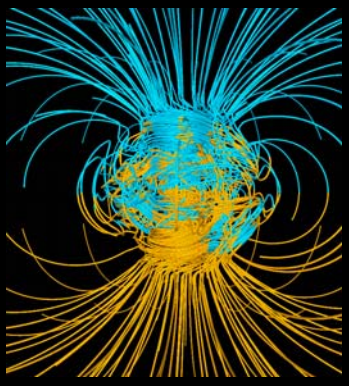
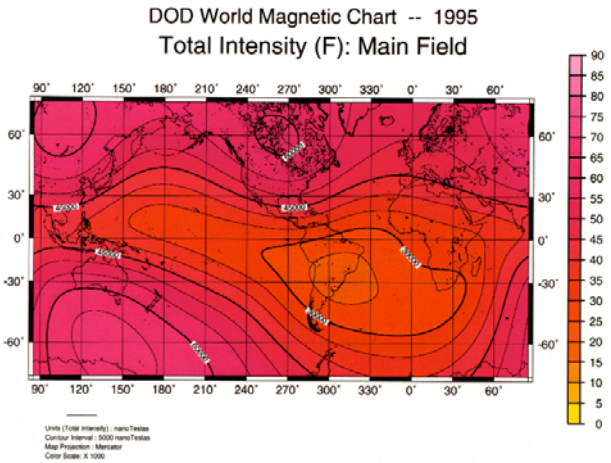


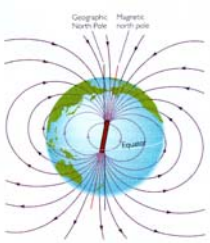
The geodynamo

Reading: Fowler Ch 8, p373-381
Glatzmaier et al. *Nature* **401**, 885 - 890 1999

Previously…

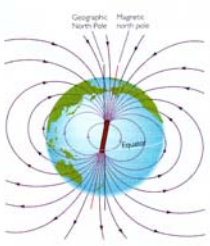
The Earth's magnetic field

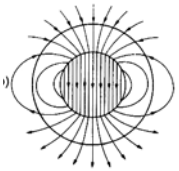




TODAY: how is the Earth's field generated?

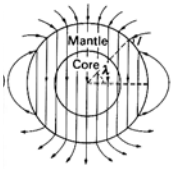
Generating the
Earth's magnetic field





Uniformly magnetized core

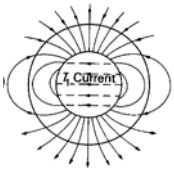
- Material is above Curie temperature (6000 K in the inner core)
- Mag field is changing with time



Uniformly magnetized core and mantle

- Silicates: not a candidate for a permanent magnetic field
- Material is above Curie temperature

...also need time dependent field

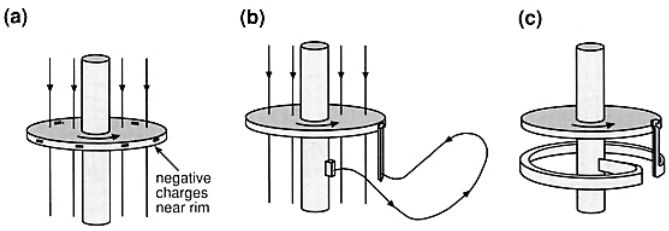


East-west current around core-mantle boundary

- Earth's mag field has been in existence for 3500 Ma (palaeomag)

➔ Current must be maintained **how?**

Self-exciting dynamo



Note: can reverse the current and field – magnetic reversal

But, the field cannot reverse itself

plus, seems unlikely that this process can operate in the conductive core without short-circuiting itself

Earth's magnetic field

What continues to generate the Earth's magnetic field?

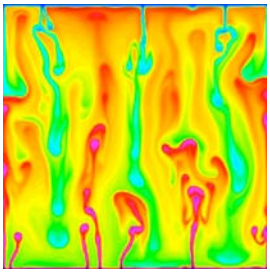
- **Temperature of the Earth's core is too high for a permanent magnetic field**
- **Magnetic field reverses every ~200,000 years (5,000 to 50 mill)**
- **The magnetic field would decay away within 20,000 years given the size and electrical conductivity of the Earth's core**

➔ **the field must be continually generated**

A convective dynamo operating in the Earth's fluid outer core?

➔ **Magnetohydrodynamics**

Coupling of fluid motion and generation of a magnetic field



Magnetohydrodynamics

Coupling of fluid flow and generation of the Earth's magnetic field

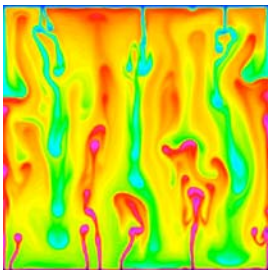
Need to solve interrelated set of non-linear partial differential equations:

a) Electromagnetic equations
relate the magnetic field to the velocity of fluid flow in the outer core

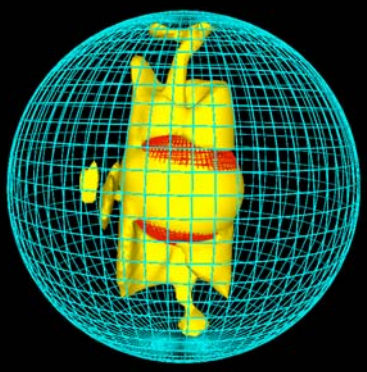
b) Hydrodynamic equations
conservation of mass and momentum, and the equation of motion for fluid flow

c) Heat transfer and compositional convection equations
in a fluid flow

d) Boundary and initial conditions



A convective dynamo?



Red mesh: inner-outer core boundary
Blue mesh: core-mantle boundary
Yellow: region of greatest flow

Glatzmaier and Roberts 1995

Thermal and compositional buoyancy causes flow

Earth's rotation – the Coriolis force – results in helical flow within tangential cylinder

Glatzmaier and Roberts solved the magnetohydrodynamic equations to test this hypothesis

Inner core:
- size of the moon (r_{moon} = 1,738 km)
- temperature of the surface of the Sun (~6000°C)

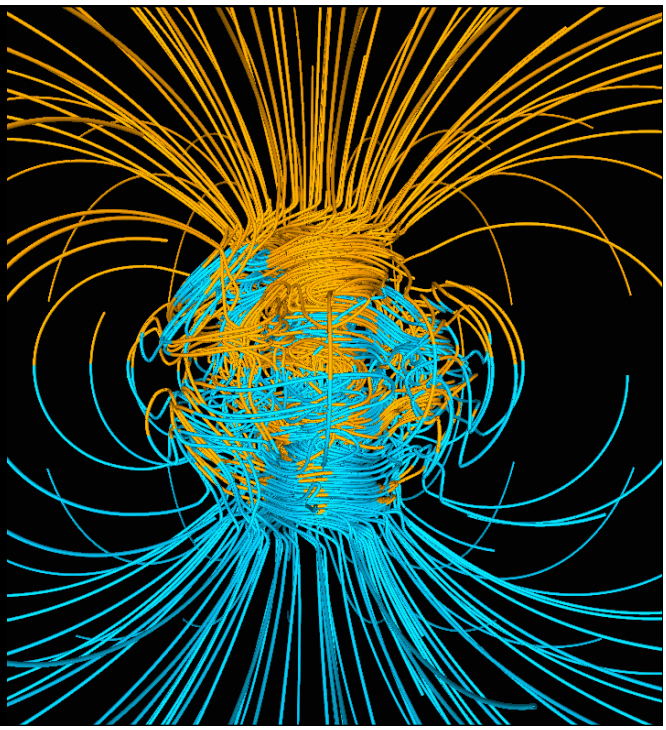
Magnetic field generated by outer core flow

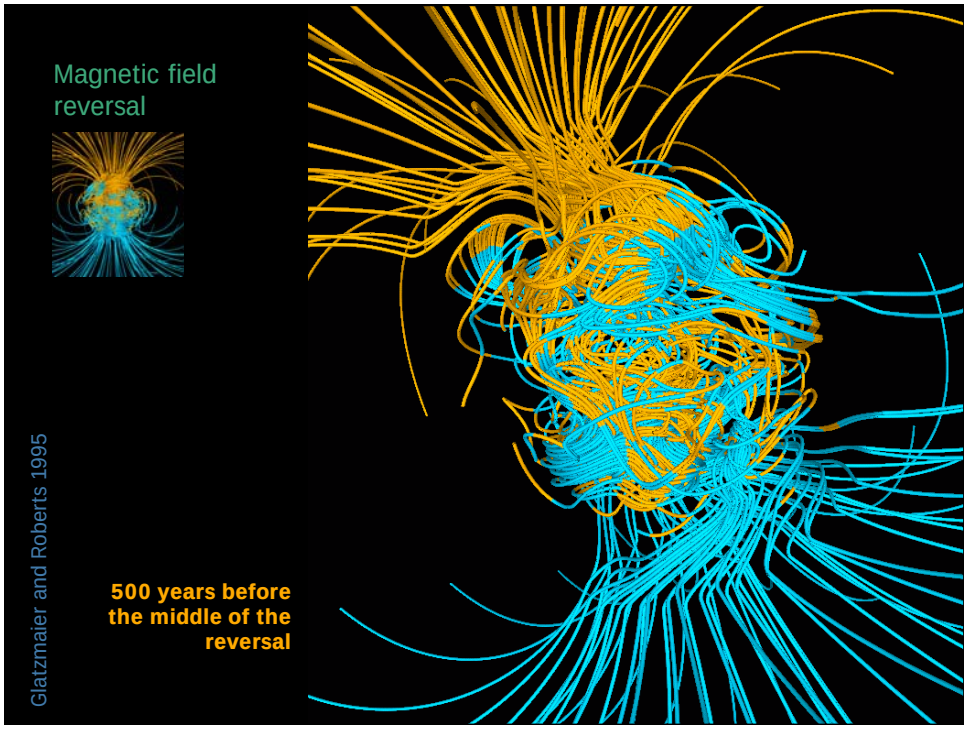
Simulated magnetic field has
- intensity and a dipole dominated structure that is very similar to the Earth's
- westward drift of non-dipolar structure

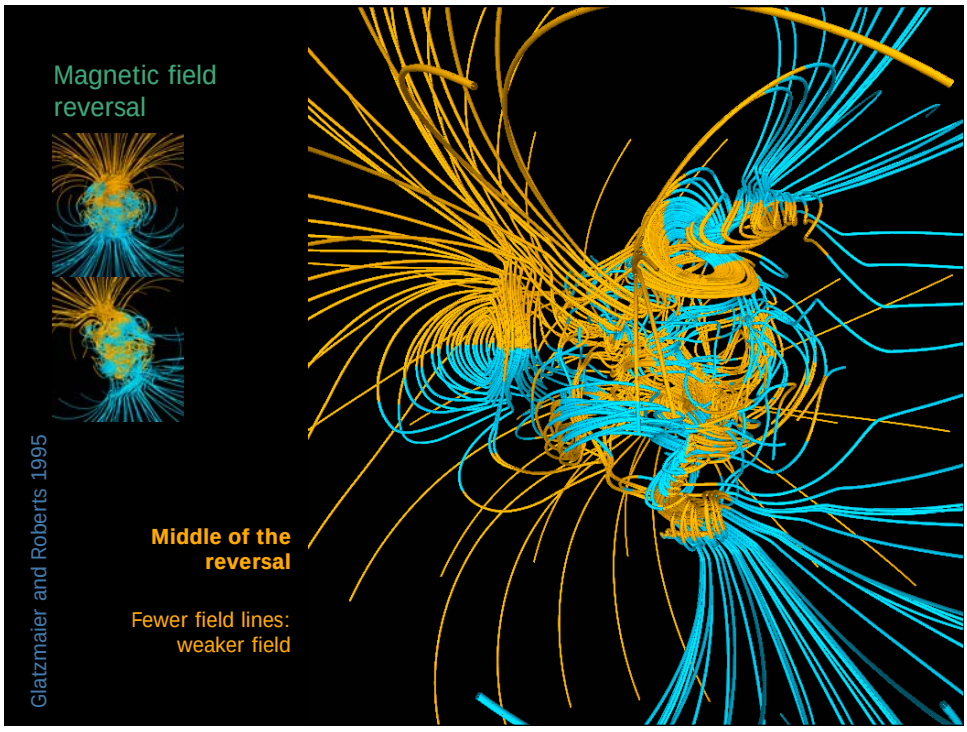
Blue: inward field

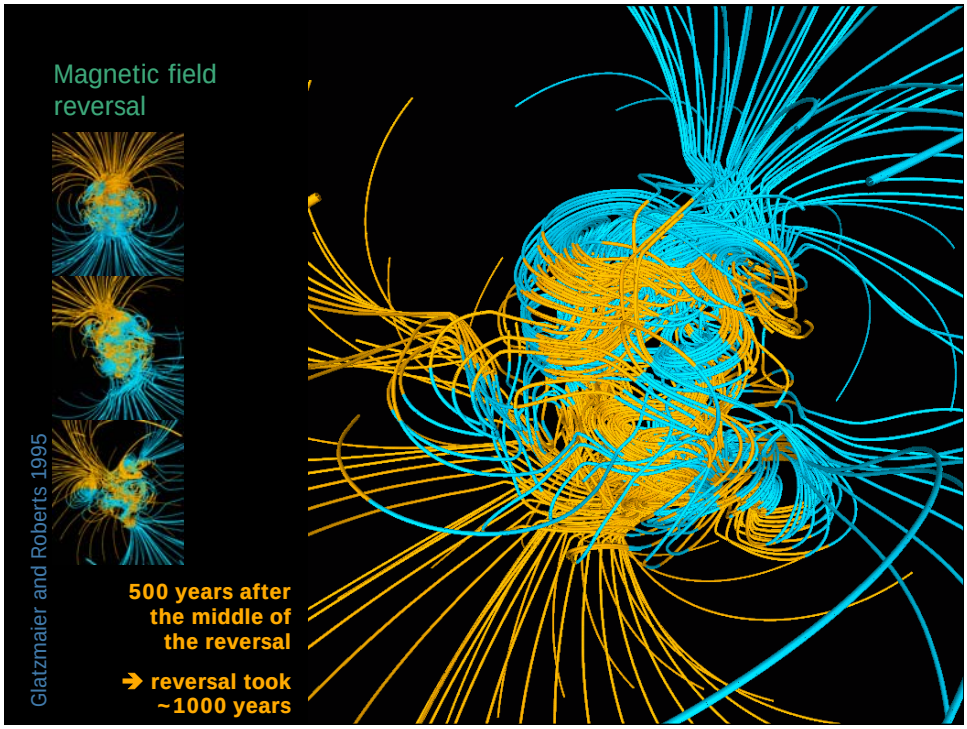
Orange: outward field

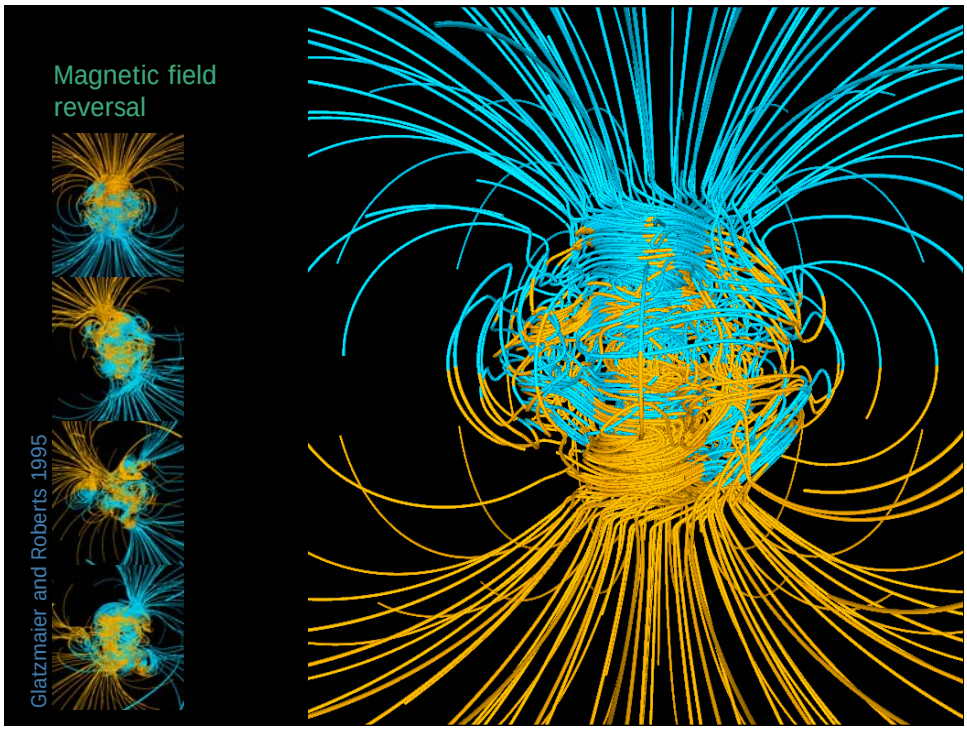
Glatzmaier and Roberts 1995




Magnetic field reversal
Glatzmaier and Roberts 1995
500 years before the middle of the reversal

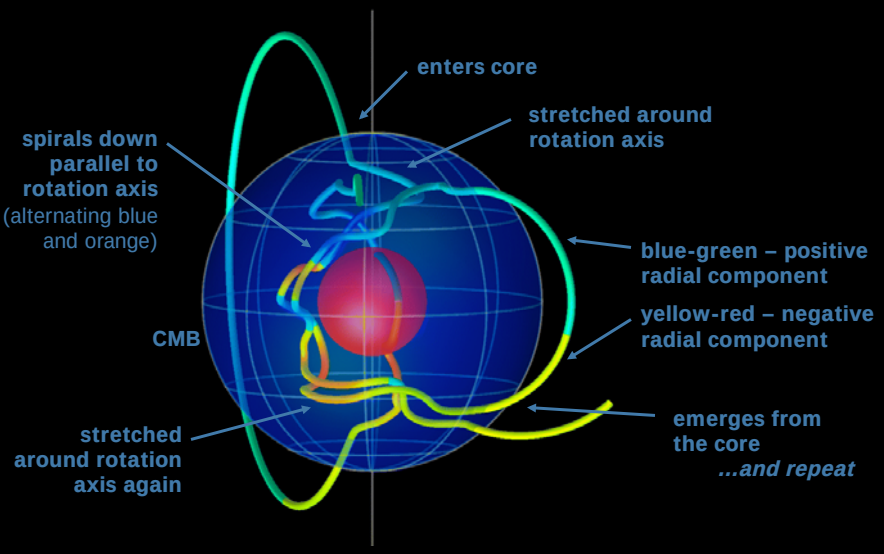

Magnetic field reversal
Glatzmaier and Roberts 1995
Middle of the reversal
Fewer field lines: weaker field


Magnetic field reversal
Glatzmaier and Roberts 1995
500 years after the middle of the reversal
➔ reversal took ~1000 years


Magnetic field reversal
Glatzmaier and Roberts 1995

Magnetic field lines

Kuang and Bloxham
Nature **389**, 371 - 374 1997



articles

The role of the Earth's mantle in controlling the frequency of geomagnetic reversals

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* Earth Sciences Department, University of California, Santa Cruz, California 95064, USA
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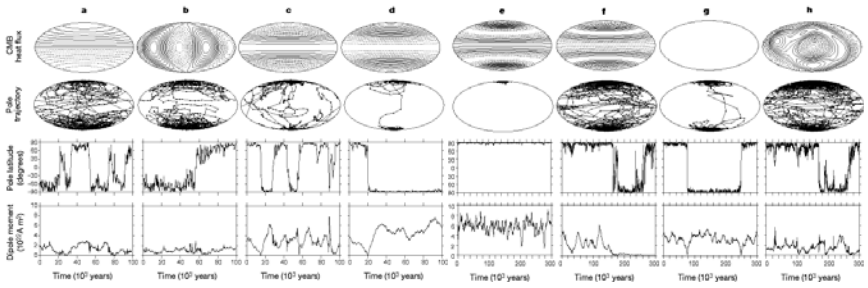
A series of computer simulations of the Earth's dynamo illustrates how the thermal structure of the lowermost mantle might affect convection and magnetic-field generation in the fluid core. Eight different patterns of heat flux from the core to the mantle are imposed over the core–mantle boundary. Spontaneous magnetic dipole reversals and excursions occur in seven of these cases, although sometimes the field only reverses in the outer part of the core, and then quickly reverses back. The results suggest correlations among the frequency of reversals, the duration over which the reversals occur, the magnetic-field intensity and the secular variation. The case with uniform heat flux at the core–mantle boundary appears most 'Earth-like'. This result suggests that variations in heat flux at the core–mantle boundary of the Earth are smaller than previously thought, possibly because seismic velocity anomalies in the lowermost mantle might have more of a compositional rather than thermal origin, or because of enhanced heat flux in the mantle's zones of ultra-low seismic velocity.

Glatzmaier et al.
Nature **401**, 885 - 890 1999
doi:10.1038/44776
Available on the class website

What can cause variations to the behavior of the Earth's magnetic field?

What parameters can we vary in our numerical model to reproduce the characteristics of the Earth's field?

➔ use their magnetohydrodynamic model to say some thing about interpreting seismic velocity anomalies in the lower mantle



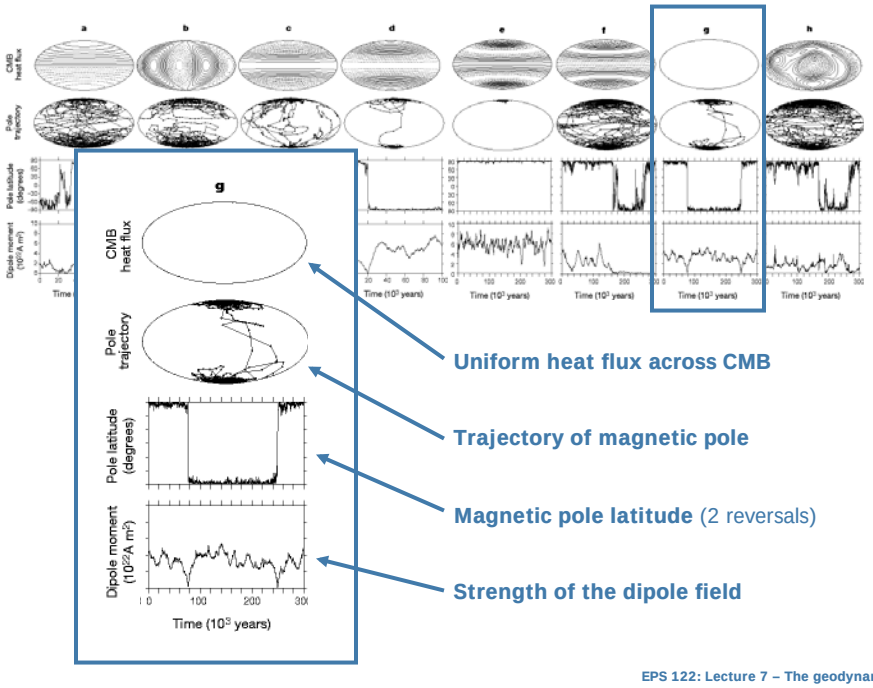
They vary the heat flux across the core-mantle boundary and explore the effect on the reversal history

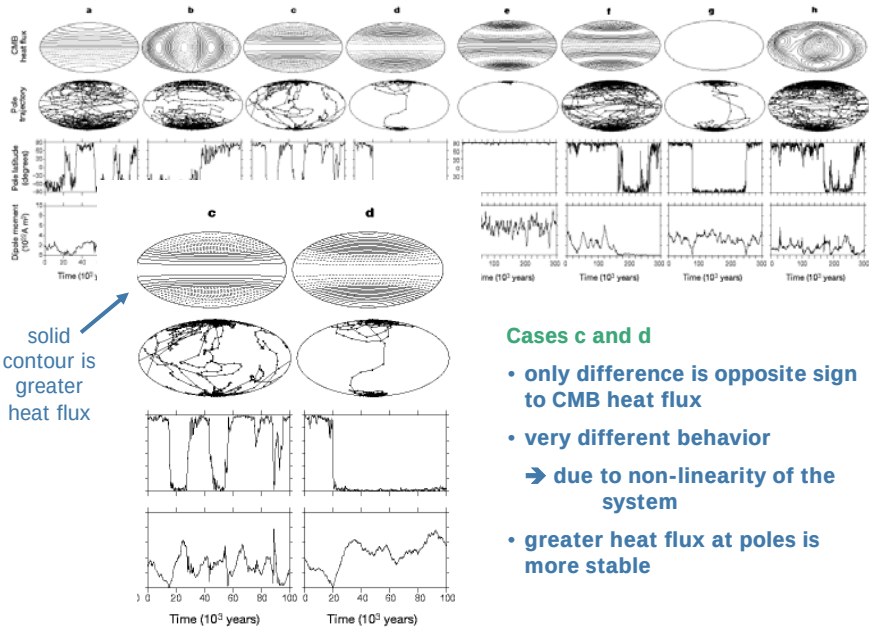
Characteristics of the Earth's field they want to match:

- **reversal durations are short (1000-6000 years)**
- **field intensity decreased significantly during reversals**
- **geomagnetic excursions occur more frequently than reversals**

  geomag excursions: when the mag pole deviates > 45° from the spin axis

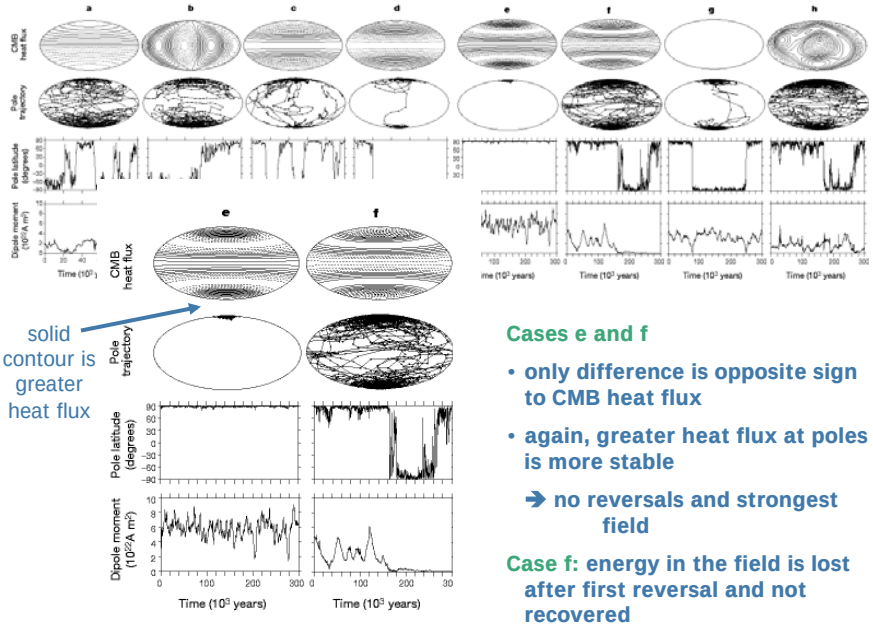
  e.g. 14 excursions since the last reversal (780,000 years ago)





Cases c and d

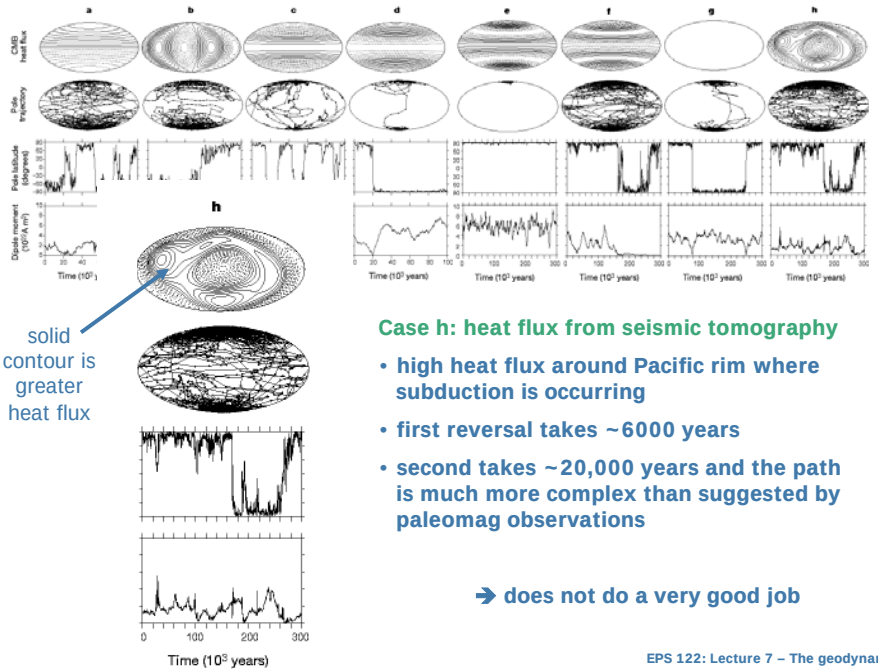
- **only difference is opposite sign to CMB heat flux**
- **very different behavior**
  - ➔ **due to non-linearity of the system**
- **greater heat flux at poles is more stable**



Cases e and f

- **only difference is opposite sign to CMB heat flux**
- **again, greater heat flux at poles is more stable**
  - ➔ **no reversals and strongest field**

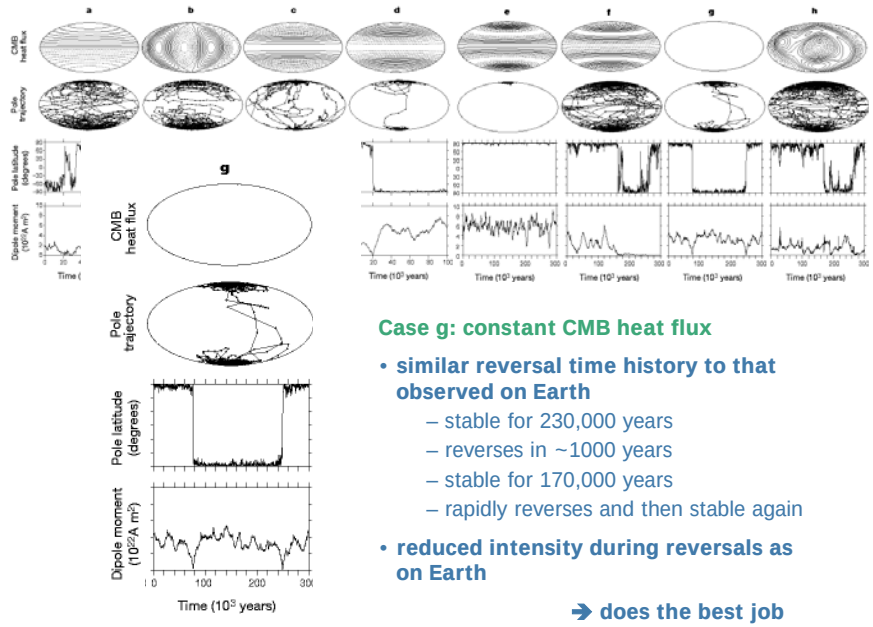
Case f: energy in the field is lost after first reversal and not recovered



Case h: heat flux from seismic tomography

- **high heat flux around Pacific rim where subduction is occurring**
- **first reversal takes ~6000 years**
- **second takes ~20,000 years and the path is much more complex than suggested by paleomag observations**

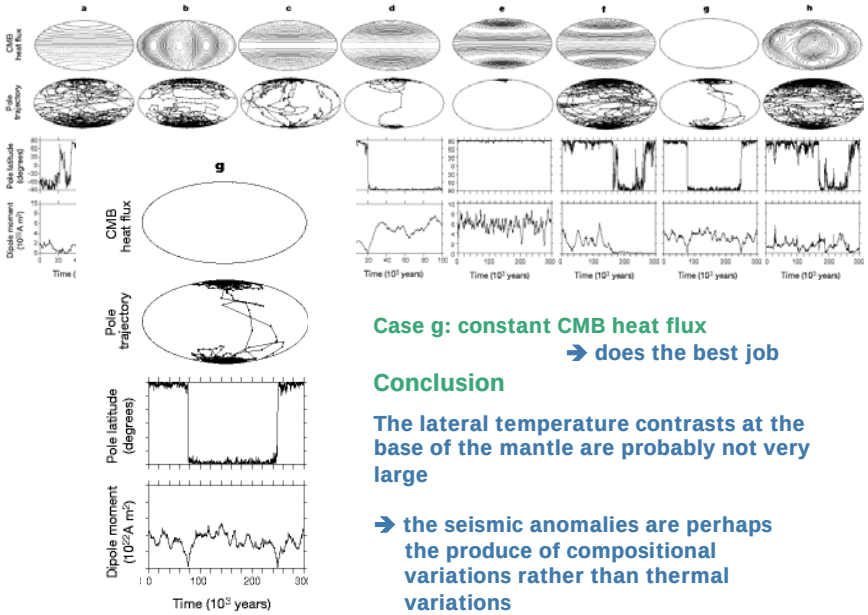
➔ **does not do a very good job**



Case g: constant CMB heat flux

- **similar reversal time history to that observed on Earth**
  - stable for 230,000 years
  - reverses in ~1000 years
  - stable for 170,000 years
  - rapidly reverses and then stable again
- **reduced intensity during reversals as on Earth**

➔ **does the best job**



Case g: constant CMB heat flux

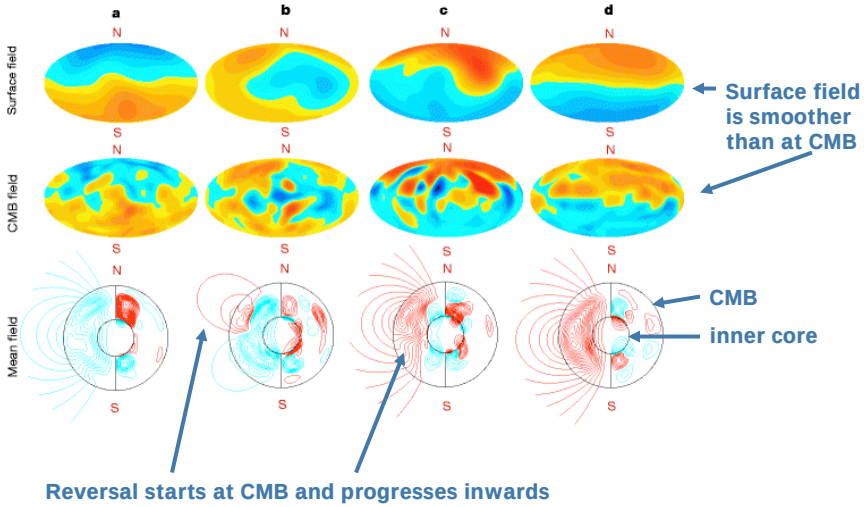
➔ does the best job

Conclusion

The lateral temperature contrasts at the base of the mantle are probably not very large

➔ the seismic anomalies are perhaps the produce of compositional variations rather than thermal variations

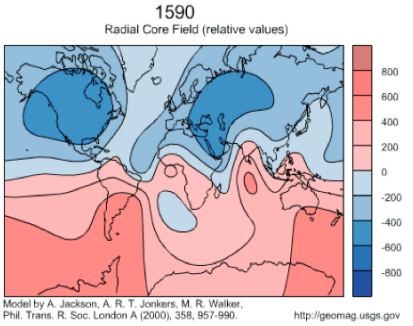
How does the field reverse?



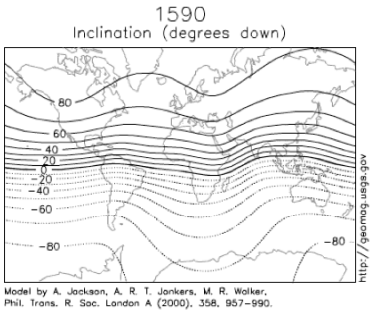
The field is highly unstable and an instabilities occur continuously,
they usually die away but occasionally continue to grow while the old field dies away

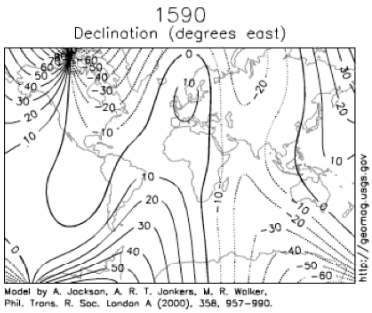
Core vs. surface field

shorter wavelength components of the field don't make it out to the surface



Note the westward drift of the field around the equator

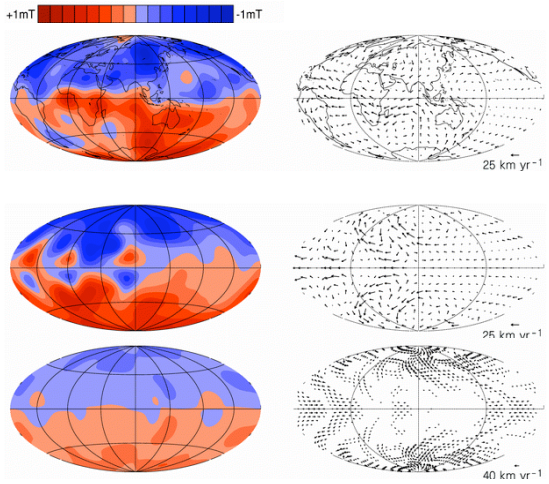




Download: http://geomag.usgs.gov/movies/

Fluid flow in outer core

CMB radial mag field | **Fluid flow**



"Both dynamo models generate magnetic fields that have a basically dipolar structure like the Earth's field, although the Glatzmaier–Roberts model is only 30% of the strength of the geomagnetic field."

Kuang and Bloxham , 1997

Viscosity of the outer core 10^{-3} Pa s (like water)

Westward flow at the equator from Indian Ocean to Americas

Orders of magnitude faster than in the mantle

➔ **current westward drift of mag field**

Kuang and Bloxham , 1997

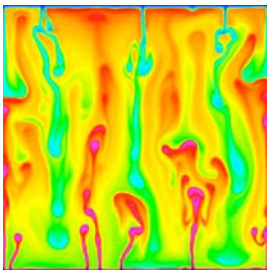
Glatzmaier and Roberts 1995

What drives the dynamo?

Dynamo energy requirements: **10^{11}-10^{12} W**

Heat flow across CMB: **~4×10^{12} W**

~20% of heat flux at surface, but CMB area is about ¼ the surface area



Density instabilities required:

Heat

- radioactive isotopes 235U, 40K
- primordial heat
- latent heat of crystallization

Chemical variations

- crystallization of Fe crystals which then sink
- lower density fluids rise

➔ **gravitational energy drives the dynamo** (most likely)

Inner core formation and magnetic field generation are linked
Earth has had a mag field since the Archaean ➔ inner core formed early