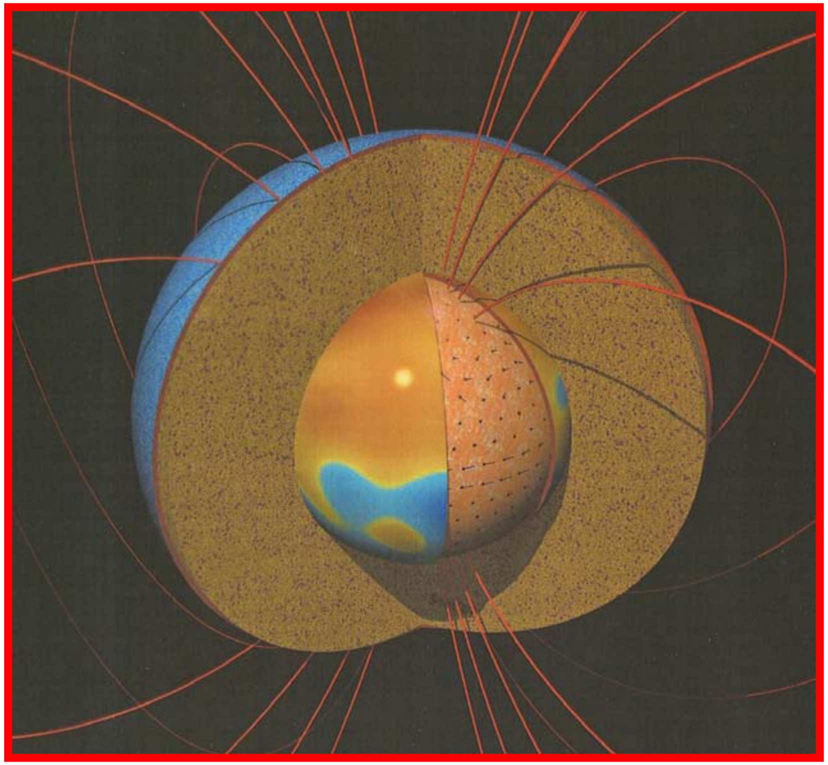
Planetary magnetic fields



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The only viable explanation for a strong global magnetic field is a dynamo, operating in a fluid, electrically conducting and convecting region inside the planet. The existence of such a field therefore puts constraints on the internal structure and on the thermal evolution of the planet and provides a window to the core.

Geomagnetic field

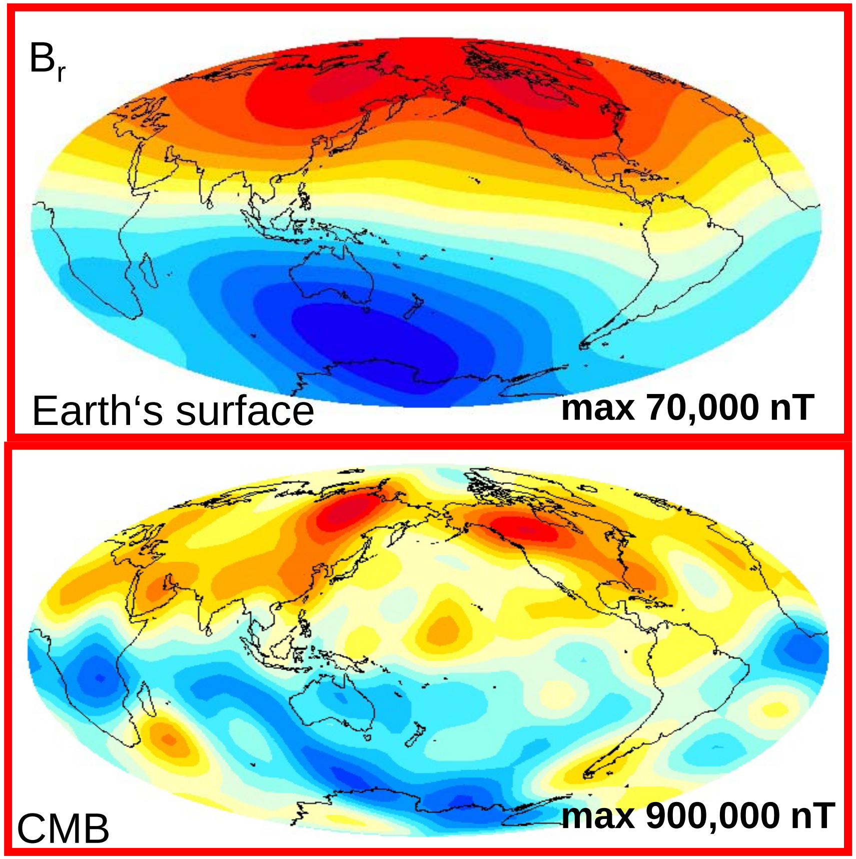
$$\mathbf{B} = -\,\mathrm{grad}\left(a \sum_{n=1}^{\infty} \left(\frac{\mathrm{a}}{\mathrm{r}}\right)^{n+1} \sum_{m=0}^{n} P_n^m(\cos\theta)\ [\ g_n^m \cos m\varphi + h_n^m \sin m\varphi\ ] \right)$$

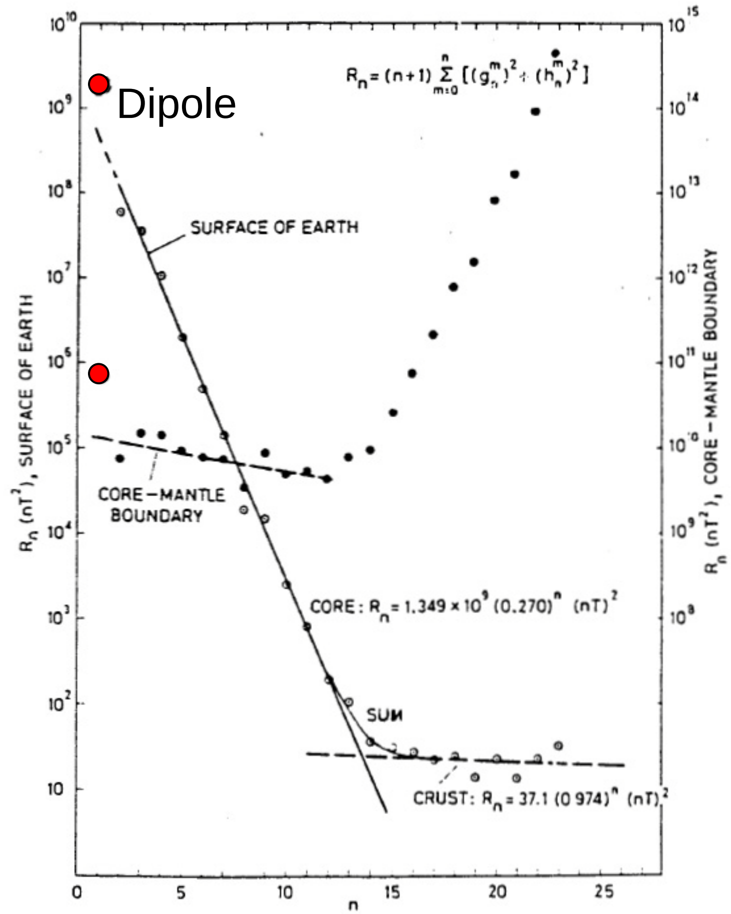
In regions without field sources, **B** is a potential field. The internal field is described by the Gauss coefficients g_n^m, h_n^m.

To first approximation, the Earth‘s field is that of a dipole, (n=1 term), which is approximately aligned with the rotation axis. The tilt of the magnetic dipole is 11º (currently).

The magnetic field strength at the surface lies between 30,000 and 70,000 nT

Observed geomagnetic field





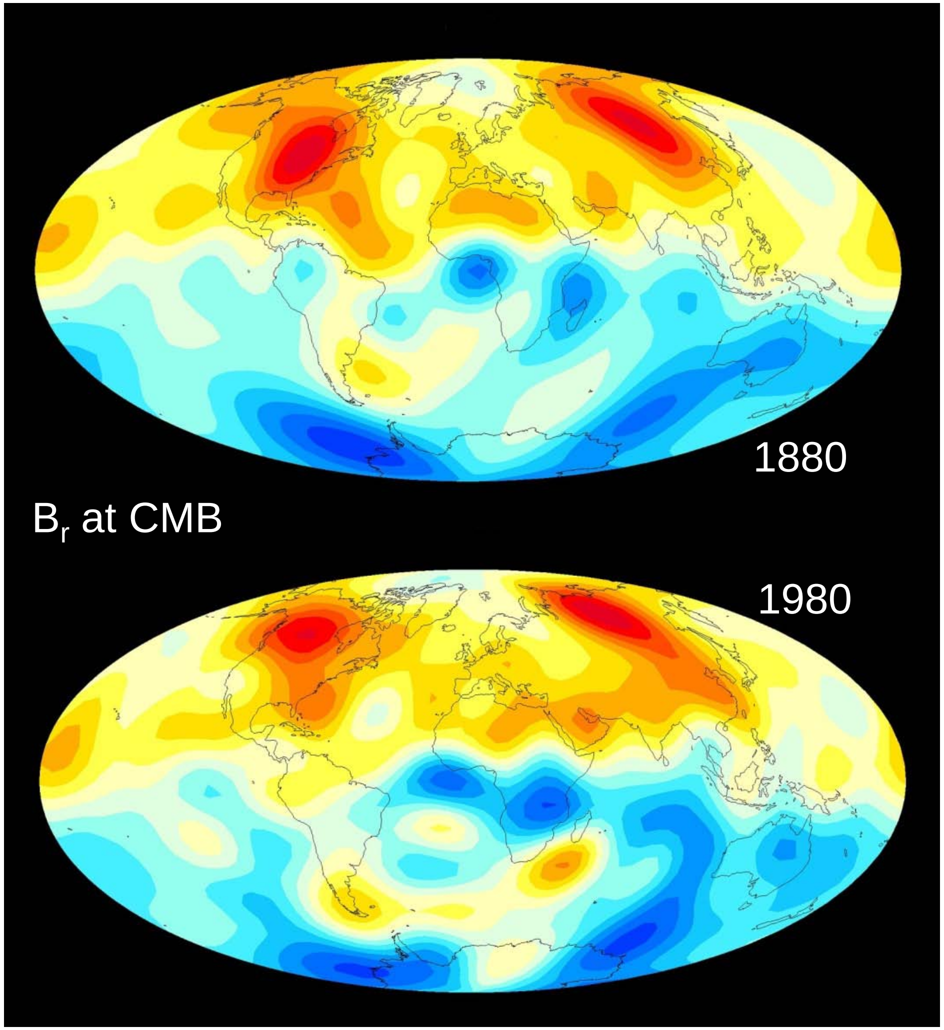
Assuming that there are no field sources in the crust and mantle, the magnetic field can be continued downward from the surface to the core-mantle boundart (CMB). Consideration of the power spectra as function of n suggests that structures described by n<13 come from the core, whereas those with larger n habe a shallow origin (crustal remanent magnetisation).

Secular variation

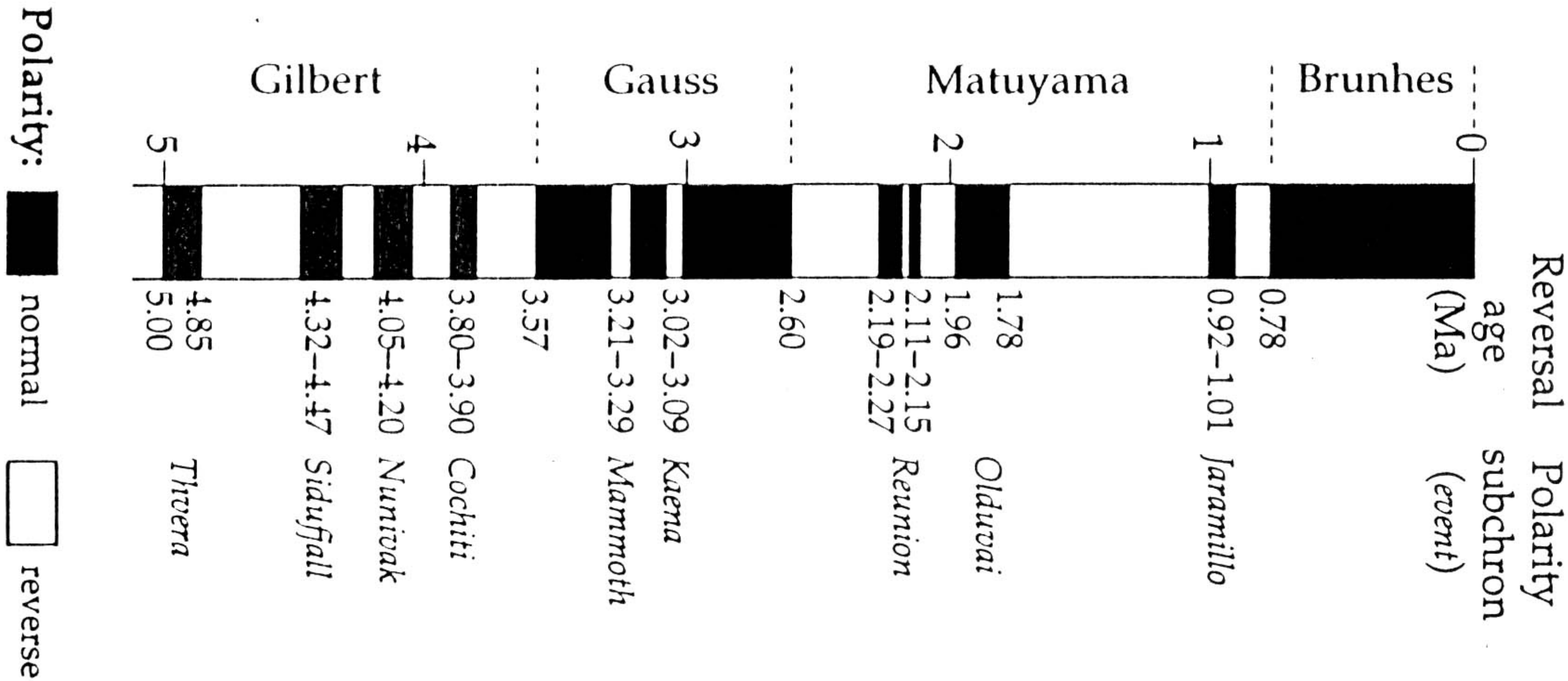
The Earth's field changes appreciably within decades.

In part this change consists of a systematic migration of magnetic structures, for example a westward drift over Africa and the tropical Atlantic. This allows to estimate velocities in the core, which are ~0.5 mm/s.

The dipole moment currently decreases by about 5% per century.



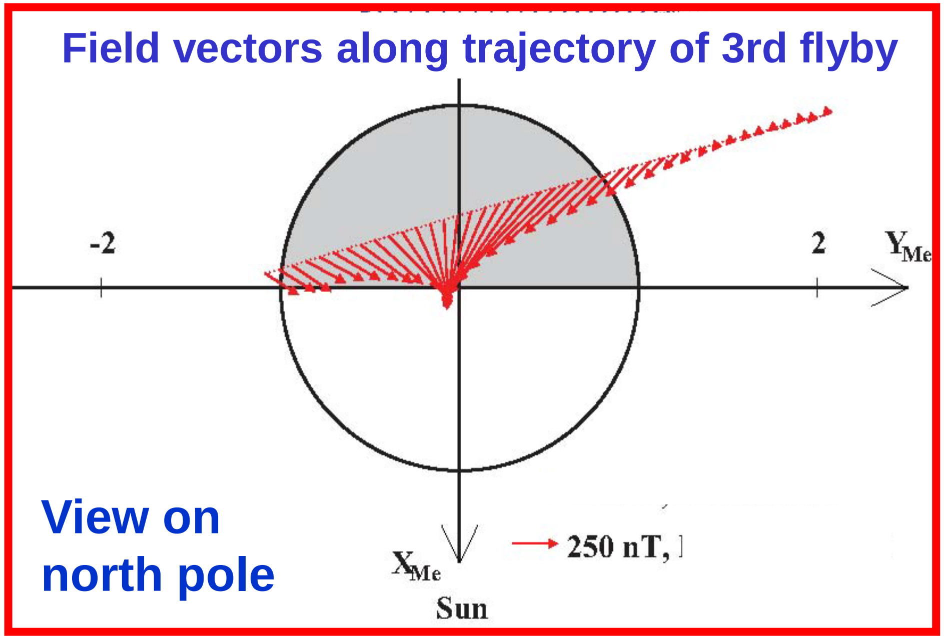
Polarity of Earth‘s dipole during the past 5 Myr

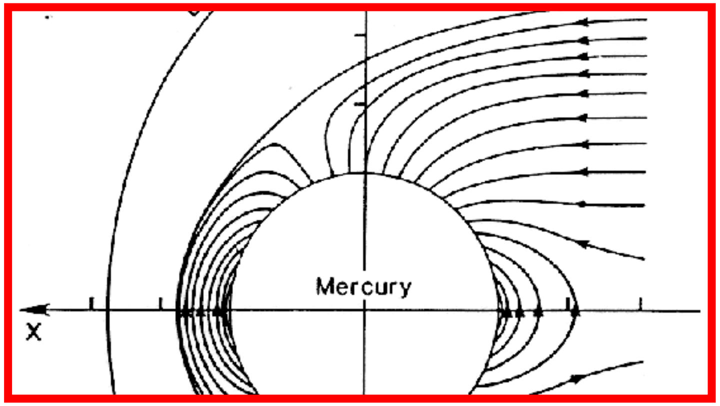


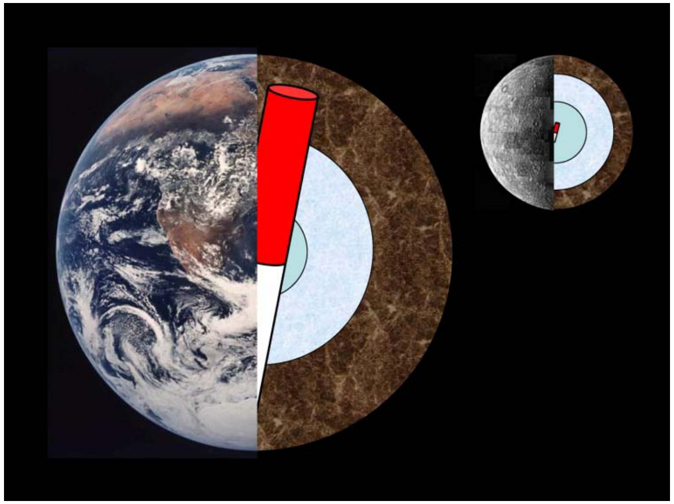
Reversals of the Earth‘s dipole polarity occur stochastically a few times per million years. The transition itself takes 1,000 – 10,000 yrs. During a reversal the surface field is weak and probably not dominated by the dipole part.

Remanent magnetisation of rocks suggest that the geomagnetic field existed > 3 Gyr ago.

Mercury‘s magnetic field







Mariner 10 detected global magnetic field

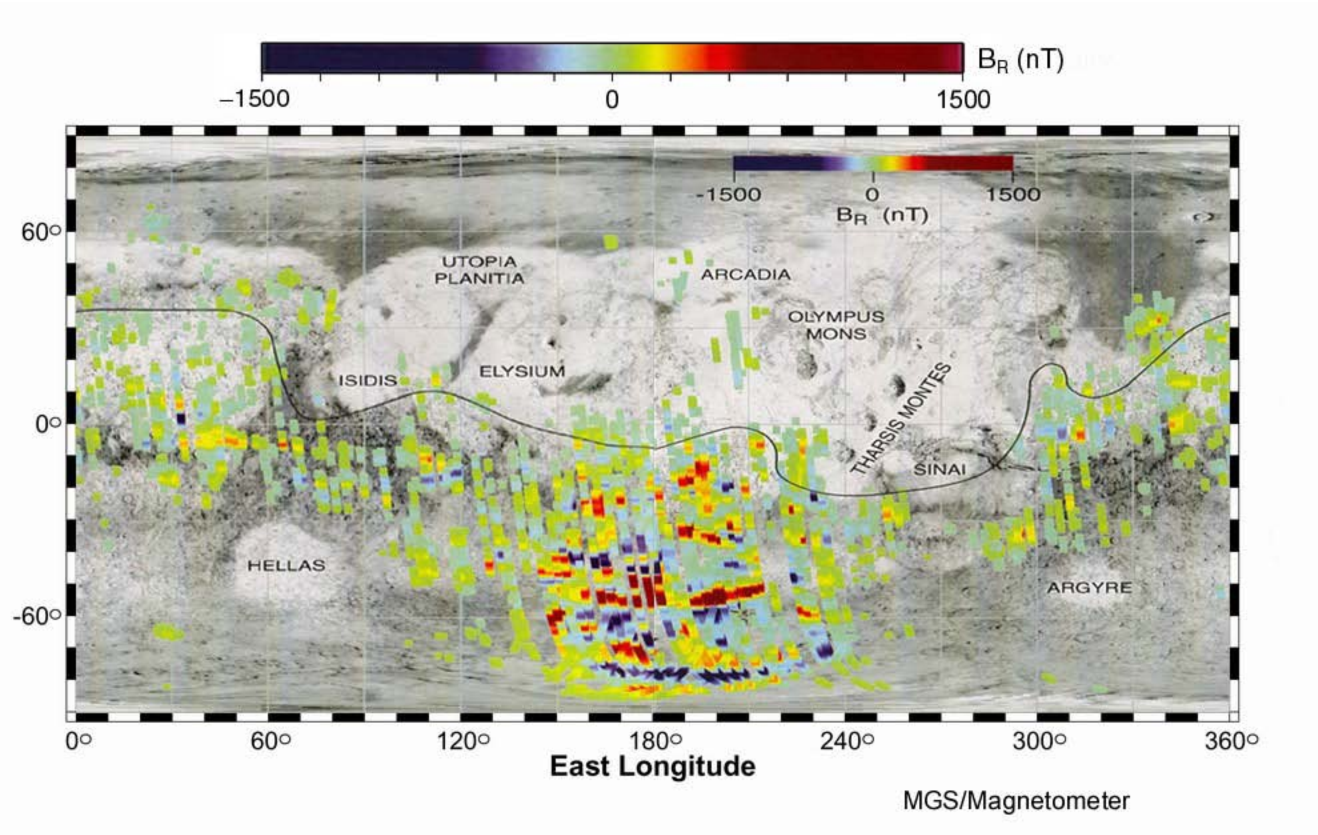
Confirmed by Messenger flybys

Surface field strength 1% of Earth value

Slightly tilted (< 5^o ?) dipole fits observations

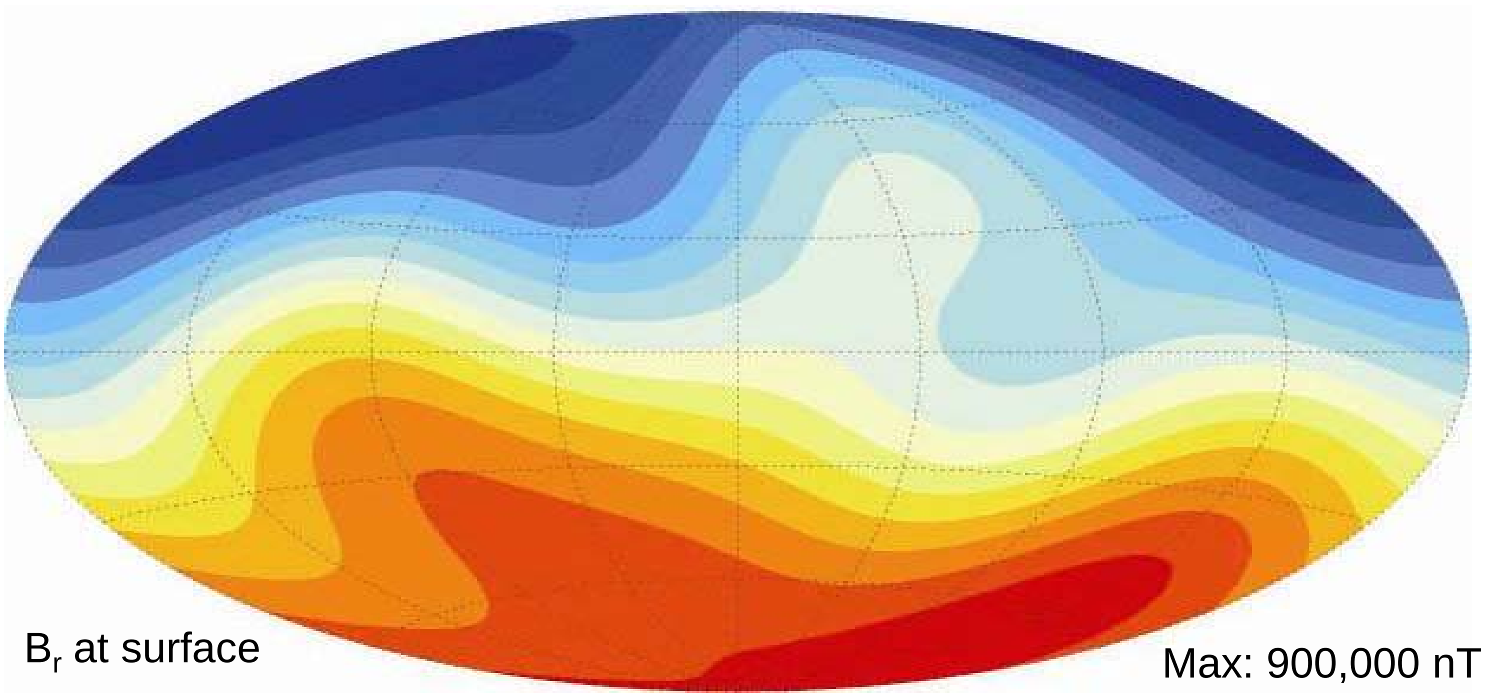
Quadrupole/dipole ratio is unconstrained

Mars' magnetic field



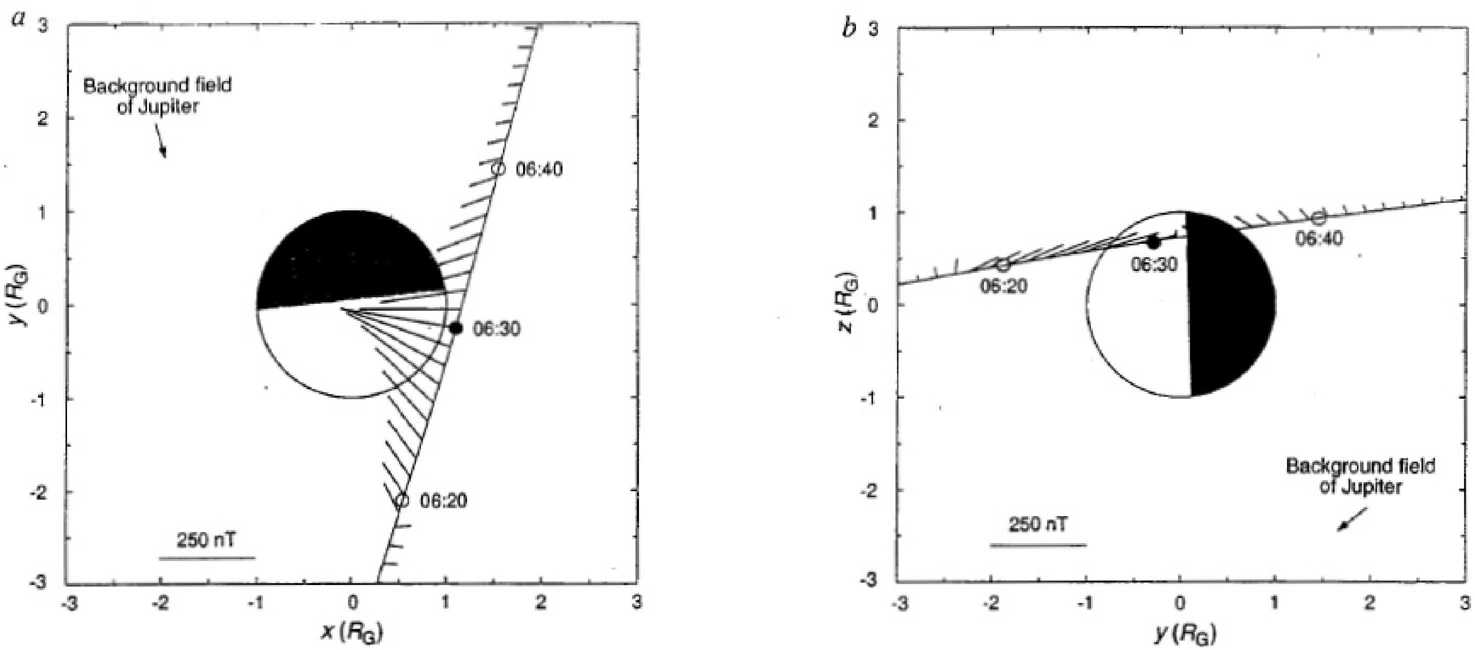
Mars does not have a global magnetic field. However, locally strong fields are found. They resemble magnetic anomalies caused by crustal remanent magnetisation on Earth (but are stronger). The magnetic structures concentrate in the old southern highlands. **Conclusion**: Mars once had a dynamo that generated a strong magnetic field, but it stopped operating around 4 Gyr ago.

Jupiter‘s magnetic field



Jupiter‘s field is dipole-dominated with a dipole tilt relative to the rotation axis of 10^o, similar as Earth today. Higher multipoles contribute. The field strength at the surface is 10 times Earth‘s field strength. Little change of the field was observed between the Vogayer and Galileo missions (25 yrs), but a 0.5^o-change in dipole tilt was deduced, indicating secular variation at a similar rate as for Earth.

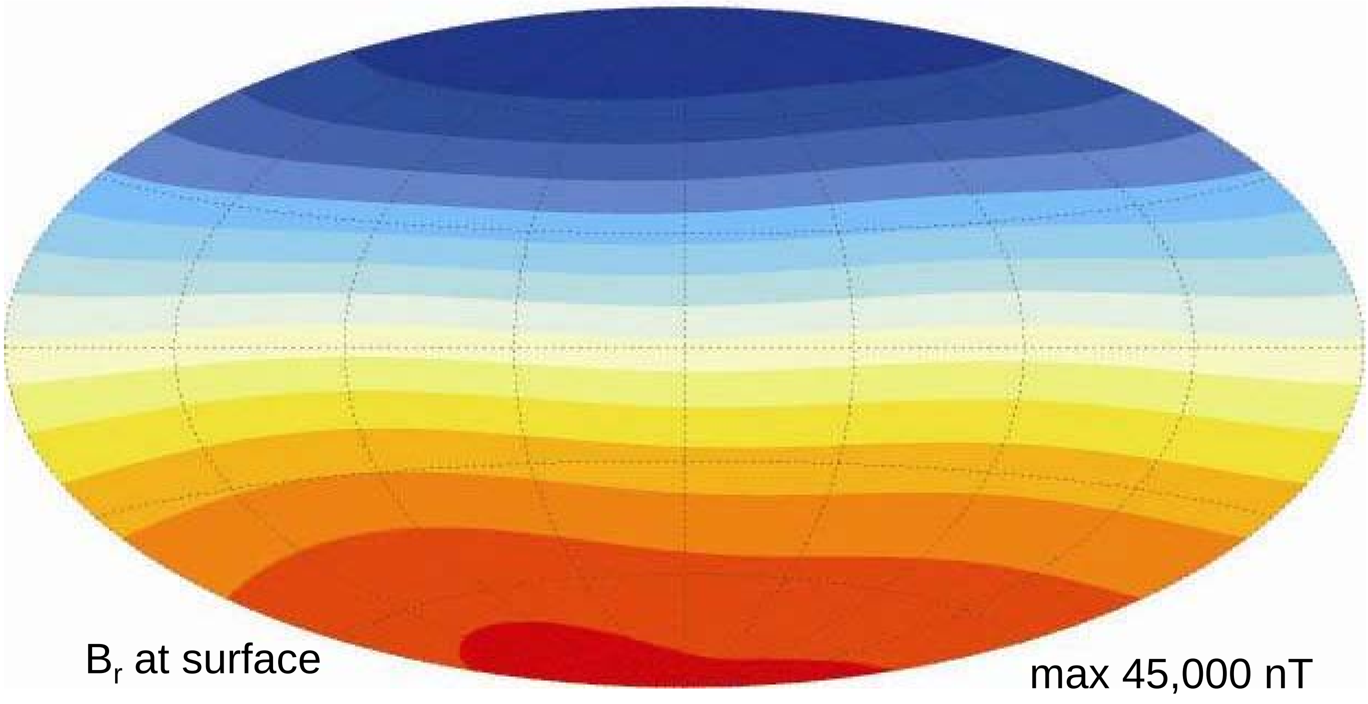
Ganymede‘s magnetic field



Close flybys of the Galileo S/C at Ganymede revealed a magnetic field that is several times stronger than Jupiter‘s background field at the location of Ganymede.

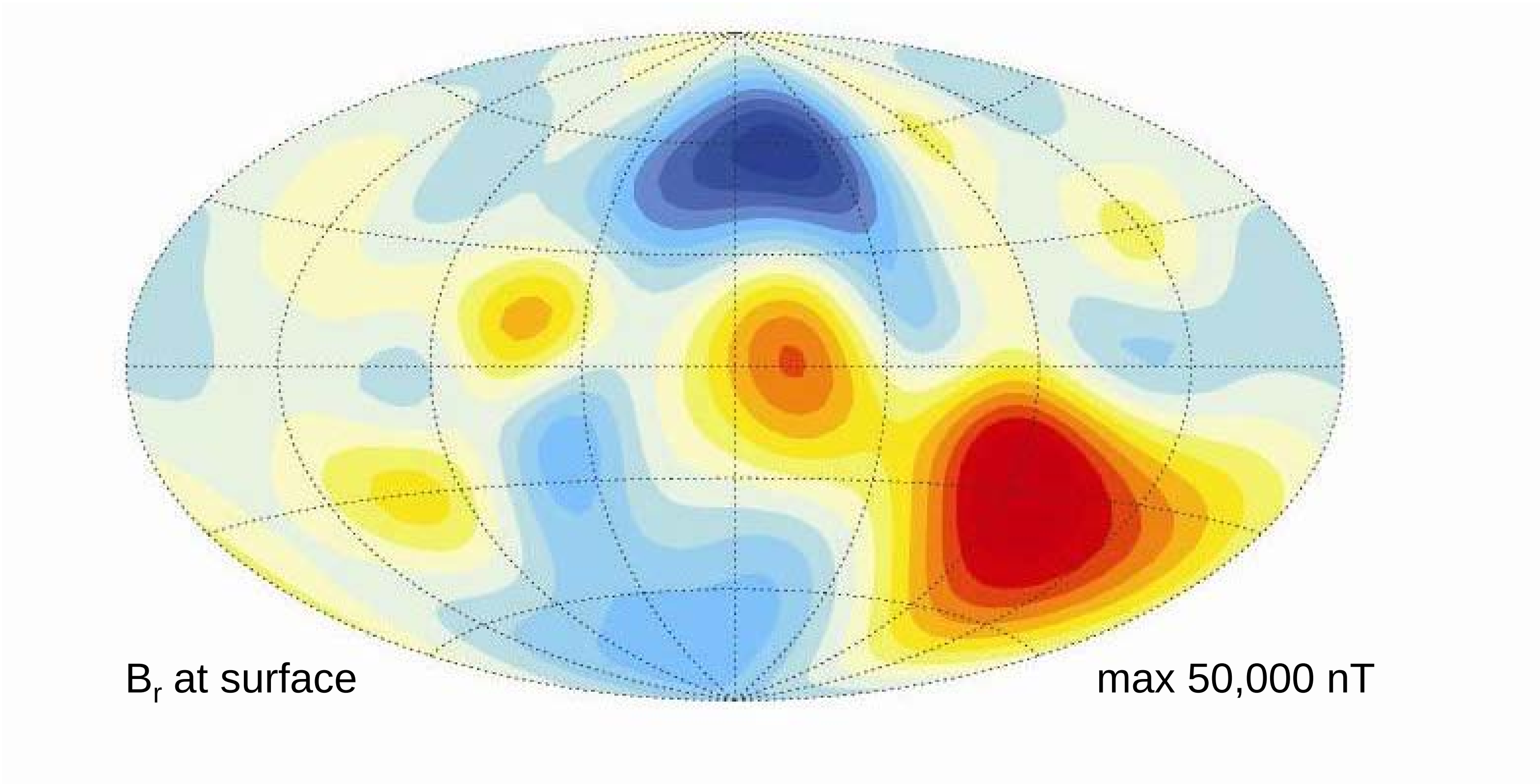
The field is dipole-dominated and has a surface strength of 750 nT.

Saturn‘s magnetic field



The surface field strength is 2/3 of Earth‘s field strength.
Saturn‘s magnetic field is very axisymmetric. The dipole tilt is less than 1º (recent analysis of Cassini data < 0.06º) and the available observations do not demand any deviation from axisymmetry. This is enigmatic, because Cowling‘s theorem (based on first principles) says that a homogeneous dynamo cannot generate a purely axisymmetric magnetic field.

Neptune‘s magnetic fields



The magnetic fields of Uranus and Neptune are similar in structure, but differ from the fields of other planets. The magnetic dipole is strongly tilted against the rotation axis and higher multipole terms contribute at a similar level.

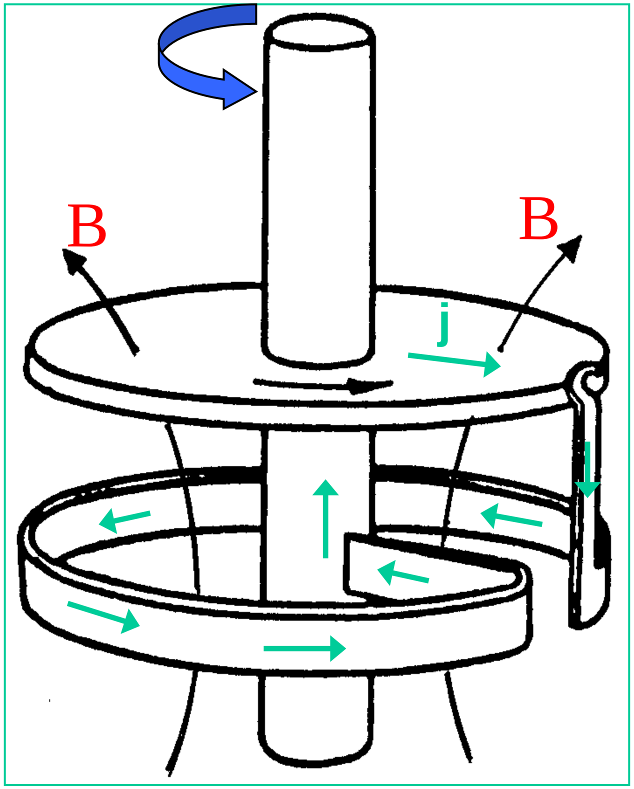
The surface magnetic field strength is of the order of Earth‘s field strength.

Toy model of a dynamo

Needed for a natural dynamo:

- **Fluid electrical conductor**: Liquid iron, liquid metallic hydrogen, ionic fluid
- **A means for driving motion**: Thermal convection, compositional convection

The disc dynamo is a toy model illustrating the principle: When the disc rotates in a pre-existing magnetic field B, currents j are induced that close through the stationary loop connecting the edge of the disc with the axis. The current in this loops sets up a magnetic field with the right sense to support the original field. If the disc rotates fast enough and the conductivity is high enough, the induced magnetic field can replace the external field and we have a self-sustained dynamo.

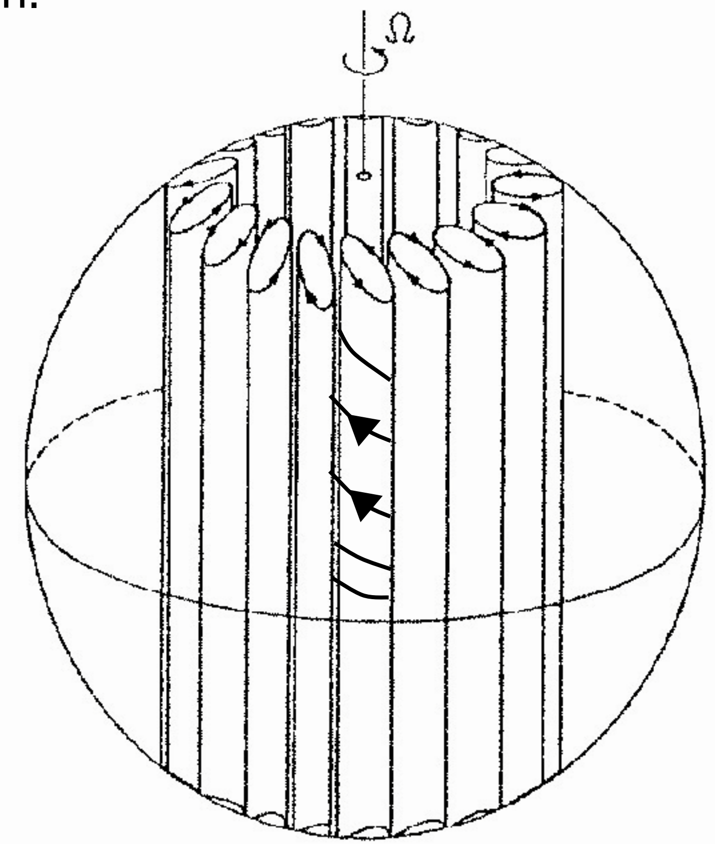


Christensen et al., Planetary Interiors and Surfaces, June 2011

Homogeneous dynamos

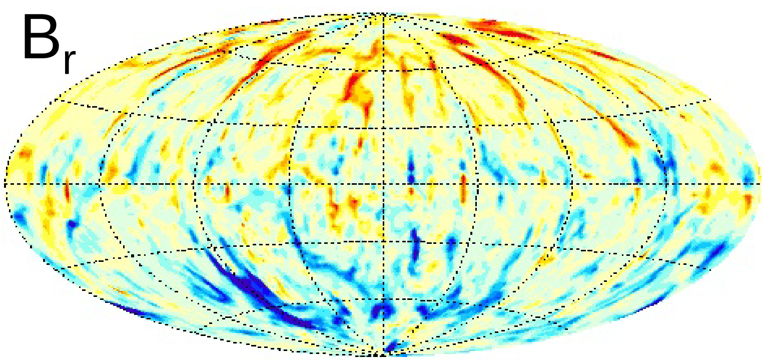
The disc dynamo can work because of the specific arrangement of the electrical conductor. In contrast, planetary cores are unstructured homogeneous conductors to first approximation.

A homogeneous dynamo can work when the fluid motion has a certain type of complexity. In a rapidly rotating convecting spherical shell, the fluid motion occurs in columns elongated parallel to the rotation axis with a **helical** (cork-screw like) particle motion. This type of flow is suitable for homogeneous dynamo action. The preferred arrangement along the rotation is the basis for the magnetic dipole to align with the rotation poles.

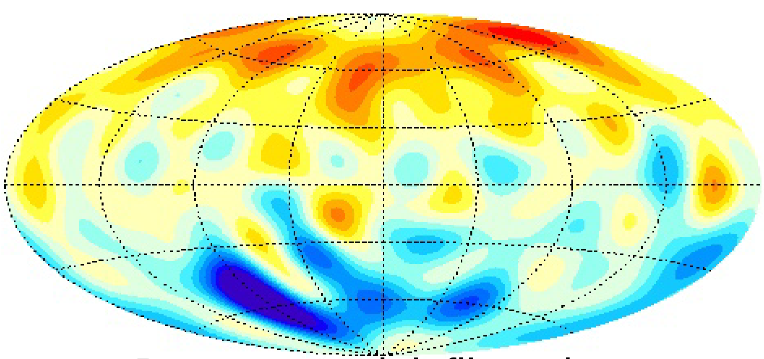


Numerical dynamo models

Numerical models that solve the fundamental equations of magnetohydrodynamics for convection-driven flow of an electrically conducting fluid in a rotating spherical shell show a magnetic field that (1) fits Earth‘s field strength, (2) is dominated by the axial dipole and (3) has a morphology at the top of the core similar to observation.

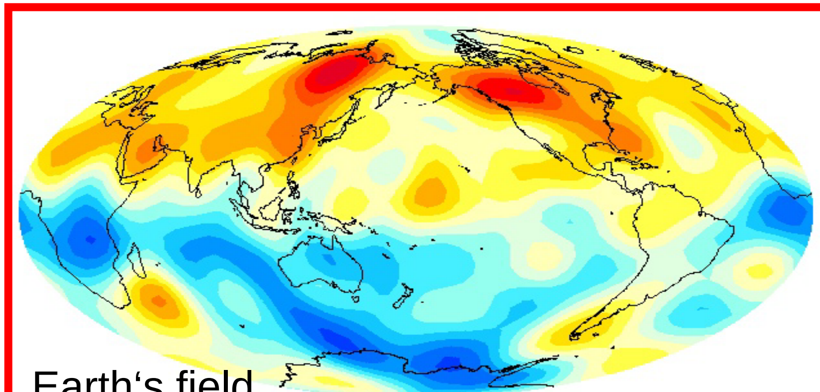


Dynamo model, full resolution



Dynamo model, filtered

Because the field contribution of crustal origin dominates at degrees n>13, we do not know the small-scale core field. The model field has been low-pass filtered to n<13 on the lower left.



Earth‘s field

Christensen et al., Planetary Interiors and Surfaces, June 2011

Magnetic Reynolds number

In an incompressible fluid conductor, magnetic induction is described by:

$$\frac{\partial \vec{B}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{B} = \vec{B} \cdot \vec{\nabla} \vec{u} + \frac{1}{Rm} \nabla^2 \vec{B}$$

Advection Induction Diffusion

Rm = UD$\mu_o\sigma$: **Magnetic Reynolds number**

U is characteristic velocity, D size of the dynamo and σ electrical condutivity.

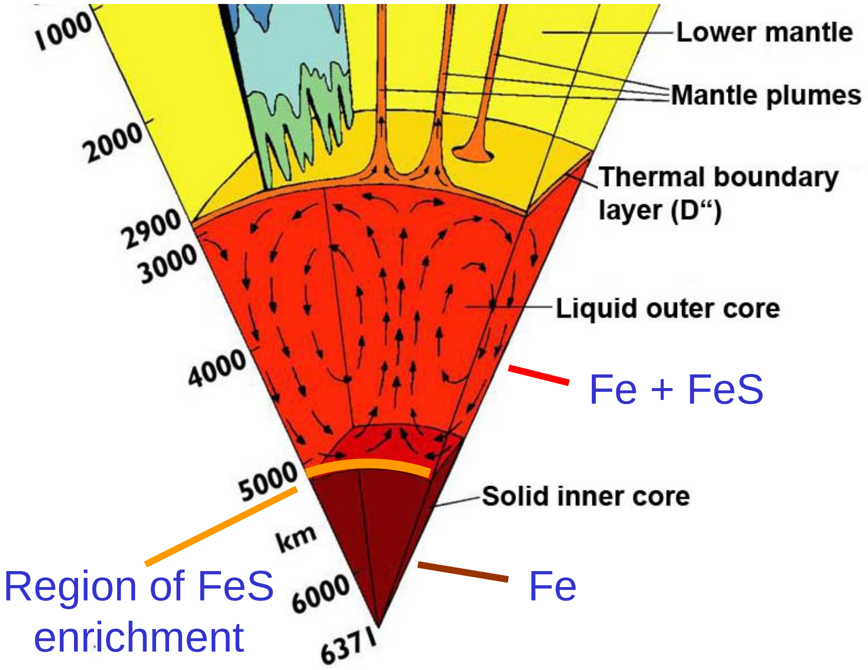
For a working dynamo, Rm must be large, so that inductive effects dominate over the diffusion (destruction) of magnetic field. The critical value of Rm is ≈ 50. The estimated value of Rm is 1000 in the Earth and 10^4 for Jupiter.

Symbols: B – magnetic field (induction), u – velocity, U – characteristic value for velocity, D – characteristic length (depth of fluid shell), σ – electrical conductivity, μ_o – magnetic permeability

Driving core convection

Thermal convection requires that the temperature gradient is (at least slightly) larger than the adiabatic temperature gradient. The heat flow from the iron core of a terrestrial planet is controlled by how much heat mantle convection is able to transport (the mantle is the master, the core is the slave). If this heat flow can be transported in the core by conduction along a temperature gradient that is less than the adiabatic gradient, the core is stable against thermal convection. Estimates of the heat flow at the CMB in the Earth are somewhat larger (but not by much) than the „adiabatic“ heat flow.

When a solid inner core exists and grows with time, it rejects in this process the light alloying elements in the fluid core. These will concentrate above the inner core boundary and drive compositional convection (getting mixed into the bulk of the liquid core).



What controls magnetic field strength ?

Two different assumptions:

Balance of electromagnetic Lorentz force and Coriolis force on the flow in the dynamo. The ratio between the two forces is often described by the Elsasser number

$$\Lambda = \frac{\sigma B^2}{\rho \Omega}$$

which should be of order one. B is the characteristic field strength inside the dynamo and should be approximately $B \sim (\rho\Omega/\sigma)^{1/2}$. For the Earth this predicts a field strength of ≈ 1 mT in the core, which is reasonable. For Jupiter it predicts a similar value, which seems low (surface field 10 times stronger than at Earth).

Balance of power generated by convection and ohmic dissipation. A scaling law based on numerical dynamo models gives $B \sim \mu_o^{1/2}\rho^{1/6}D^{-2/3}P^{1/3}$, where P is the available power. With reasonable estimates for P, it predicts 1 mT for the interior of Earth‘s core, and ≈ 10 mT for Jupiter‘s core.

Symbols: ρ – density, μ_o – permeability, σ –electrical conuctivity, Ω – rotation angular frequency, P – power, D – fluid shell thickness

Open questions and possible answers

Why did the early dynamo of Mars stop to operate ?

Perhaps the core heat flow dropped below the adiabatic heat flow 4 Gyr ago and Mars has not nucleated an inner core, so that the fluid core does not convect today.

Why has Venus no magnetic field ?

Perhaps also in Venus the core heat flow is less than the adiabatic heat flow. Because plate tectonics is absent, less heat is removed from the interior. Since Venus‘ core cools more slowly, no inner core may have formed and the fluid core is stably stratified.

Why is Mercury‘s field so much weaker than that of other planets?

(1) It may not be generated by a presently active dynamo, but is due to crustal remanence.
(2) The fluid core may form a thin shell around a large solid core $\Rightarrow$ different type of dynamo.
(3) The dynamo may operate deep down below a stagnant core layer attenuating the field.

Why is Saturn‘s field so axisymmetric ?

Perhaps the dynamo operates below a helium-depleted stable layer in the upper part of the metallic hydrogen core. Zonal flow in this conducting layer does not allow the non-axisymmetric field components to pass, but is no obstacle to the axisymmetric part.

Why do Uranus and Neptune have strongly tilted dipoles and strong multipoles ?

(1) Perhaps they are presently in a state of dipole reversal.
(2) Perhaps the lower conductivity than in other planets leads to a different type of dynamo.
(3) Perhaps the dynamo operates in a thin shell in the top part of the conducting „ice“ region.