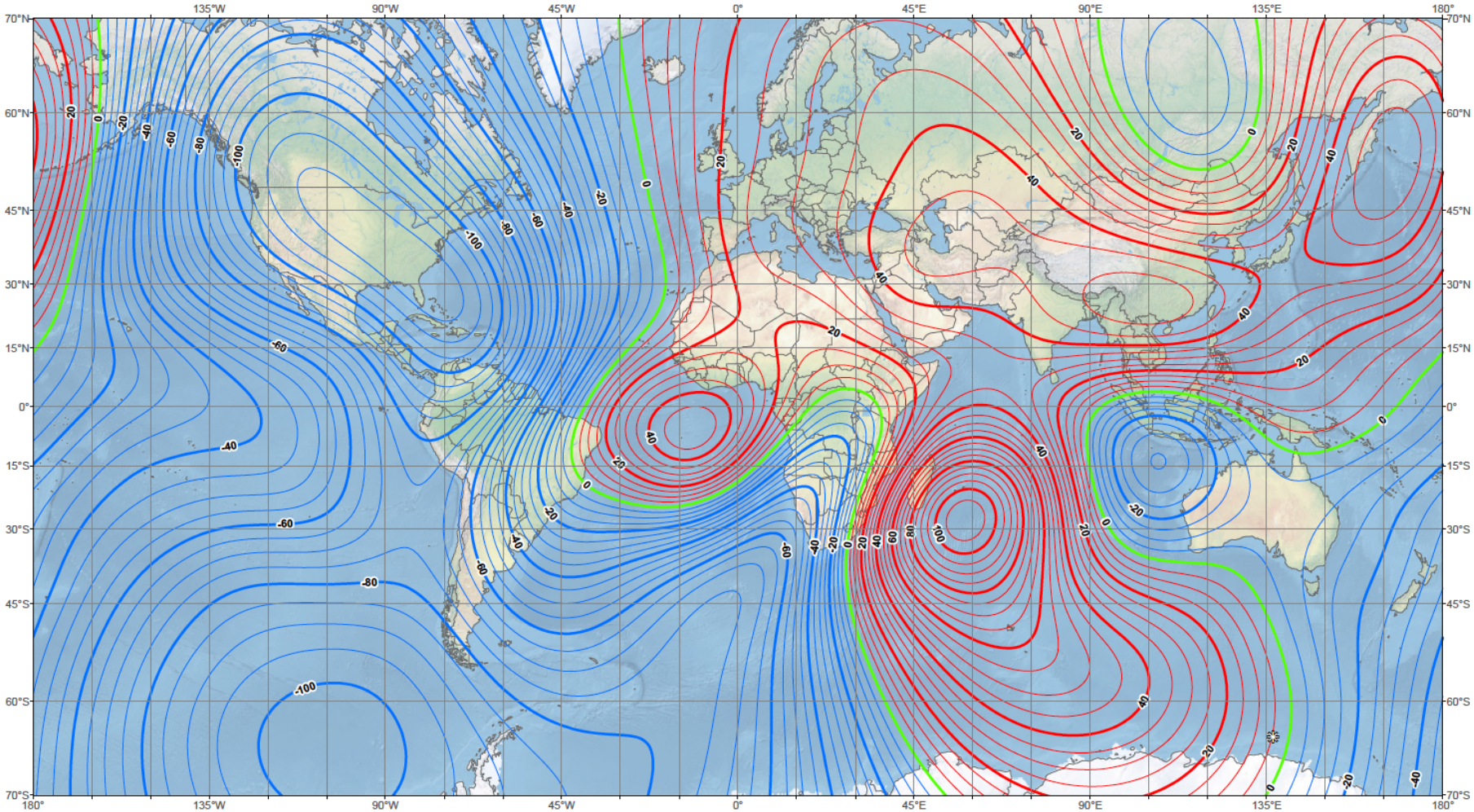
US/UK World Magnetic Model - Epoch 2015.0
Main Field Total Intensity (F)



Main Field Total Intensity (F)
Contour interval: 1000 nT.
Mercator Projection.
: Position of dip poles

Map developed by NOAA/NGDC & CIRES
http://ngdc.noaa.gov/geomag/WMM
Map reviewed by NGA and BGS
Published December 2014

US/UK World Magnetic Model - Epoch 2015.0
Annual Change Total Intensity (F)



Annual change total intensity (F)
Contour interval: 5 nT / year, red contours positive change; blue negative change; green zero change.
Mercator Projection.
❄: Position of dip poles

Map developed by NOAA/NGDC & CIRES
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Outline

1. The magnetic field at the core surface
2. Recent changes in the core field
3. Long-term evolution
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Core field modeling: basis functions

- Outside sources, the magnetic field is a potential field:

$$\mathbf{B} = -\nabla V$$

- The potential can be expanded in spherical harmonics:

$$V = a \sum_{l=1}^{L} \sum_{m=0}^{l} \left(\frac{a}{r}\right)^{l+1} (g_l^m(t) \cos m\phi + h_l^m(t) \sin m\phi) P_n^l(\cos\theta)$$

a = 6371.2 km (assuming the Earth is spherical)

- Time-varying Gauss coefficients are often represented using B- splines:

$$g_l^m(t) = \sum_n {}^n g_l^m B_n(t)$$

(Notations from Jackson et al., 2000)

Core field modeling: regularization

- The objective function to be minimized is often the sum of the least-square fit of model to data and a norm measuring model complexity:

$$\Theta(\mathbf{m}) = [\boldsymbol{\gamma} - \mathbf{f}\,(\mathbf{m})]^{\mathrm{T}} C_{\mathrm{e}}^{-1} [\boldsymbol{\gamma} - \mathbf{f}\,(\mathbf{m})] + \mathbf{m}^{\mathrm{T}} C_{\mathrm{m}}^{-1} \mathbf{m}$$

- C_e is the data covariance matrix (assuming a Gaussian error distribution)
- C_m is a damping matrix such that $C_m^{-1} = \lambda S^{-1} + \mu T^{-1}$
- Example of a spatial norm (minimum ohmic heating):

$$\Psi = \frac{1}{(t_{\mathrm{e}} - t_{\mathrm{s}})} \int_{t_{\mathrm{s}}}^{t_{\mathrm{e}}} \mathcal{F}(B_r)\,\mathrm{d}t = \mathbf{m}^{\mathrm{T}} S^{-1} \mathbf{m}$$

$$\mathcal{F}(B_r) = 4\pi \sum_{l=1}^{1} \frac{(l+1)(2l+1)(2l+3)}{l} \left|\frac{a}{c}\right|^{2l+4} \sum_{m=0}^{l} [(g_l^m)^2 + (h_l^m)^2]$$

- Example of a temporal norm (minimum acceleration):

$$\Phi = \frac{1}{(t_{\mathrm{e}} - t_{\mathrm{s}})} \int_{t_{\mathrm{s}}}^{t_{\mathrm{e}}} \oint_{\mathrm{CMB}} (\partial_t^2 B_r)^2\,\mathrm{d}\Omega \mathrm{d}t = \mathbf{m}^{\mathrm{T}} T^{-1} \mathbf{m}$$

Downward continuation

- Assuming the mantle is an electrical insulator, the model calculated at the Earth's surface can be downward continued to r = c = 3485 km.

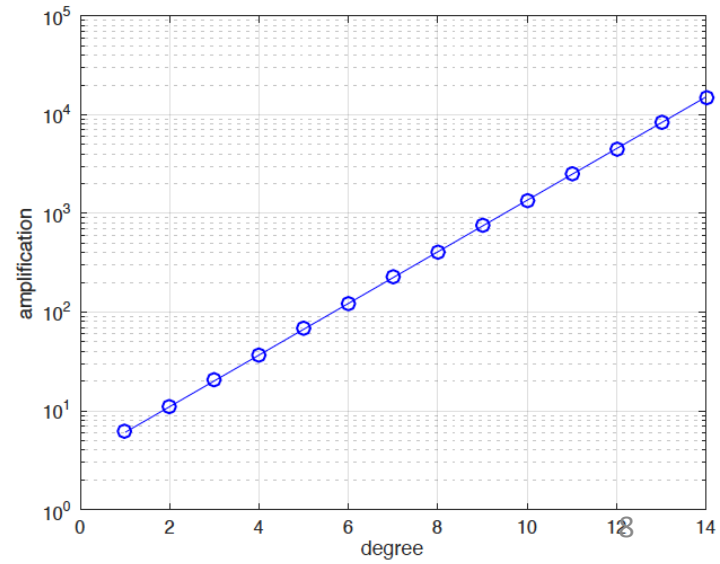
- The radial component is the only one continuous through the core-mantle boundary (CMB).

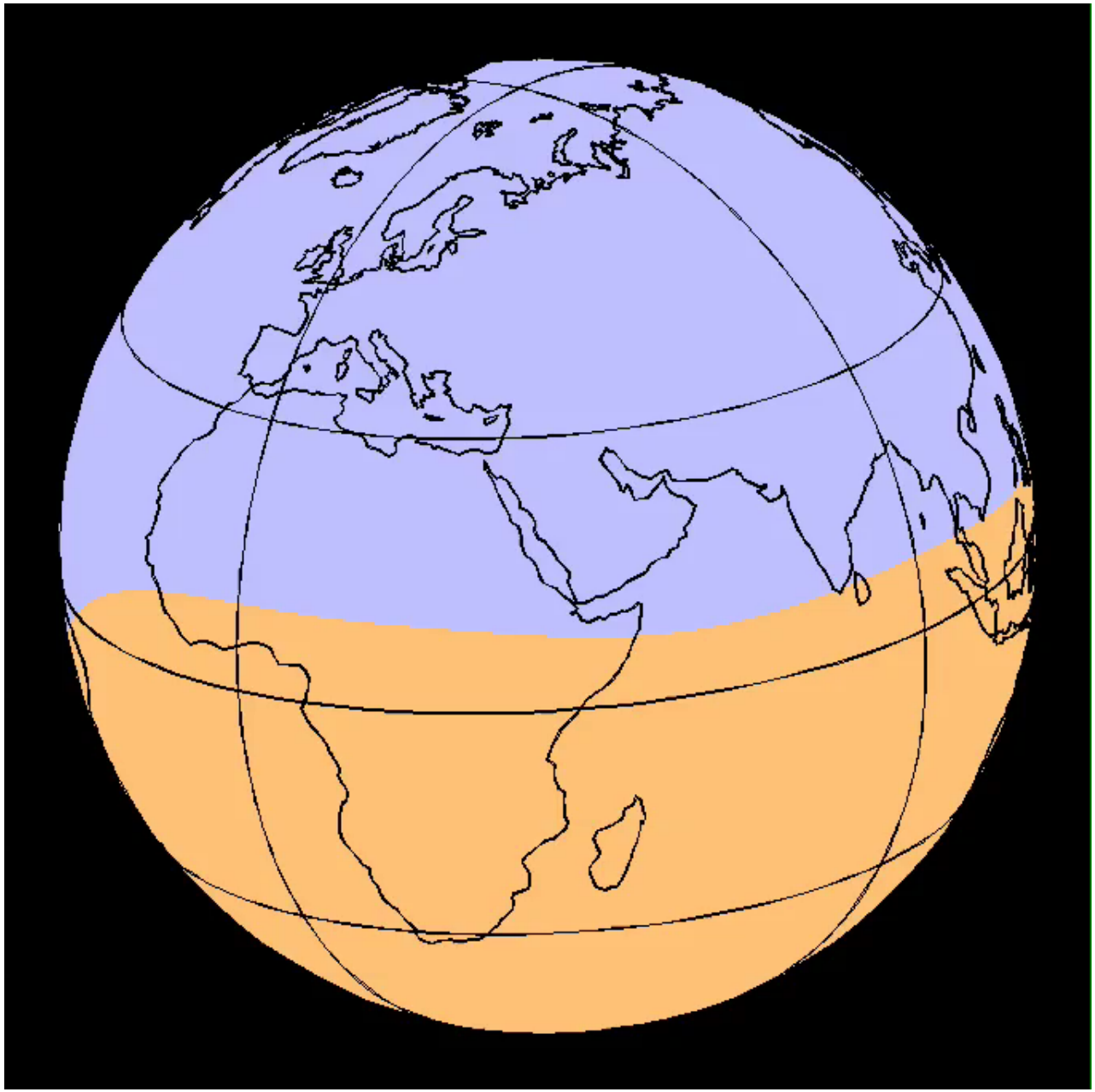
$$B_r = \sum_{l=1}^{L} \sum_{m=0}^{l} (l+1) \boxed{\left(\frac{a}{c}\right)^{l+2}} (g_l^m(t) \cos m\phi + h_l^m(t) \sin m\phi) P_n^l(\cos\theta)$$

Amplification factor for degree l

- Higher degree (small scale) harmonics are amplified the most.

- The core field spectrum is flat at the CMB.

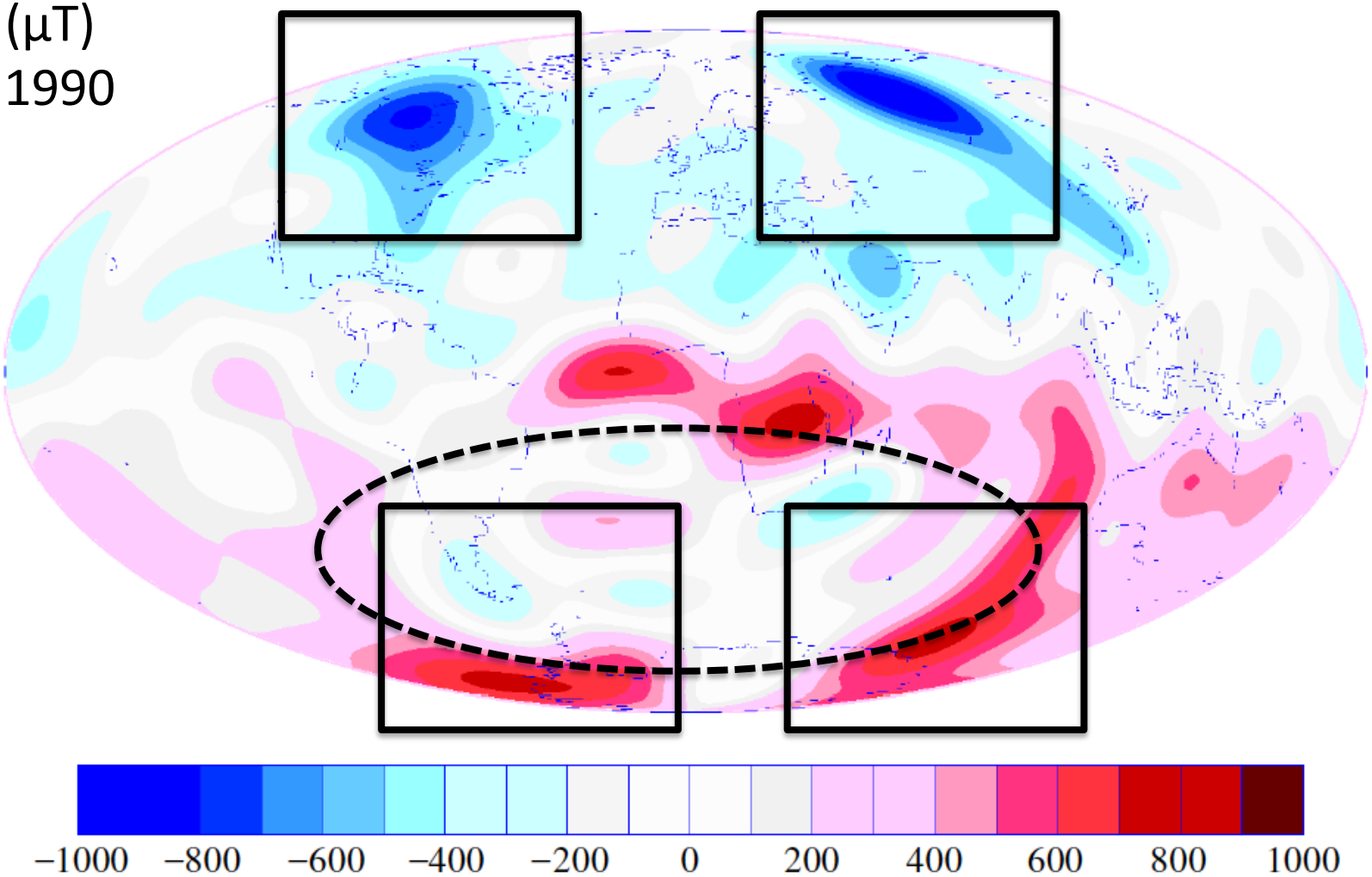




http://jupiter.ethz.ch/~cfinlay/gufm1.html

The field at the core surface

B_r (μT)
in 1990



Main characteristics

- **High-latitude flux bundles**
  - Two in each hemisphere
  - Responsible for the dipolar surface field
- **Reversed flux patches**
  - Largest under the South Atlantic
  - Responsible for the South Atlantic Anomaly at the surface
- **Low latitude wave trains**
- **Active Atlantic sector / quiet Pacific sector**
  - More and larger field concentrations under Atlantic

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Secular variation

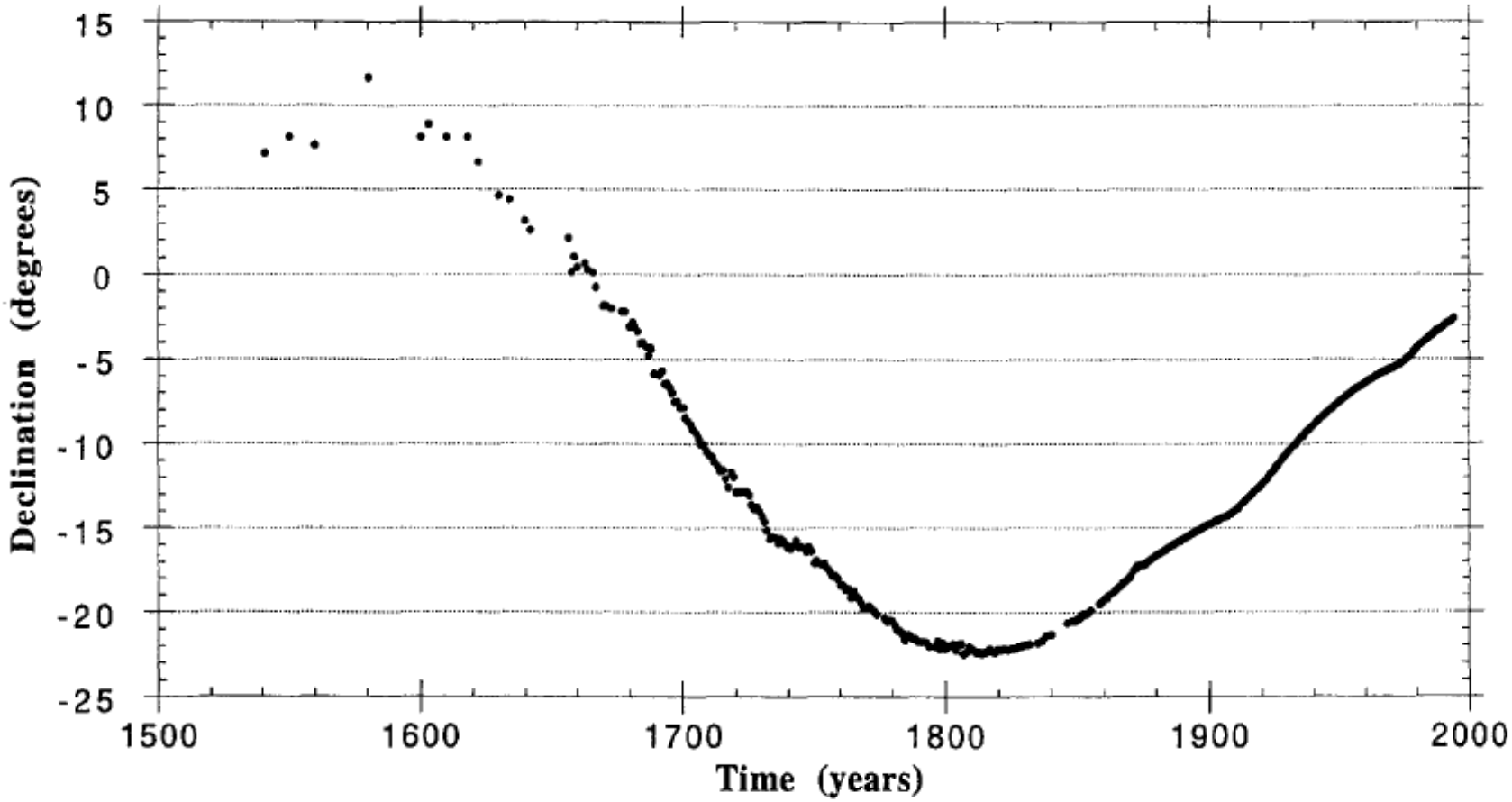
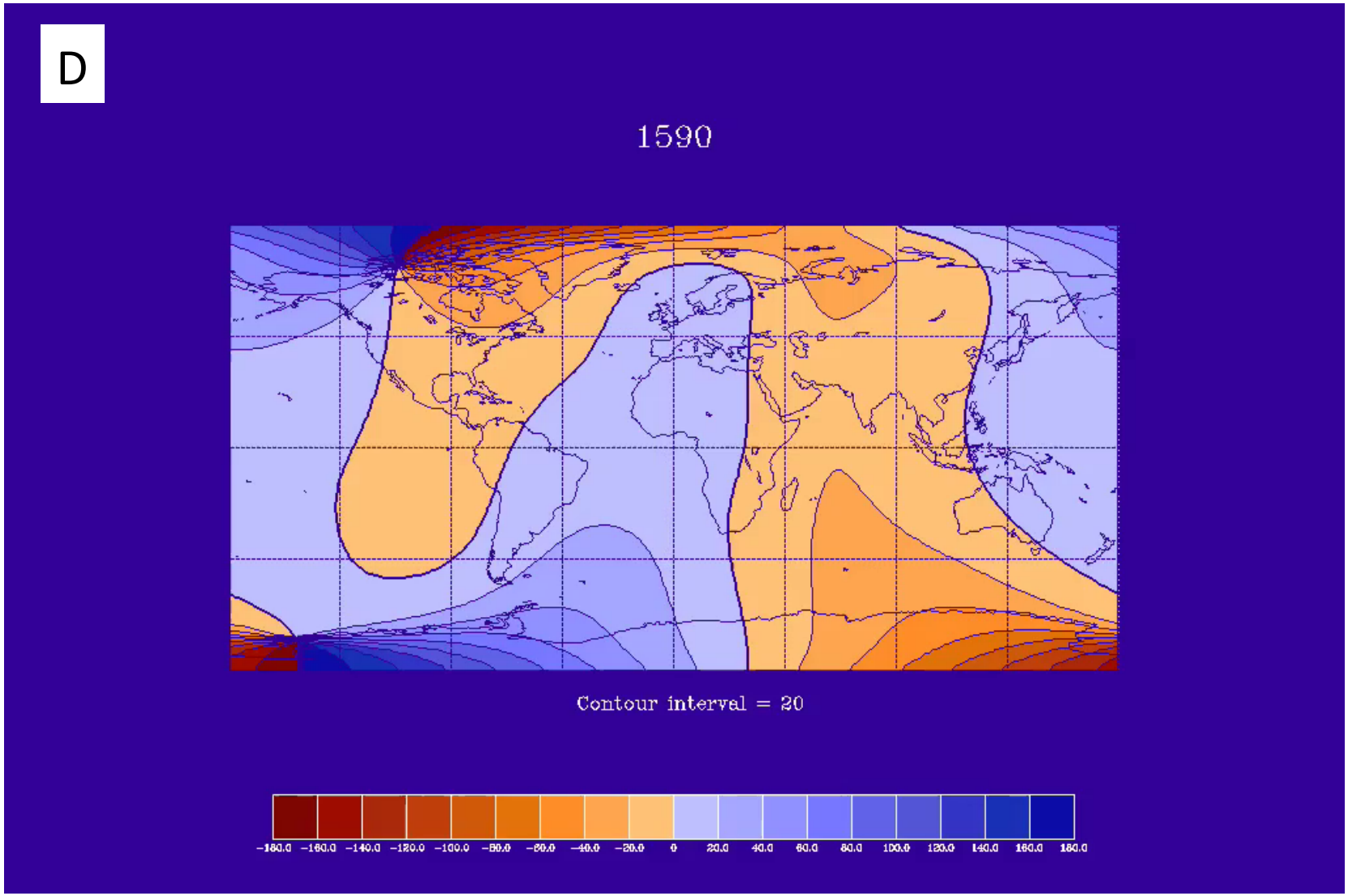


Fig. 10. Annual mean values of declination, 1541–1994, reduced to the Chambon-la-Forêt observatory.

(Alexandrescu et al., JGR, 1996)

Westward drift



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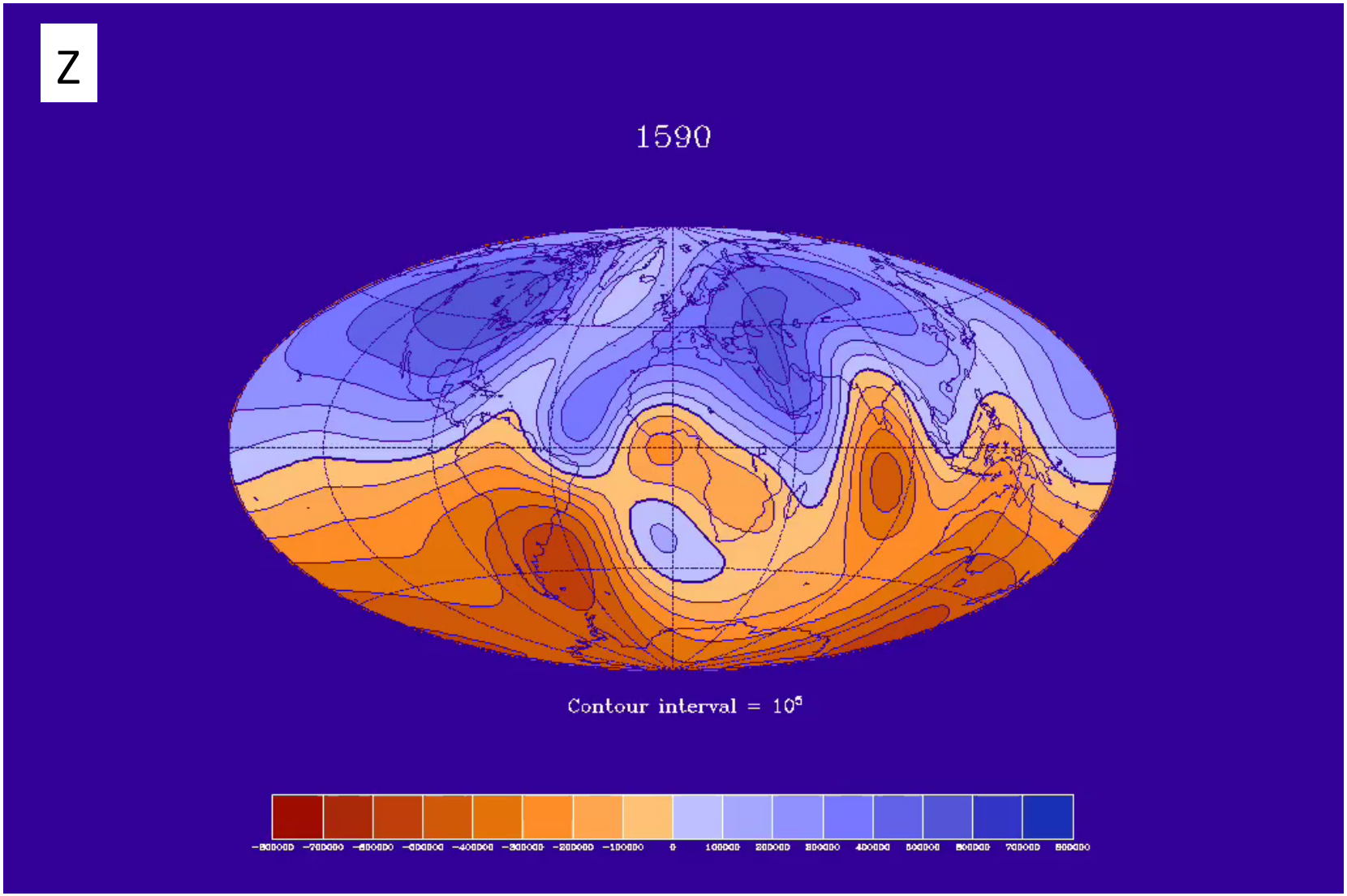
Westward drift (at the core surface)



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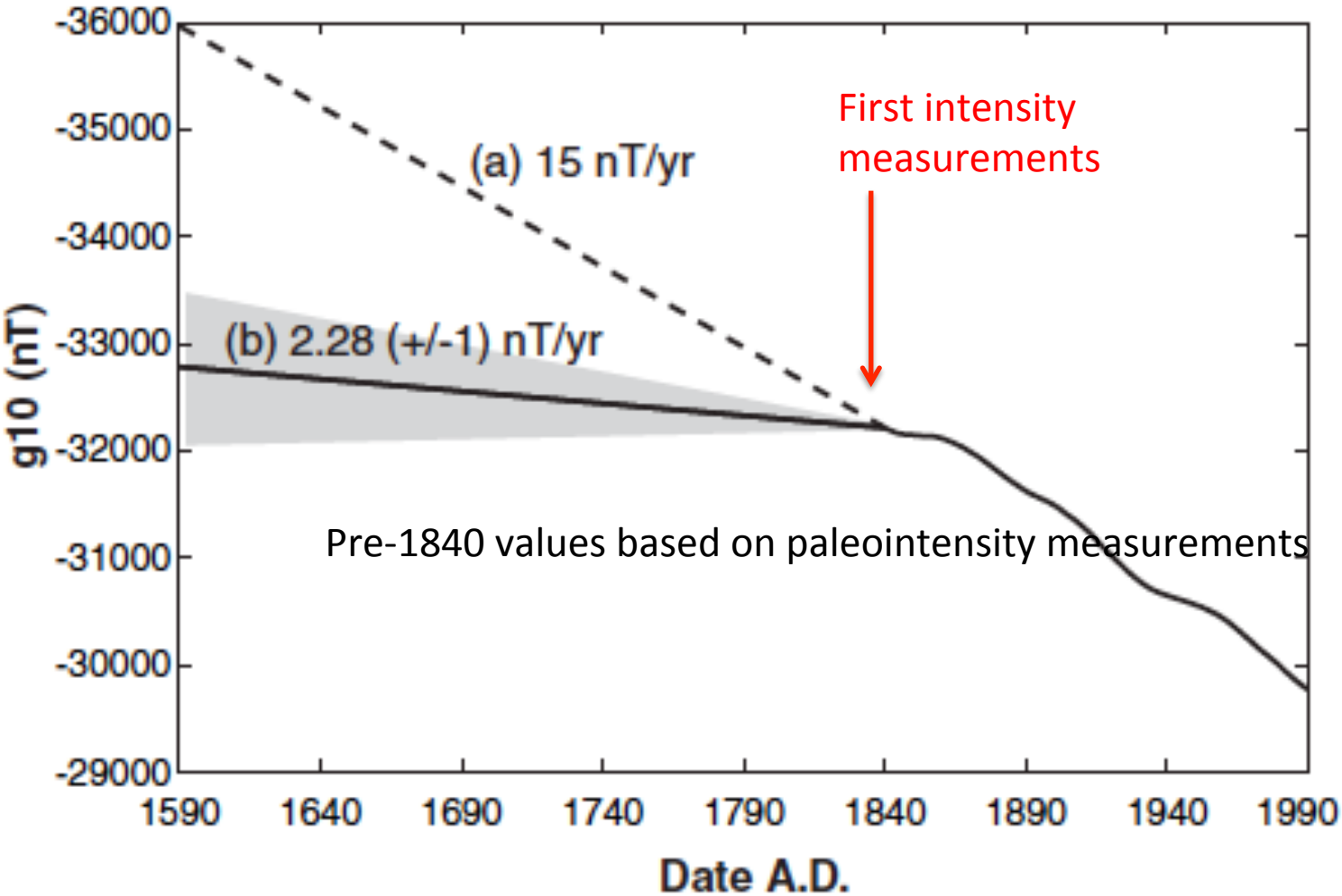
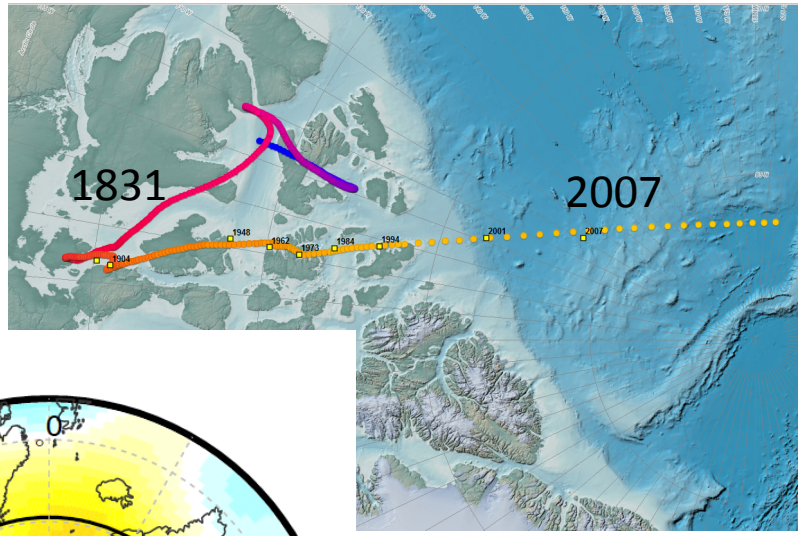
Dipole decay

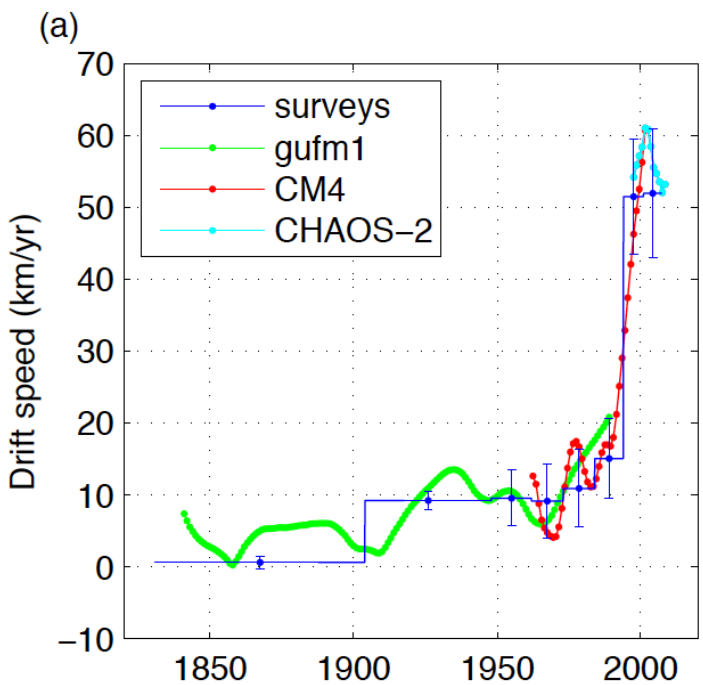


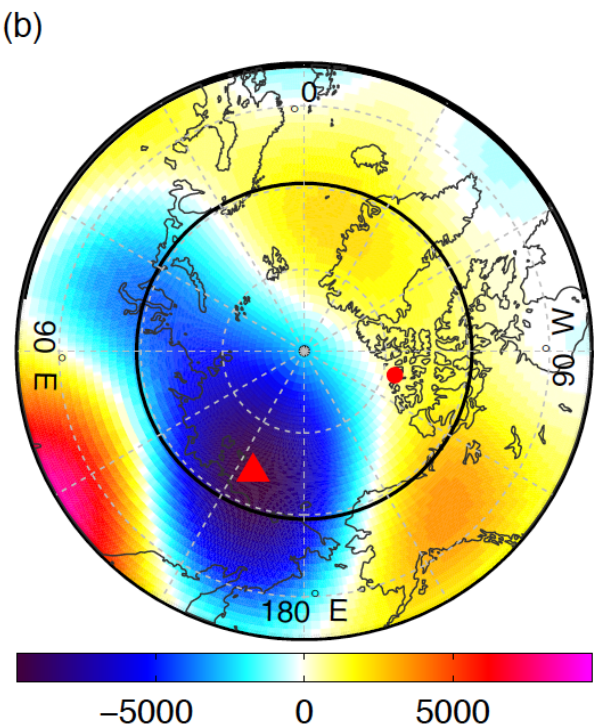
(Gubbins et al., Science, 1996)

North magnetic pole drift

- The North magnetic pole drift toward Russia has accelerated over the 1990s.
- Caused by a localized acceleration at the core surface under Siberia



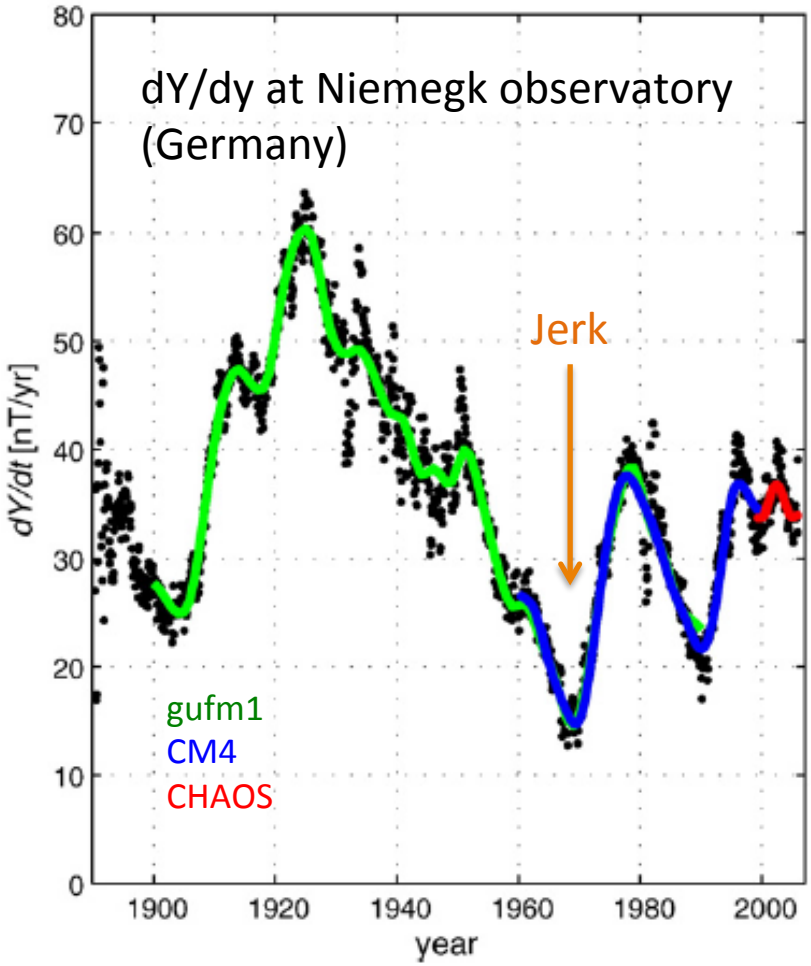


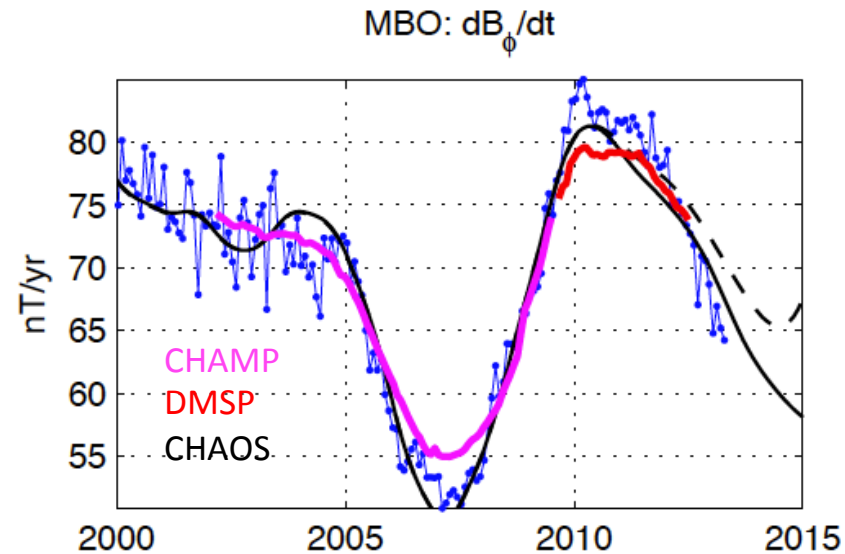


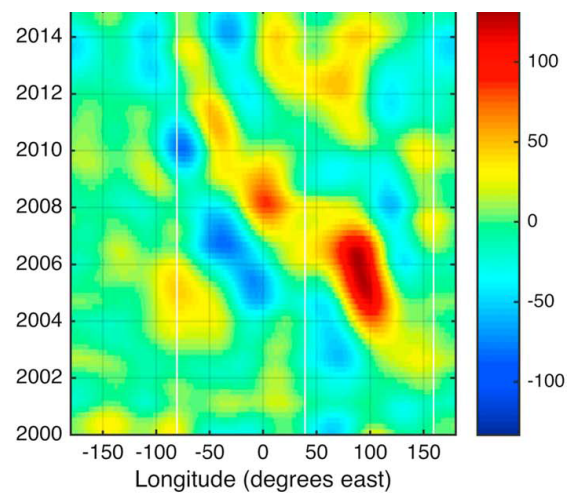
Total radial secular change (nT/yr) from 1989 to 2002

(Chulliat et al., Eos, 2010)

Geomagnetic jerks / acceleration pulses







Recent jerks are associated with fast waves in the equatorial region.

(Olsen & Mandea, EPSL, 2007; Chulliat & Maus, JGR, 2014; Chulliat et al., GRL, 2015)

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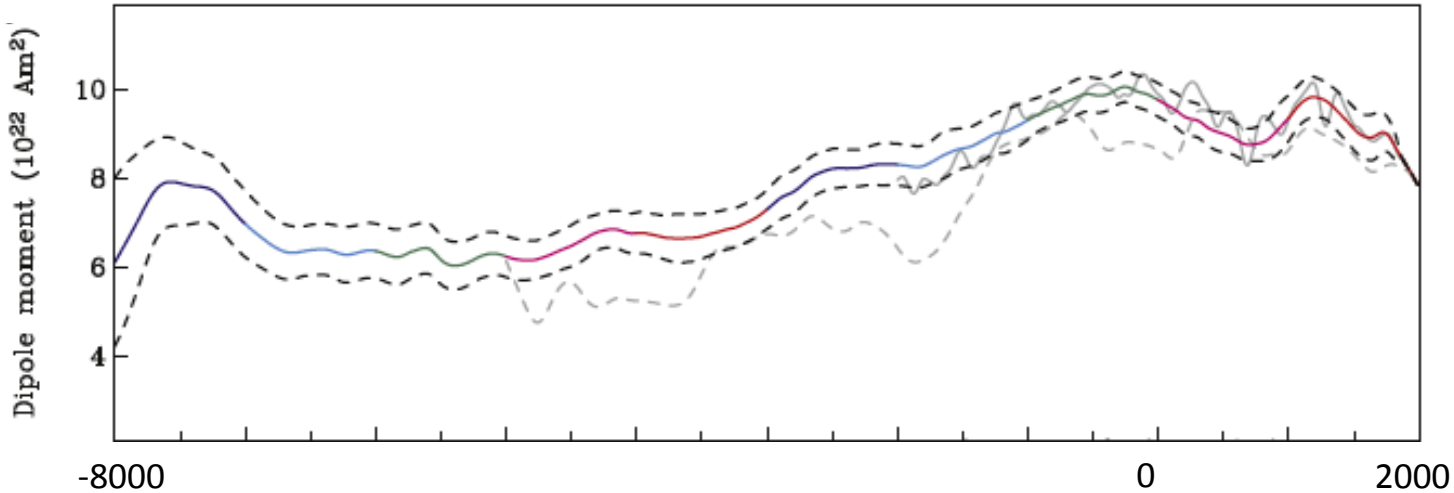
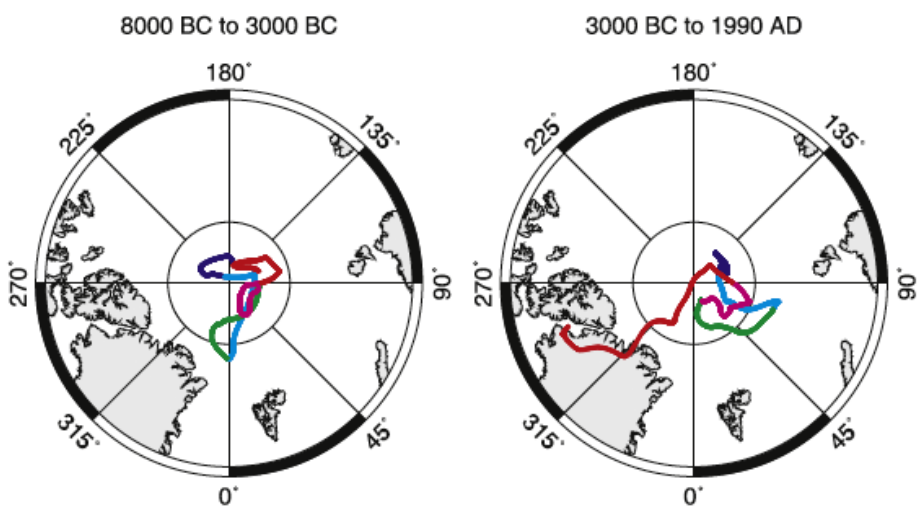
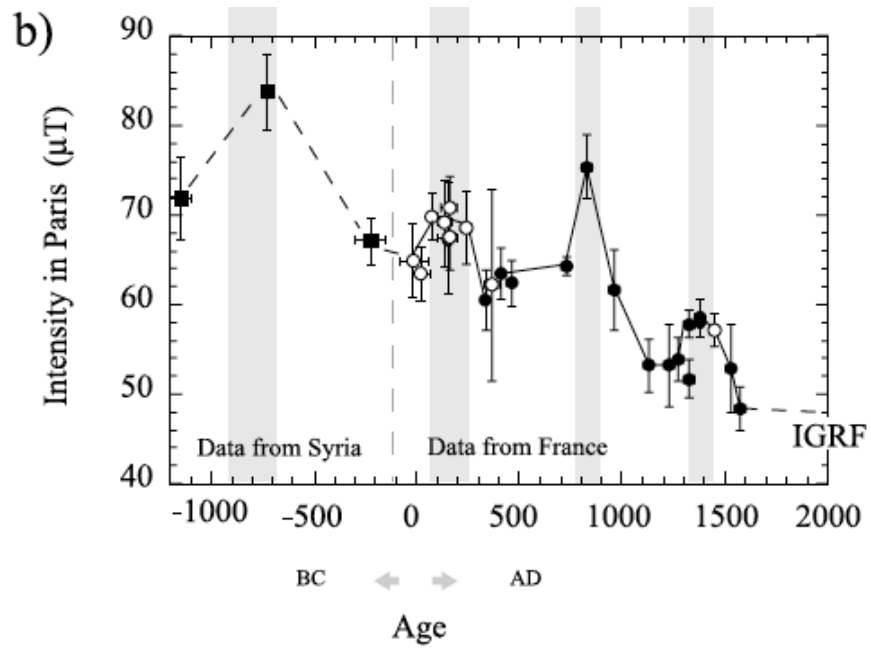
Millennial changes

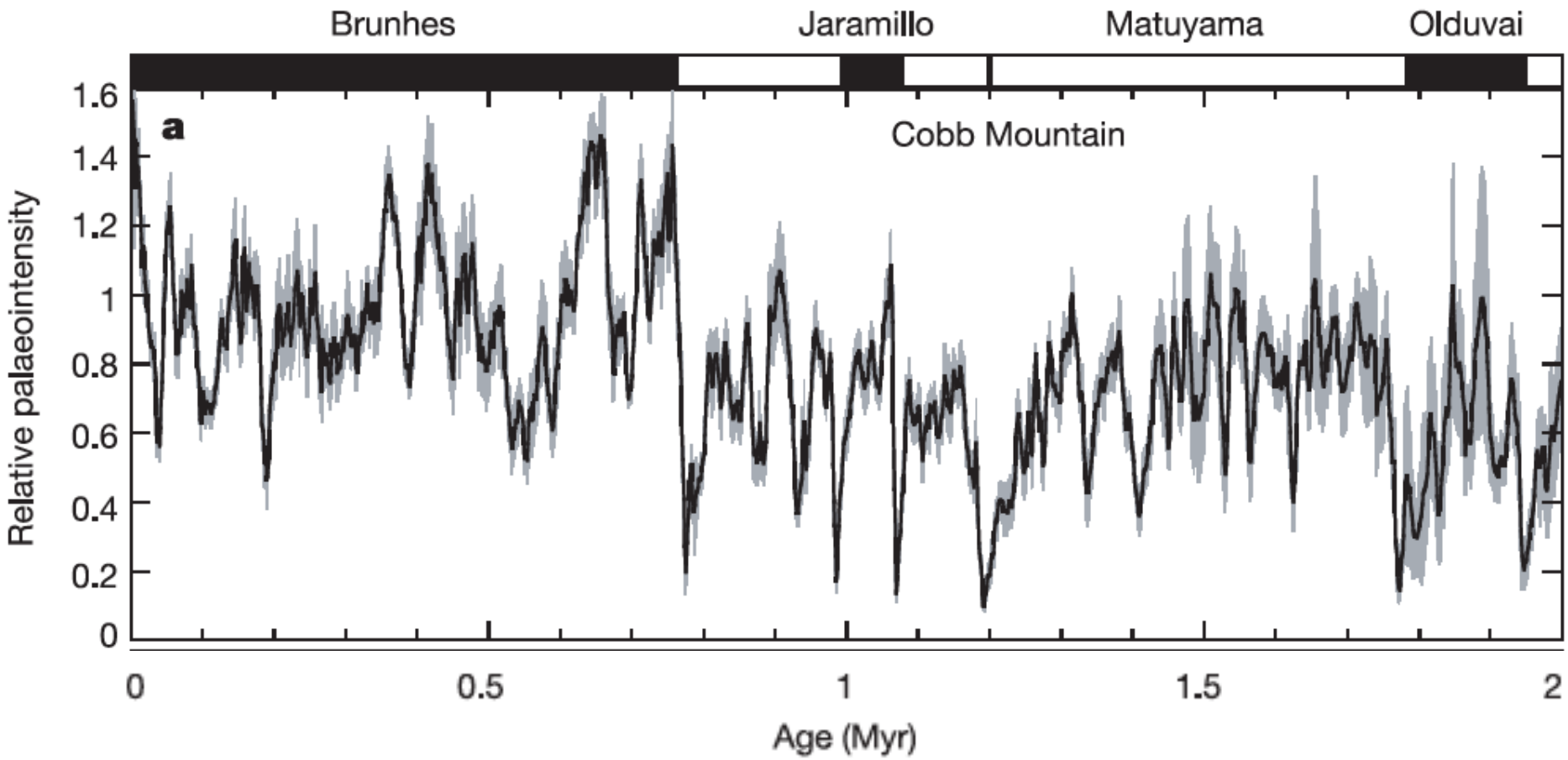






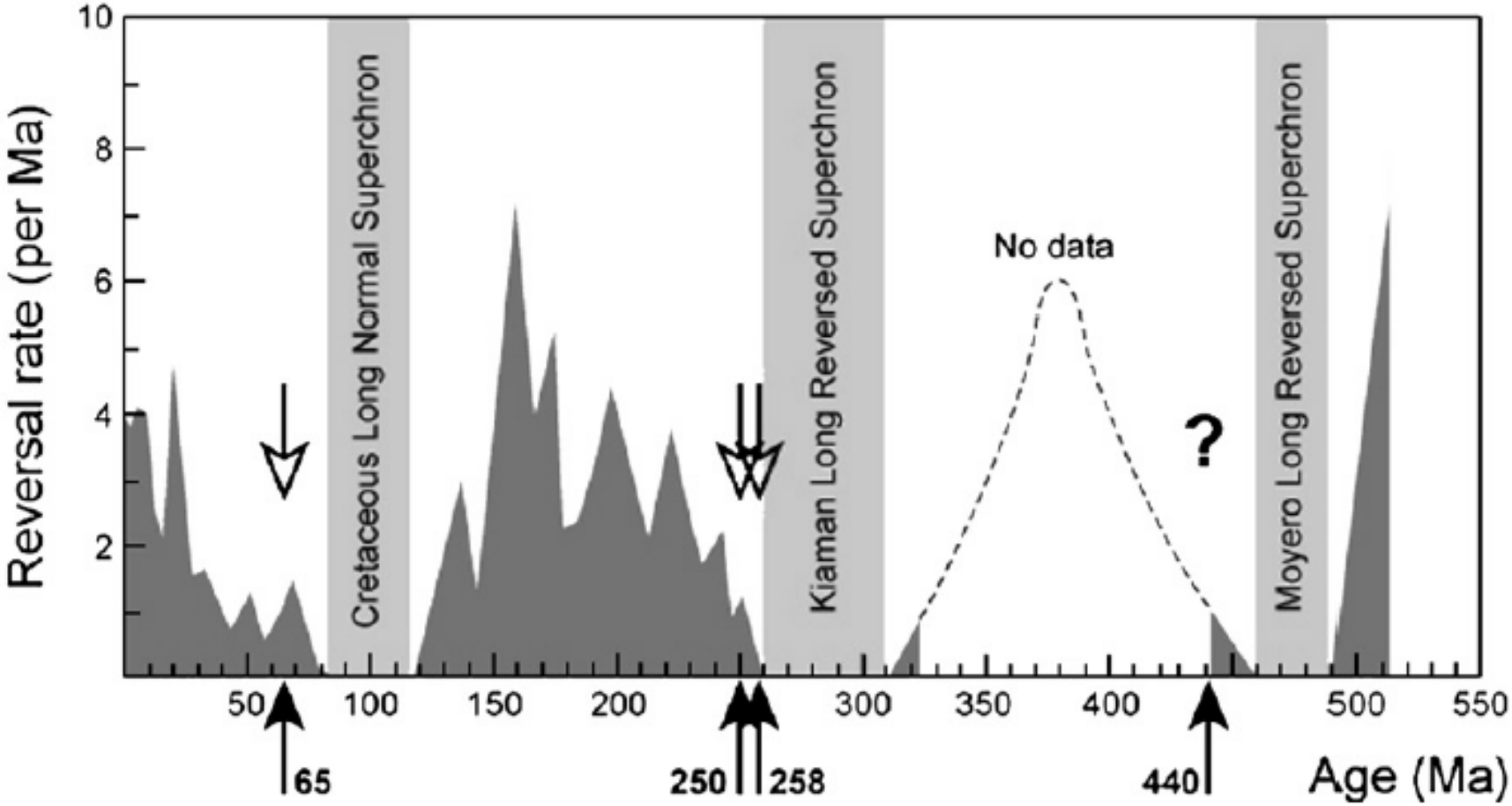
(Korte et al., GGG, 2009; Gallet et al., EPSL, 2003)

Reversals and excursions



(Valet et al., Nature, 2005)

Chrons and superchrons



(Coutillot & Olson, EPSL, 2007)

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Magnetic induction equation

- Ohm's law in a moving, electrically conducting medium:

$$\vec{J} = \sigma\left(\vec{E} + \vec{u}\times\vec{B}\right)$$

- Combining Ohm's law with Maxwell equations yields:

$$\frac{\partial \vec{B}}{\partial t} = \boxed{\vec{\nabla}\times\left(\vec{u}\times\vec{B}\right)} + \boxed{\eta\nabla^2\vec{B}}$$

Induction term Diffusion term

- To have a dynamo, the work done by the flow on the magnetic field must overcome Ohmic dissipation.

- Magnetic Reynolds number: $$\frac{\left|\vec{\nabla}\times\left(\vec{u}\times\vec{B}\right)\right|}{\left|\eta\nabla^2\vec{B}\right|} \sim \frac{UL}{\eta} = R_m$$ ~ 300 for large scale core flows

Rotating convection

- Energy sources: Earth's cooling, light elements released by inner core crystallization, radioactive elements in the core, tides.

- Navier-Stokes equation:

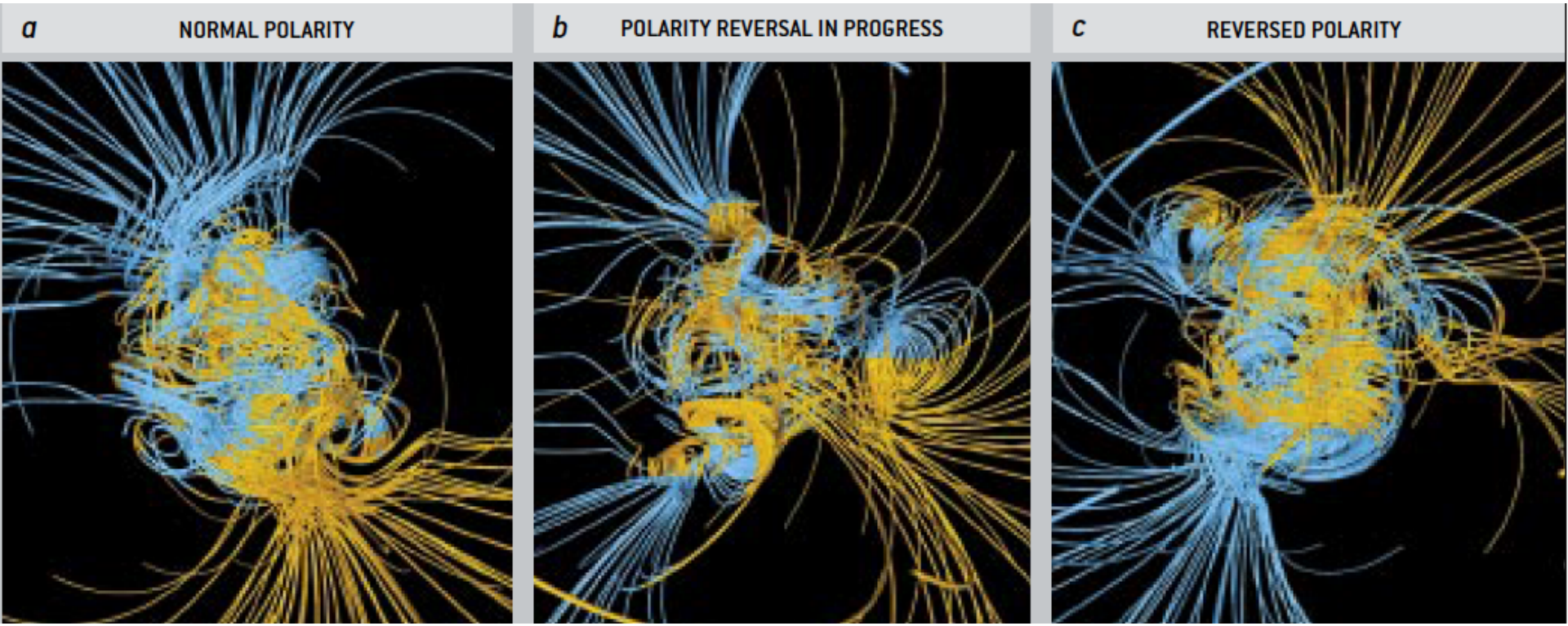
$$\rho_0\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} + \boxed{2\boldsymbol{\Omega}\times\mathbf{u}}\right) = -\nabla p + \rho'\mathbf{g} + \boxed{\mathbf{J}\times\mathbf{B}} + \rho_0\nu\nabla^2\mathbf{u}$$

Coriolis force Lorentz force

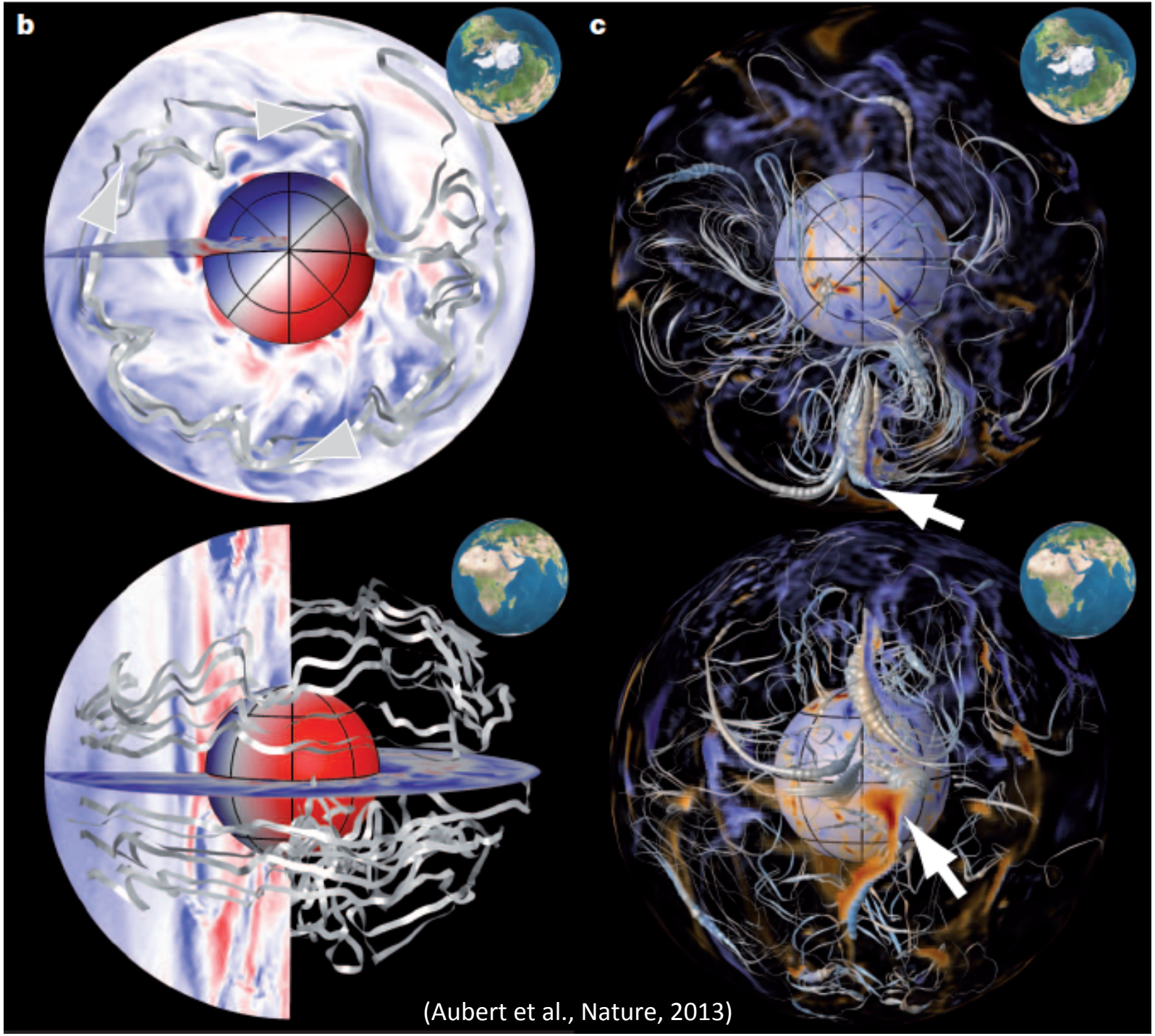
- The Coriolis force has a stabilizing influence on the flow: flows tend to become 2D in the direction of rotation (geostrophic and quasi-geostrophic flows) => columnar convection

- The Lorentz force has a similar effect in the direction of the magnetic field.

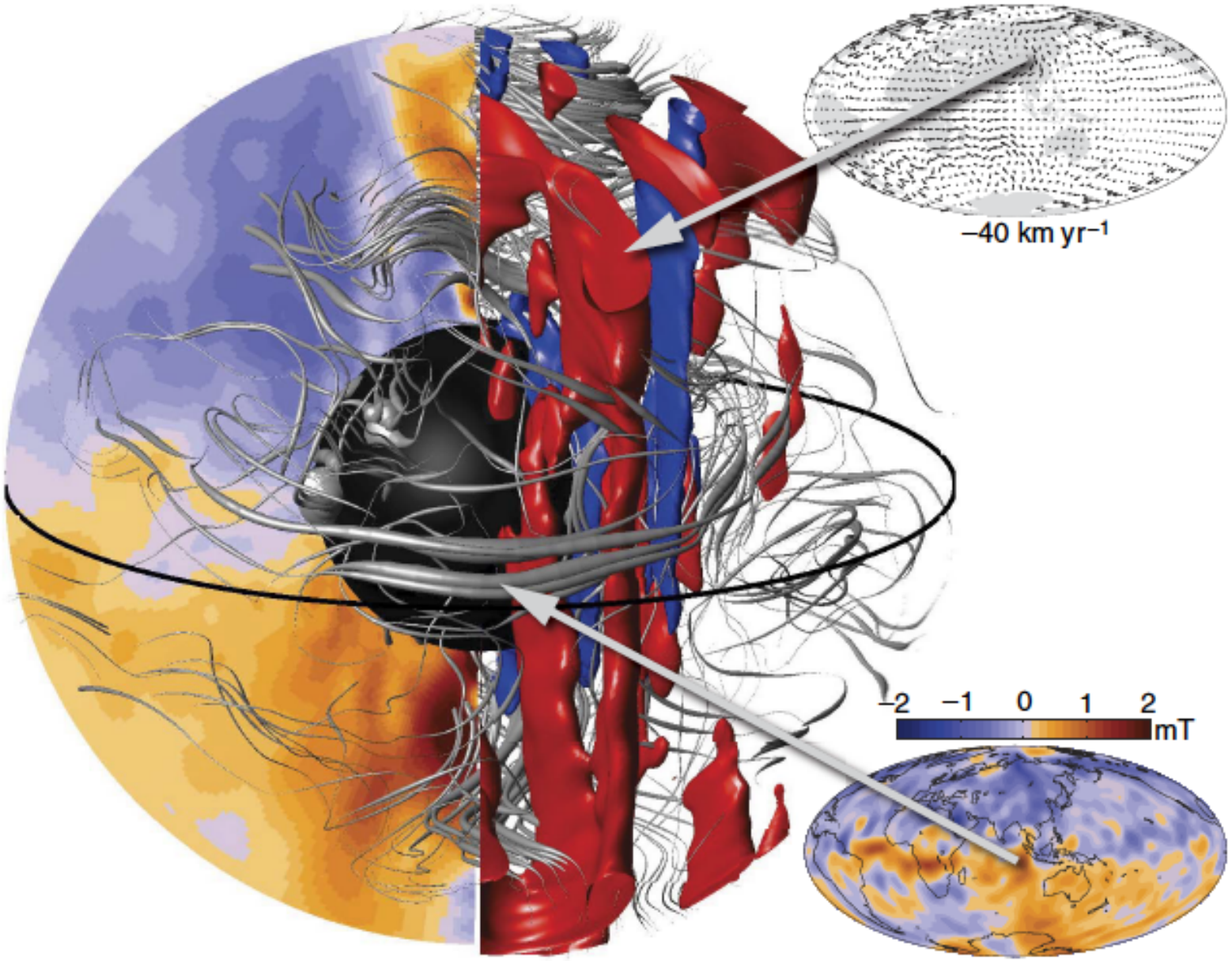
Numerical simulations of the geodynamo



- 1995: first 3D simulation reproducing a reversal (Glatzmaier & Roberts)
- Today: several characteristics of the observed field are reproduced, but there is still no satisfactory description of turbulent small-scale flows



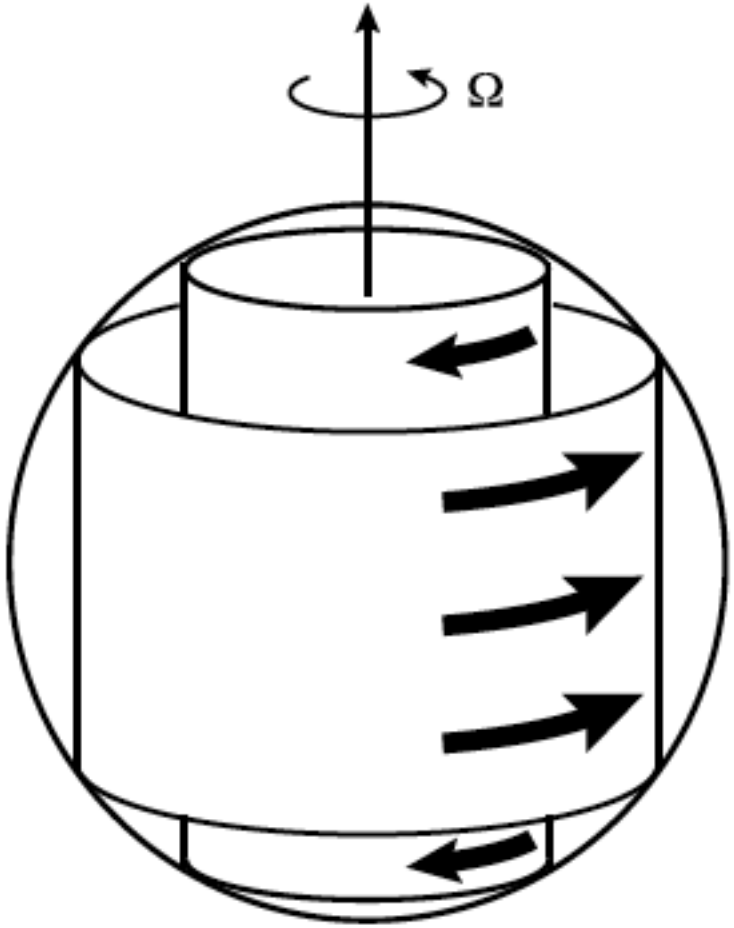
(Aubert et al., Nature, 2013)



(Finlay et al., Nature Comm., 2016)

Torsional oscillations

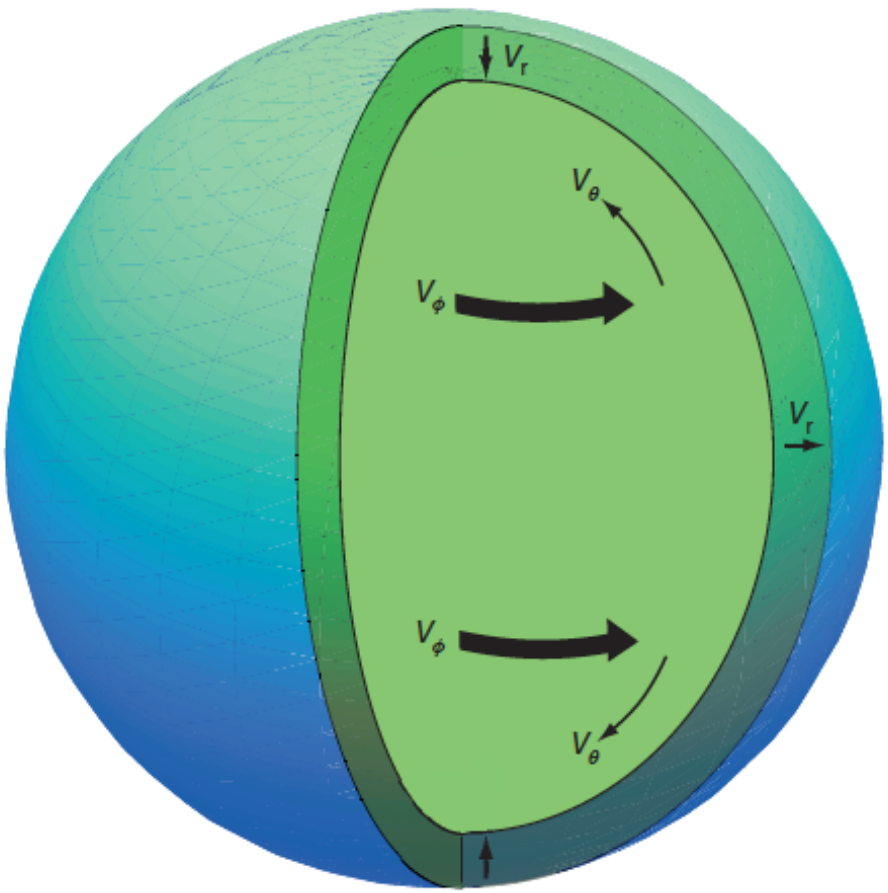
- Azimuthal oscillations of rigid cylindrical surfaces aligned with the rotation axis.
- A special class of Alfven waves in a rapidly rotating spherical geometry (restoring force is magnetic).
- Period depends crucially on the magnitude of the radial field.
- Recent observations support fast waves of period ~ 6 yrs and radial field ~ 2 mT.
- Have a measurable effect on LOD variations (core-mantle coupling).



(Finlay et al., SSR, 2010)

Is the top of the core stably stratified?

- Recently, first-principle calculations lead to an upward revision of the thermal conductivity of the core.
- Would support the existence of a (subadiabatic) stably stratified layer at the top of the core.
- Supported by seismic data analysis.
- Consequences for geomagnetism are still unclear, but
  - 60 yr fluctuations could be explained by MAC waves in the layer
  - Fast (6 yr) equatorial waves (recent jerks) could be explained by magnetic Rossby waves



(Buffett, Nature, 2014)

Self-assessment questions

1. What are the main features of the core field at the core-mantle boundary?

2. By how much did the axial dipole decrease over the past ~150 years and is this decay rate unusual?

3. What are the fastest observed variations in the core field?

4. How does the Earth's rotation affect core dynamics?

5. What would happen if flows in the core suddenly stopped?