Bottom-up control of geomagnetic field evolution

Chris Finlay

DTU Space

Julien Aubert, Alexandre Fournier

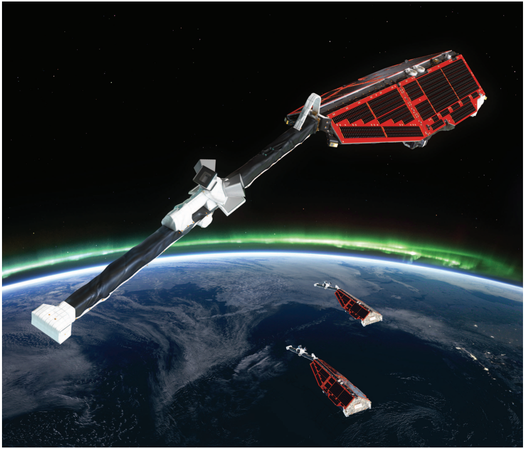
IPG, Paris

DTU Space

National Space Institute

Swarm: to be launched tomorrow!

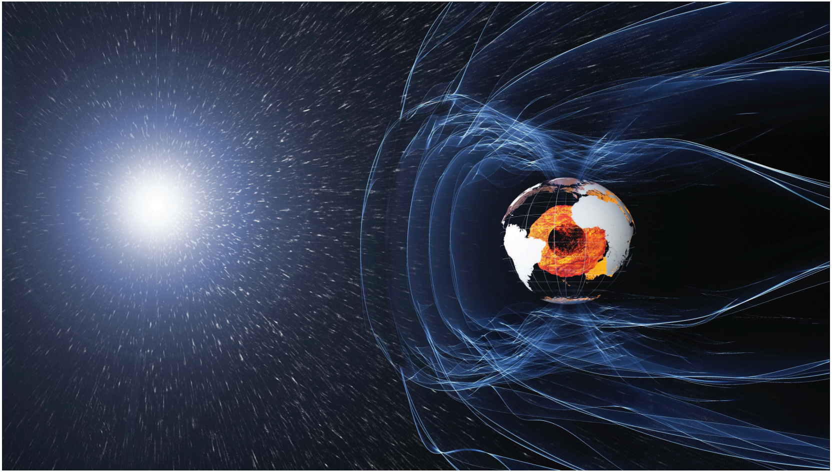
- ESA's satellite trio aims to perform the best ever survey of Earth's magnetic field.



Credit: ESA

The Earth's magnetic field

- Core-generated field mediates between Earth and the wider solar system.



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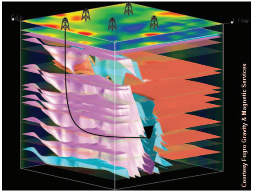
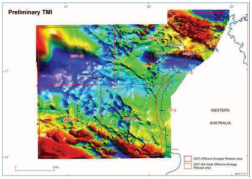
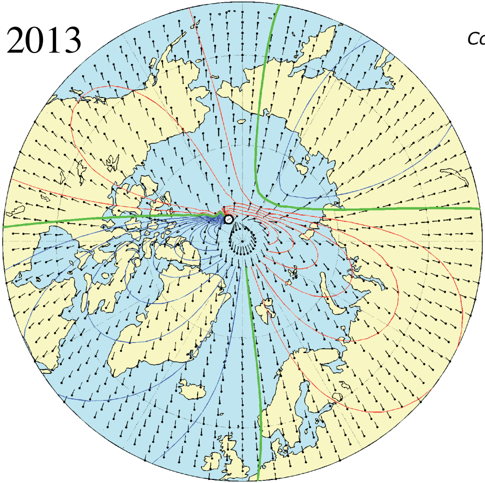
Applications: providing directional information





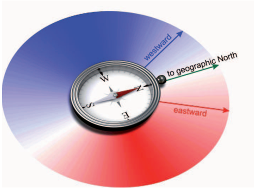
- Use of electronic compasses now very widespread in mobile phones & compact cameras. Also for drill orientation in hydrocarbon industry.
- $\sim$ 2 million queries per year of online calculators.
- Applications requires very accurate models of the current geomagnetic field.

Magnetic compass direction

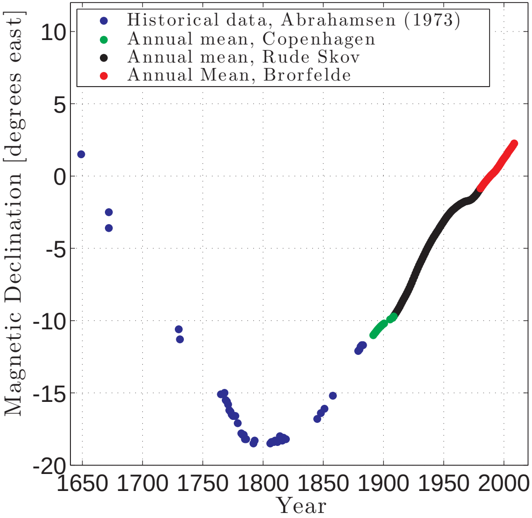


Compass points in direction
eastward / westward
of geographic pole

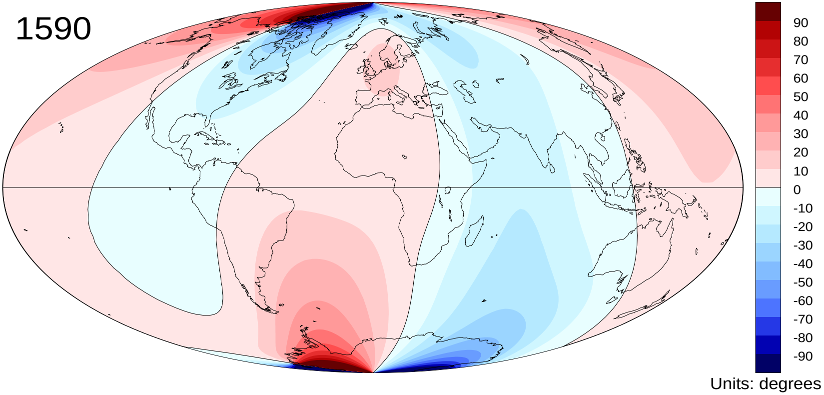
Compass points towards
geographic pole



Evolution of Earth's magnetic field in Denmark



Global change in declination over the past 400 years



- Declination at Earth's surface (Jackson et al., 2000) Units: degrees.

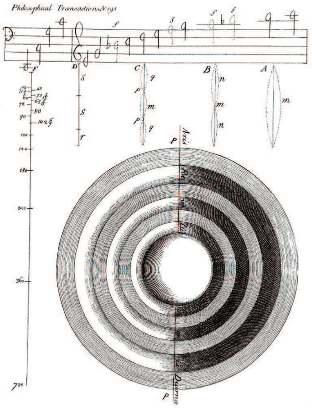
Edmund Halley: Observer, Astronomer & Geophysicist

DTU

Edmund Halley in 1687.

Halley's 1701 map of declination.

Edmund Halley: Observer, Astronomer & Geophysicist



Halley's rotating, magnetized, hollow spheres theory of secular variation, 1692.

Edmund Halley in 1736, aged 81.

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- 1. Detailed characterization with global, high quality, magnetic observations.

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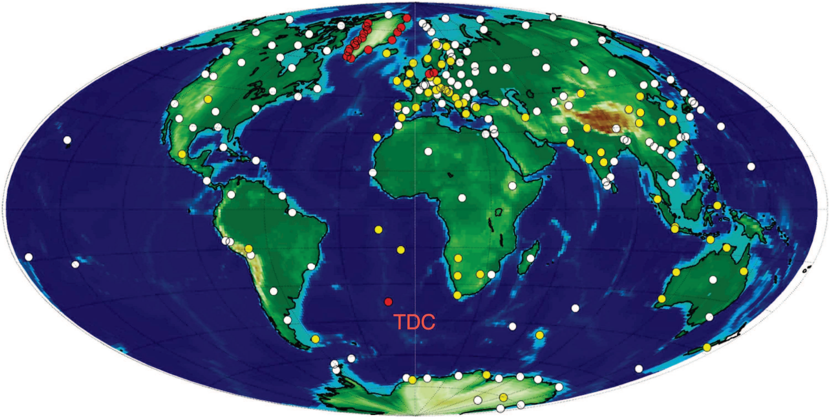
- The Modern Approach:

- 1. Detailed characterization with global, high quality, magnetic observations.

- 2. Physically consistent models of deep Earth processes generating field change.

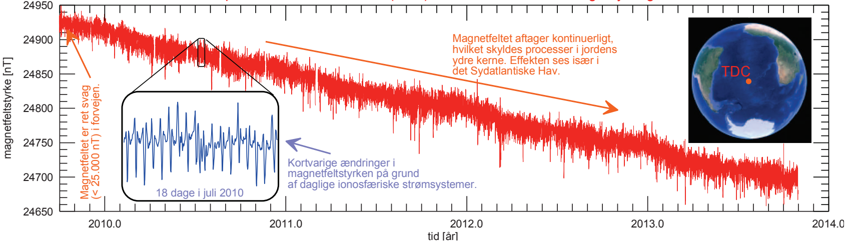
Global network of ground observatories



- DTU Space operates stations in Denmark, Greenland and Tristan Da Cunha.
- Also provide fluxgate (FGE and DI) instruments to many observatories.

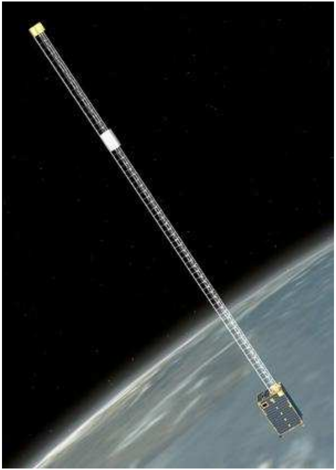
Example DTU magnetic observatory: Tristan da Cunha

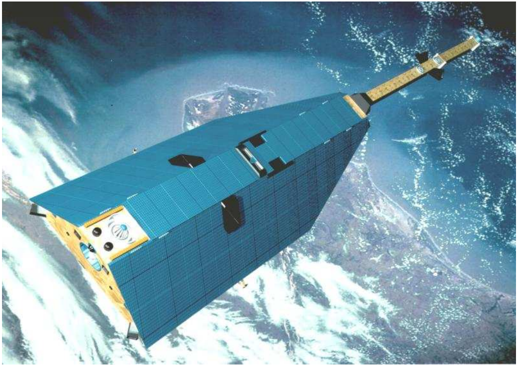
I den Sydatlantiske Anomali bliver magnetfeltet svager og svager: målinger fra DTUs magnetiske observatorium på øen Tristan da Cunha (TDC) viser dette fænomen meget tydeligt.



Ørsted and CHAMP satellite magnetometry missions

- Dedicated satellite missions: Ørsted 1999 - present and CHAMP 2000 - 2010.

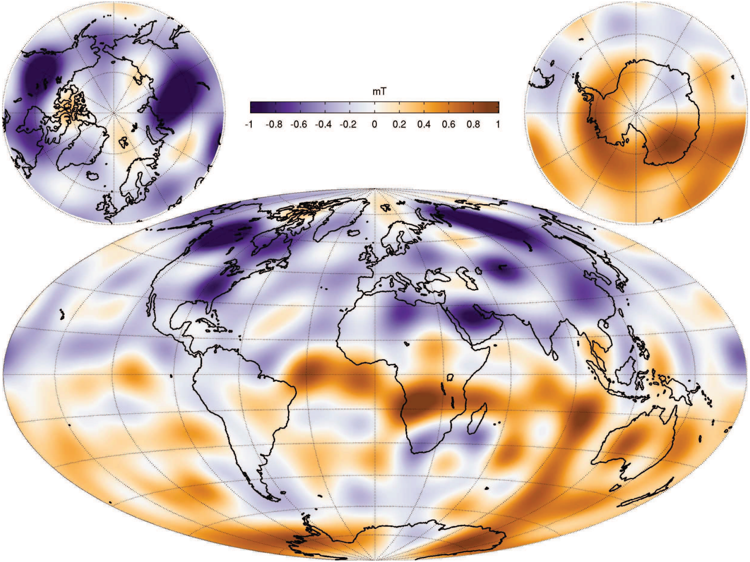




Instruments from DTU Space

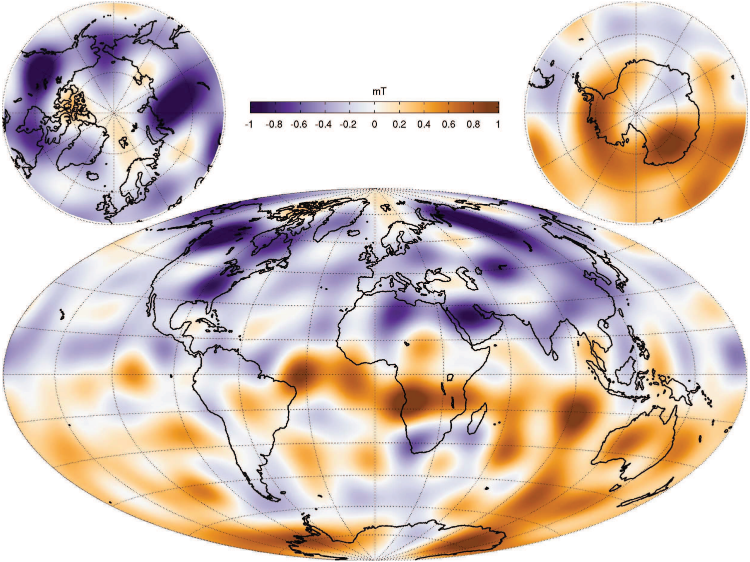
- Vector Field Magnetometers and star trackers from MI division were used on Ørsted and CHAMP, and will also be key in the Swarm mission.

Radial field at core surface in 1999.5



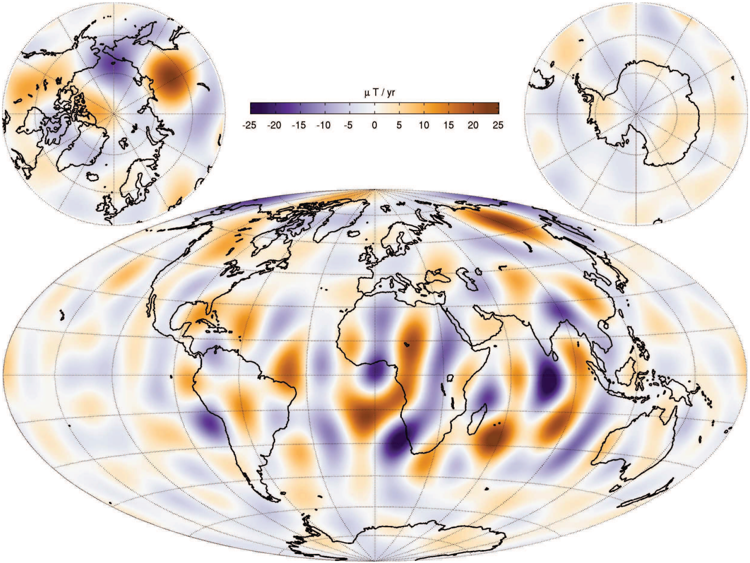
- Radial field in 1999.5,from the CHAOS-4 field model (Olsen et al., 2013).

Radial field at core surface in 2013.5



- Radial field in 2013.5, from the CHAOS-4 field model (Olsen et al., 2013).

Rate of change of radial field in 2006.5



- Rate of change of the radial field in 2006.5, from CHAOS-4 (Olsen et al., 2013).

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- Westward drifting field features at surface.
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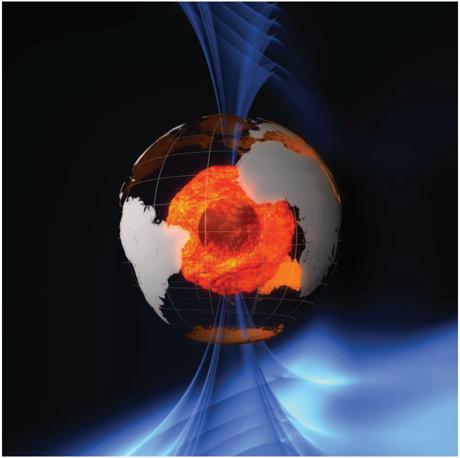
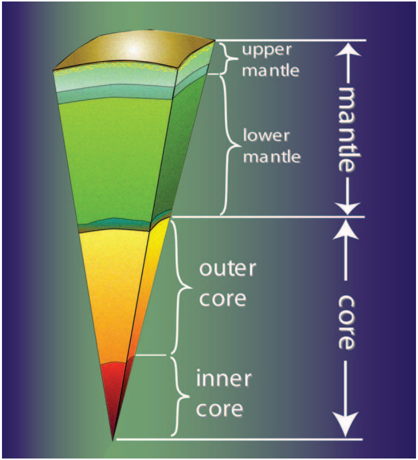
- Field change is localized at longitudes under the Atlantic hemisphere.
- And it occurs predominantly at latitudes < 30 degrees.
- **What mechanism could produced such geographically localized westward drift?**

Earth's deep interior: the seat of the geodynamo



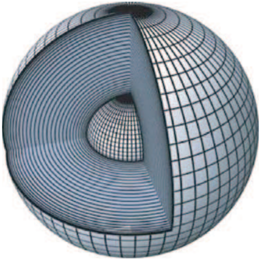


Simulating the geodynamo

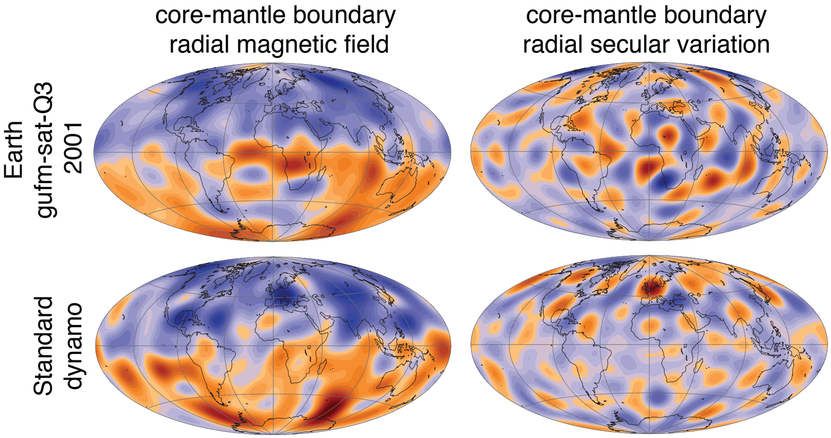
- Solid mantle and inner core.
- Simulate outer core MHD in a thick spherical shell.

- Fluid motions: Navier-Stokes eqns: Inertia, Coriolis, Viscous, Bouyancy, Lorentz.
- Electrodynamics: Maxwell's eqns simplify to Induction eqn (MHD approx).
- Heat Transport: Boussinesq approx.

- Highly nonlinear system: disparities in spatial & time scales are **challenging**.



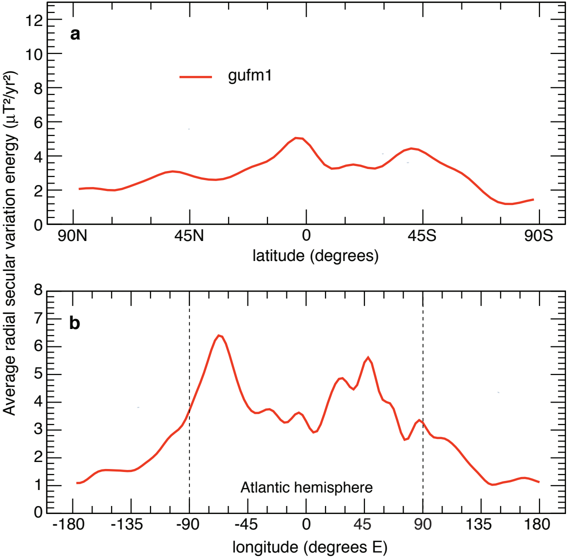
Comparison of core surface field and rate of change



Historical field evolution

- Radial field at core surface from 1590.0-1990.0, (Jackson et al., 2000): units μT.

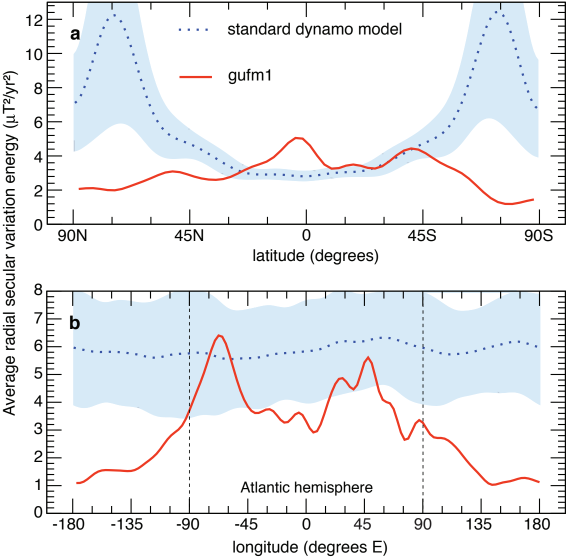
Geographical localisation of field change



Field evolution in a conventional geodynamo model

- Radial field at core surface from a standard geodynamo model, units μT

Comparison of localisation of field change



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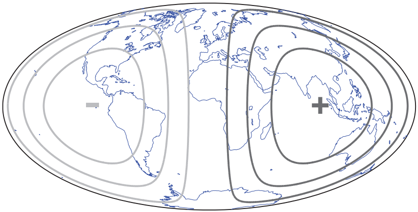
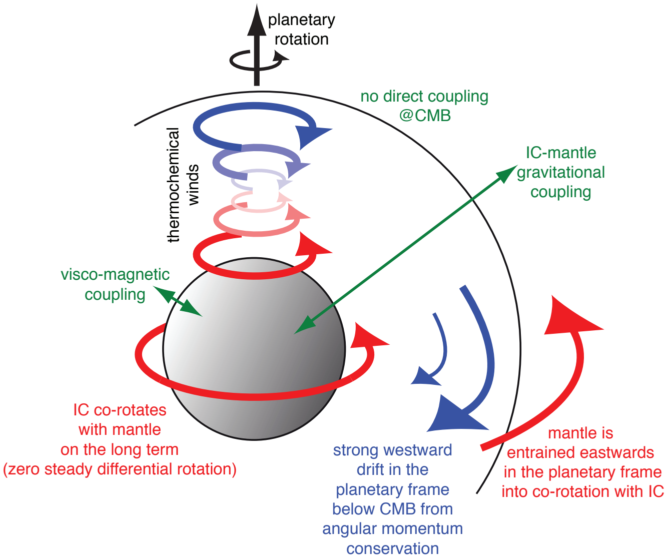
- No intense field concentrations at low latitudes.

Inner core bouyancy flux: hemispheric differences



- Inner core may be solidifying faster beneath Indonesia, releasing plumes enriched in lighter elements and preferentially driving convection in one hemisphere.

Coupling of the inner core, outer core, and mantle



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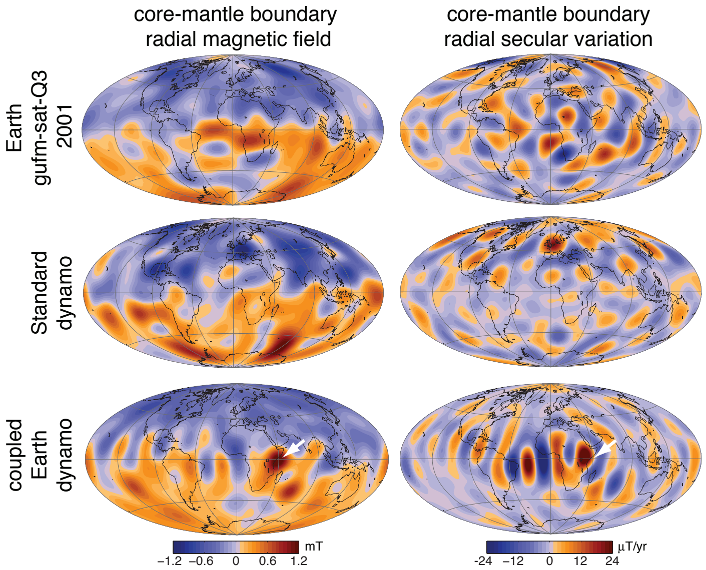
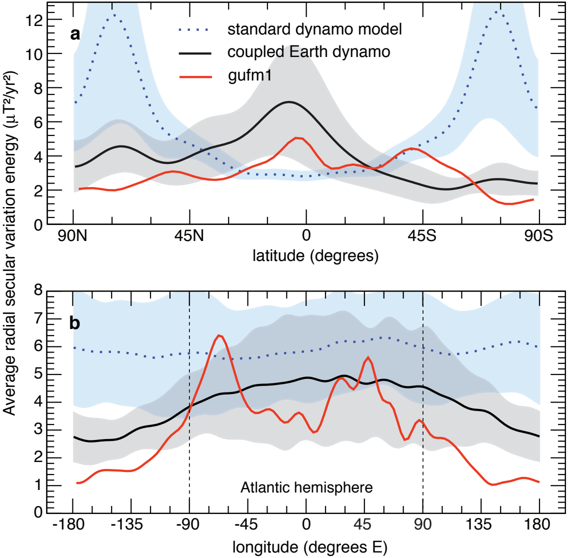


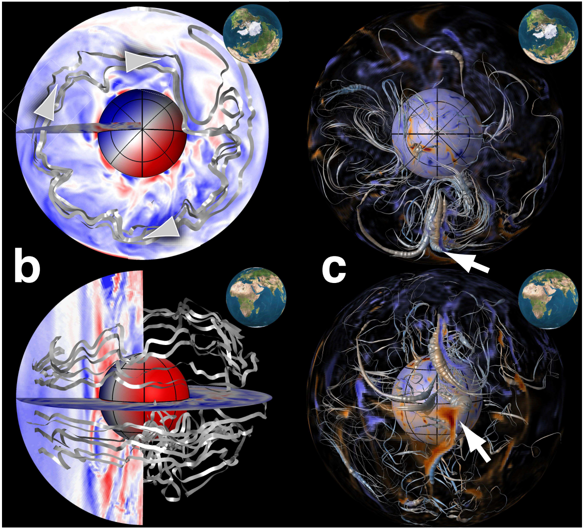
Field evolution in new coupled Earth dynamo model

- Radial field at outer boundary of coupled Earth dynamo model
  From Aubert, Finlay and Fournier (2013).

Geographical localization



A planetary scale gyre in the outer core



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Summary

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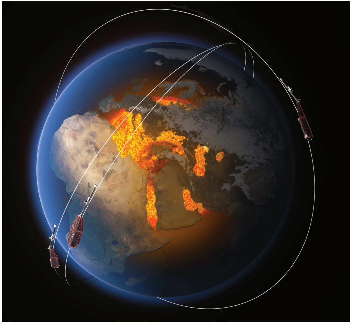
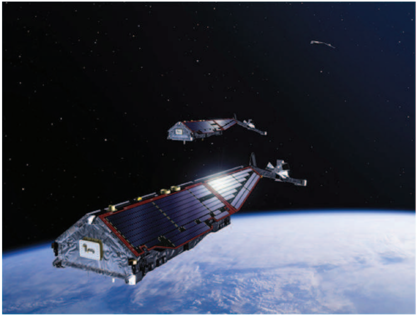
- A new proposal for the origin of geomagnetic westward drift.
- Due to a planetary scale, sheet-like gyre in the outer core.
- Gravitational and EM coupling between the inner core, outer core and mantle localizes gyre at low latitudes.
- Heterogeneous growth of inner core localizes field change to Atlantic.

A first attempt at predicting future field evolution

- Radial field at core surface, starting from 2006 field projected into the core, and using the coupled-Earth dynamo to run forward.

Looking ahead: Making the most of Swarm





Credit: ESA

- Outlook: Physics-based, short term, predictions of SV now in sight by combining dynamo models and observations via data assimilation.
- New theory predicts: Small scale gyre structure & its self-advection.
- Local time coverage (3 satellites) -> better separation of core and ext fields.

Geodynamo modelling: Governing Equations

- Conservation of momentum:

$$Ro\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}.\nabla\mathbf{u}\right) + \boldsymbol{\Omega}\times\mathbf{u} = -\nabla p - qRaC\,\mathbf{g} + (\nabla\times\mathbf{B})\times\mathbf{B} + E\nabla^2\mathbf{u}$$

- Magnetic induction under MHD approx:

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

- Transport of buoyant material (Boussinesq Approx):

$$\frac{\partial C}{\partial t} + \mathbf{u}\cdot\nabla C = q\nabla^2 C$$

- Non-dimensional control parameters:

$$Ro = \frac{\eta}{2\Omega r_o^2} \qquad Ra = \frac{g_0\alpha\beta r_o^2}{2\Omega\kappa} \qquad E = \frac{\nu}{2\Omega r_o^2} \qquad q = \frac{\kappa}{\eta}$$

- Solve numerically in spherical shell geometry: SH and FD.
- Boundary conditions:
  - (i) No slip at ICB and CMB.
  - (ii) Electrically conducting IC and insulating Mantle.
  - (iii) Homogeneous buoyancy flux at ICB and CMB.

Gravitational coupling of inner core and mantle

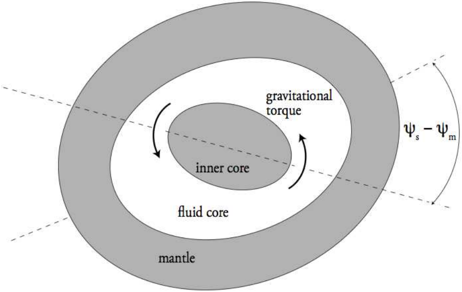


Fig : Mass distribution in mantle is not spherically symmetric, neither is gravitational field experienced by inner core. If inner core is torqued out of alignment with mantle it experiences a restoring force i.e. inner core is effectively pinned to the mantle.

Time-longitude plots of field evolution

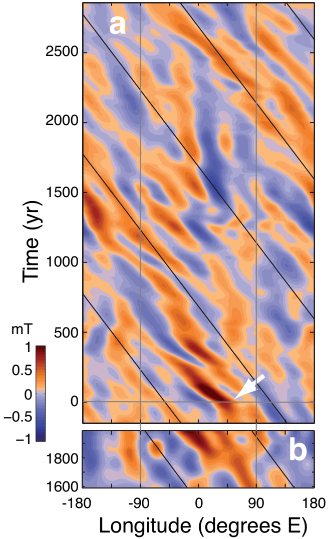


Fig : Time-longitude plot of field evolution at equator.

Westward drift at low latitudes

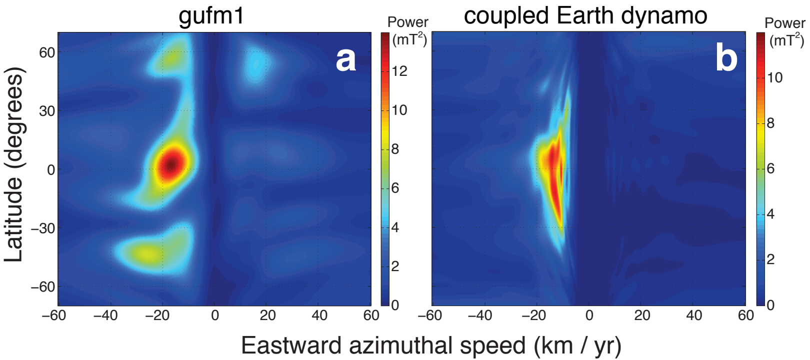


Fig : Power distribution for Latitude vs Azimuthal speed.

Core surface flow: An eccentric gyre

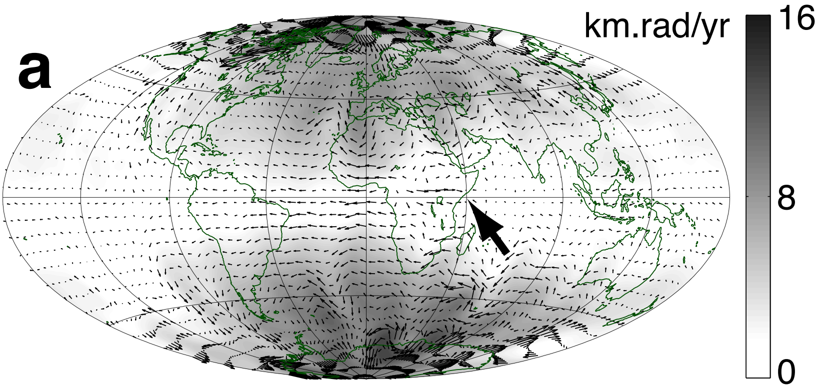


Fig : Flow close to the outer boundary of dynamo at same instant as snapshots shown earlier.

What lies beneath: flow deep within the core

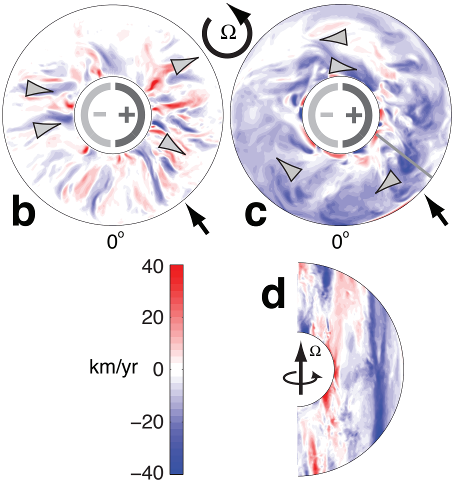


Fig : Radial flow (top left) and azimuthal flow (top right) in the equatorial plane and azimuthal flow in the meridional plane (bottom).

Inge Lehmann: Discoverer of Earth's inner core

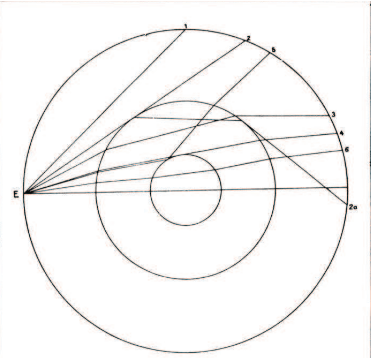


Fig : Inge Lehmann (1888-1993), Danish Seismologist, Discoverer of Earth's inner core in 1936 (left) and her interpretation of a seismic reflection from the inner core (right).