COSMIC MAGNETIC FIELDS

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Earth

DISCOVERY OF MAGNETISM

- The Ancients (this has been attributed to Thales of Miletus) discovered naturally magnetized pieces of magnetite (named after the Magnesia region of Greece or one of its colonies in Asia Minor) called the lodestones.

- The compass has been discovered in Ancient China, and used for navigation (magnetic north/south) since the Middle Ages (Shen Kua 1088, Alexander Neckham 1190).

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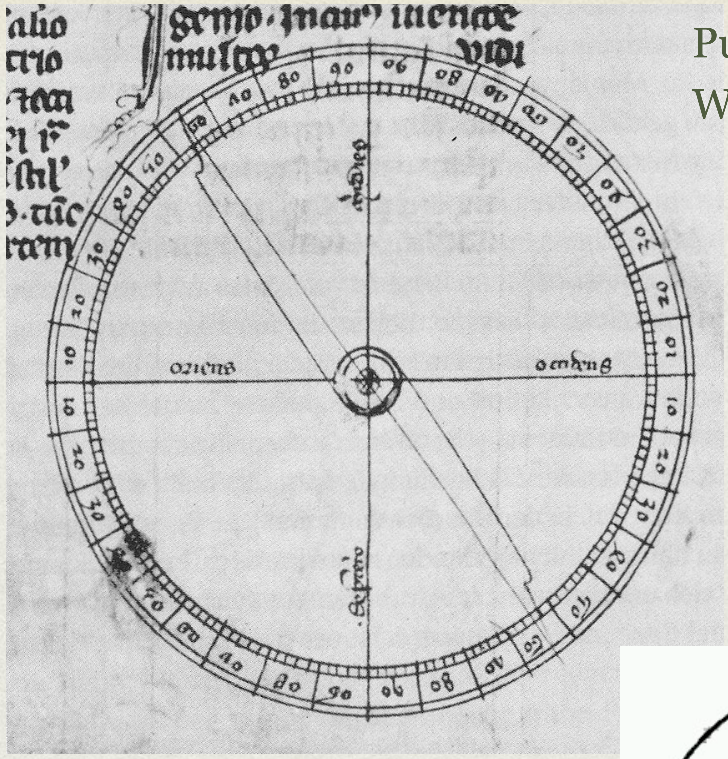
FIRST SCIENTIFIC MEASUREMENTS OF THE EARTH'S MAGNETIC FIELD

- Spherical magnets (*terella*) were used as models of the Earth. The concept of magnetic poles (attraction and repulsion) has been known at least since Petrus Peregrinus de Maricourt (1269)

- Placing a magnetic needle in a vertical plane allowed measuring the magnetic inclination (dip) (Robert Norman 1581)



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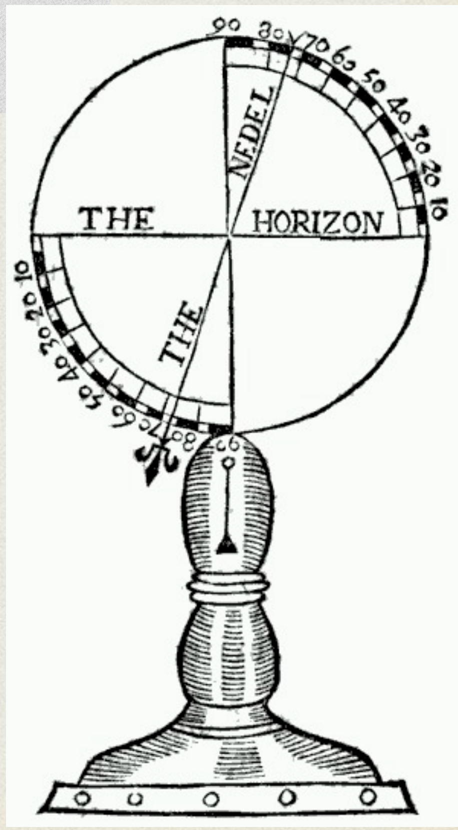

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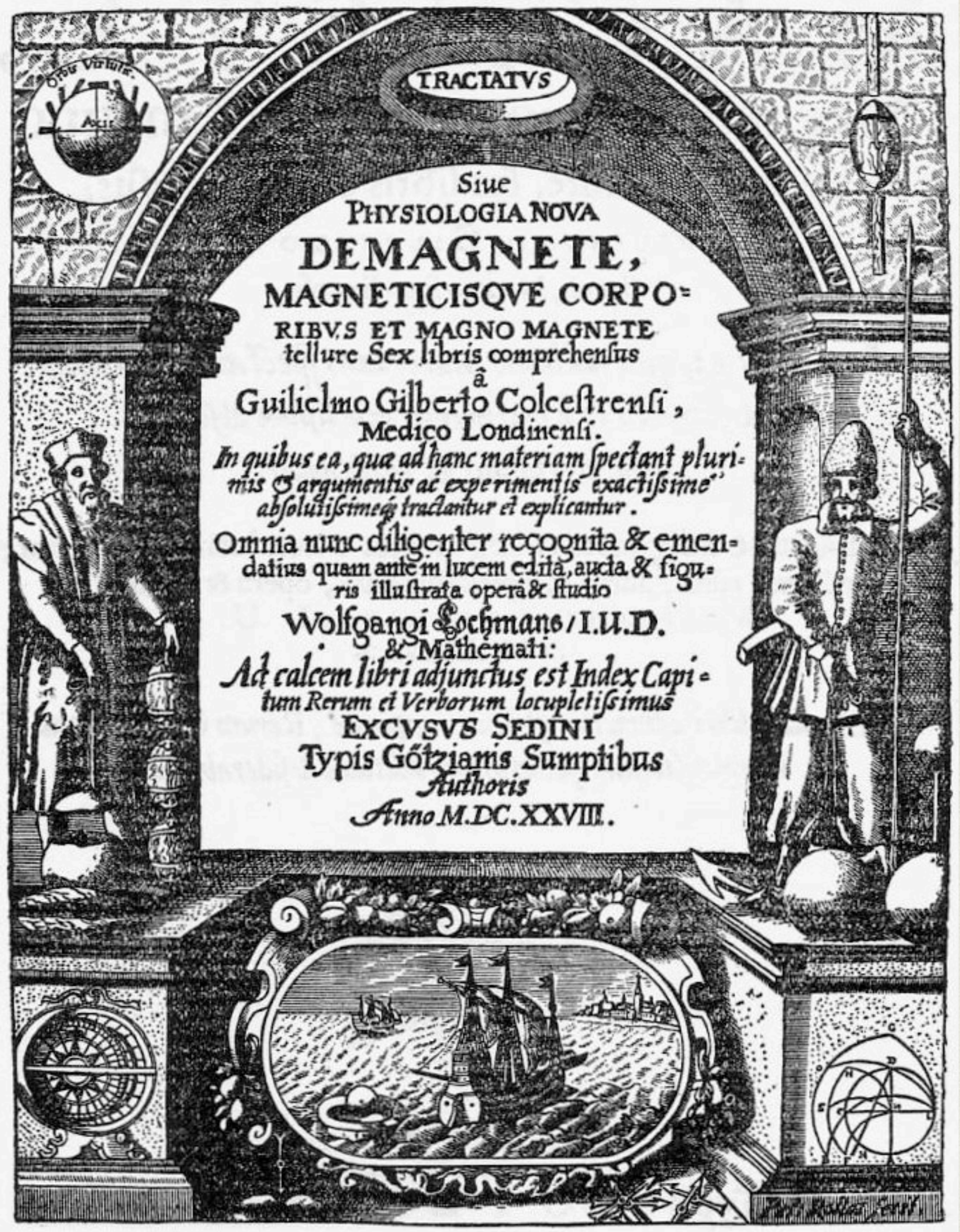
"DE MAGNETE" (W. GILBERT 1600)



TRACTATVS
Siue
PHYSIOLOGIA NOVA
DE MAGNETE,
MAGNETICISQVE CORPORIBVS ET MAGNO MAGNETE tellure Sex libris comprehensus
à
Guilielmo Gilberto Colcestrensi, Medico Londinensi.
In quibus ea, quæ ad hanc materiam spectant pluri-mis & argumentis ac experimentis exactissime absolutissimeq; tractantur et explicantur.
Omnia nunc diligenter recognita & emendatius quam ante in lucem edita, aucta & figuris illustrata operâ & studio
Wolfgangi Lochmans, I.U.D. & Mathemati:
Ad calcem libri adjunctus est Index Capitum Rerum et Verborum locupletissimus
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Typis Götzianis Sumptibus Authoris
Anno M.DC.XXVIII.

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https://en.wikisource.org/wiki/On_the_Magnet

- A *terella* has been used again to predict the geographic distribution of magnetic dip (William Gilbert 1600)

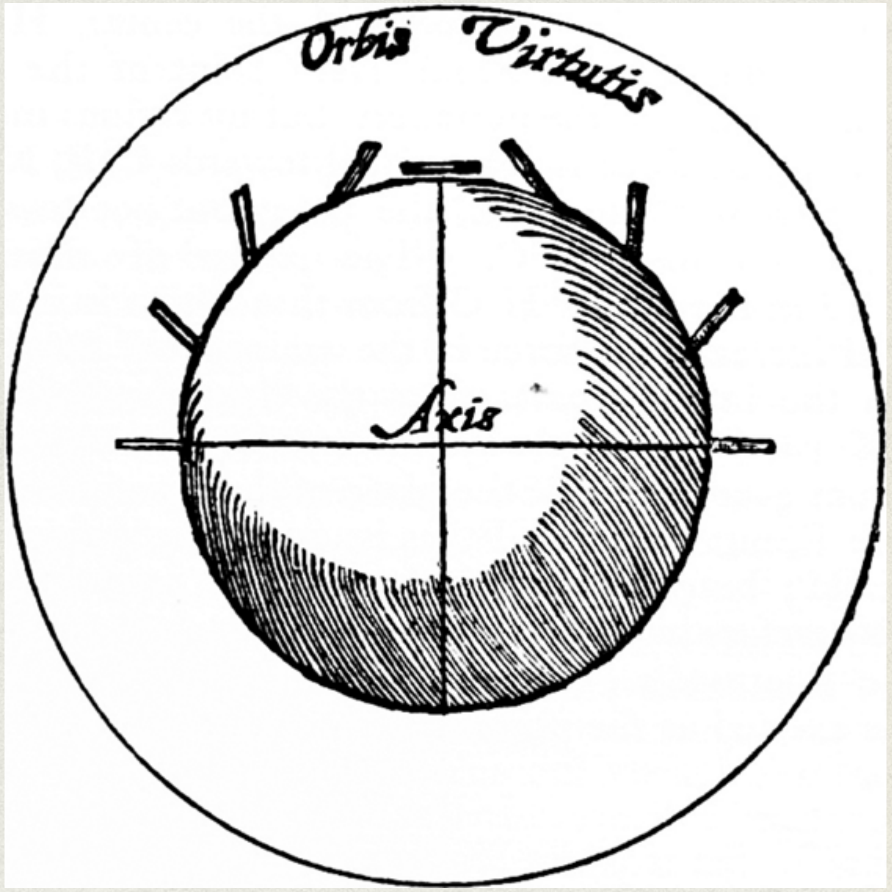


Figure 1. A sketch of William Gilbert's terrella from *De Magnete* (1600). From Chapman and Bartels (1940), with permission from OUP.

Roberts & King (2013)

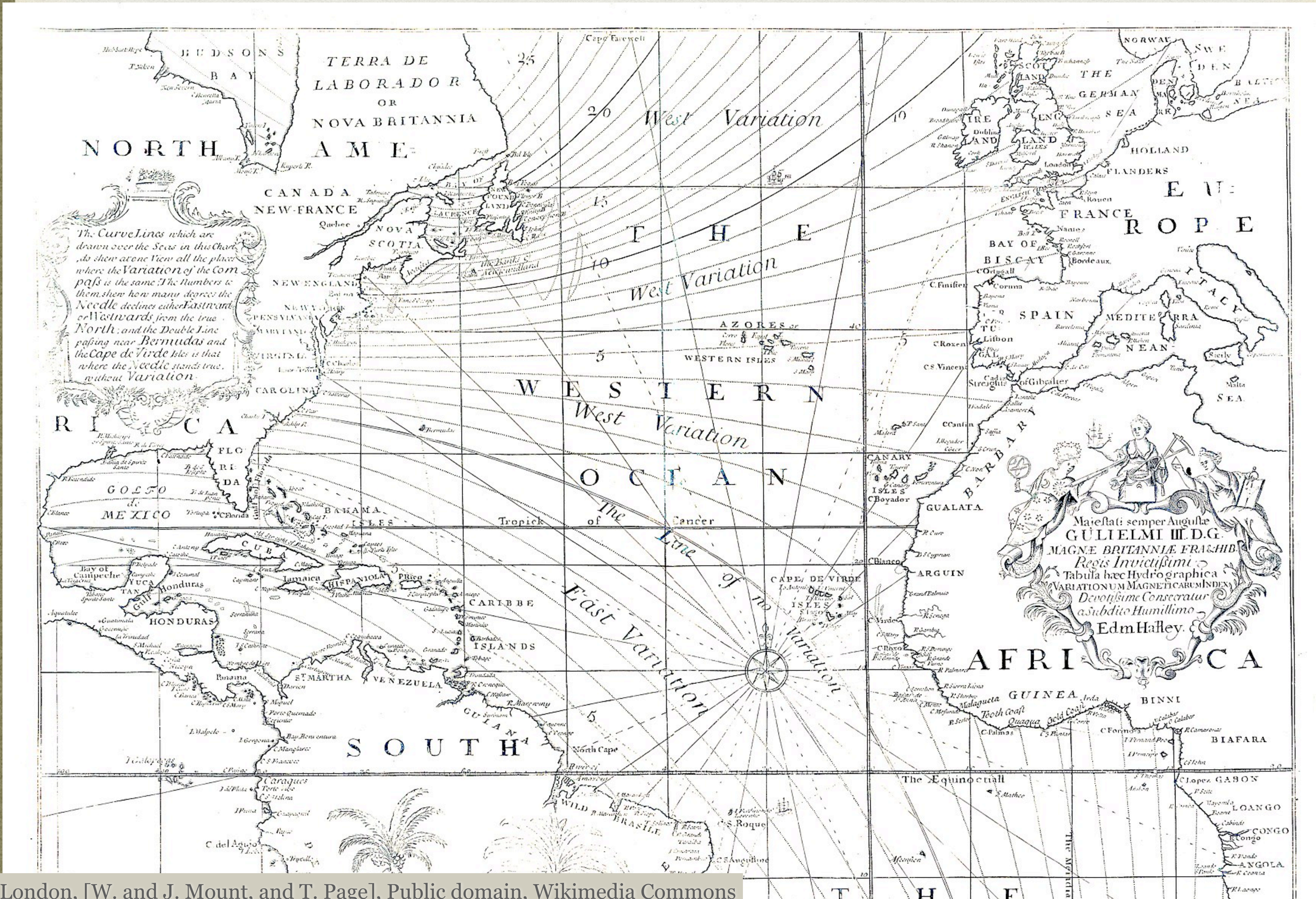
WESTWARD DRIFT OF MAGNETIC DECLINATION

- in XVII century it has been found that local magnetic declinations turn westwards over years
- Edmund Halley proposed in 1683 that the Earth has a superrotating magnetized core separated by an *effluvium*

Names of Places.	Longitude. from Lond. (gr ')	Latitude. (° ')	Anno Dom.	Variation Observed. (° ')
London	0 0	51. 32 N	1580	11 15 E
			1622	6 0 E
			1634	4 5 E
			1672	2 30 W
			1683	4 30 W
Paris	2. 25 E	48. 51. N	1640	3 00 E.
			1666	0 0
			1681	2 30 W.
Uraniburg	13. 0 E	55. 54 N	1672	2 35 W.
Copenhagen	12. 53 E	55. 41 N	1649	1 30 E.
			1672	3 35 W.
Dantzick	19. 0 E	54. 23 N	1679	7 00 W.
Mompelier	4. 0 E	43. 37 N	1674	1 10 W.
Brest	4. 25 W	48. 23 N	1680	1 45 W.
Rome	13. 0 E	41. 50 N	1681	5 0 W.
Bayonne	1. 20 W	43. 30 N	1680	1 20 W.
Hudsons Bay	79. 40 W	51 00 N	1668	19 15 W.
In Hudsons Straights	57. 00 W	61 00 N	1668	29 30 W.
In Baffins Bay at Sir Thomas Smiths Sound	80. 00 W.	78 00 N	1616	57 00 W.

E. Halley, Phil. Trans. R. Soc., 13, 208–221 (1683)

MAGNETIC DECLINATION MAP (HALLEY 1701)



London, [W. and J. Mount, and T. Page], Public domain, Wikimedia Commons

EARTH HAS A DENSE CORE

- Schiehallion experiment (1774), by measuring a deflection of 11.6″ of the vertical wrt. stars at two sides of a mountain, allowed to estimate the mean density of the Earth at 4.5 g cm^{-3}.

intire maſs of ſolid rock. It is probable, therefore, that we ſhall not greatly err, if we aſſume the denſity of the hill equal to that of common ſtone; which is not much different from the mean denſity of the whole matter near the ſurface of the earth, to ſuch depths as have actually been explored either by digging or boring. Now the denſity of common ſtone is to that of rain water as $2\frac{1}{2}$ to 1; which being compounded with the proportion of 9 to 5 above found, there reſults the ratio of $4\frac{1}{2}$ to 1 for the ratio of the denſities of the earth and rain water;

C. Hutton, Phil. Trans. R. Soc., 68, 689–788 (1778)

EARTH HAS A DENSE CORE

- For a mean rock density of 2.5 g cm^{-3}, and a mean density of metals of 10 g cm^{-3}, a metallic core radius can be estimated at 2/3 of the Earth's radius.

C. Hutton, Phil. Trans. R. Soc., 68, 689–788 (1778)

in the ſurmiſes of this wonderful man! Since then the mean denſity of the whole earth is about double that of the general matter near the ſurface, and within our reach, it follows, that there muſt be ſomewhere within the earth, towards the more central parts, great quantities of metals, or ſuch like denſe matter, to counterbalance the lighter materials, and produce ſuch a conſiderable mean denſity. If we ſuppoſe, for inſtance, the denſity of metal to be 10, which is about a mean among the various kinds of it, the denſity of water being 1, it would require ſixteen parts out of twenty-ſeven, or a little more than one-half of the matter in the whole earth, to be metal of this denſity, in order to compoſe a maſs of ſuch mean denſity as we have found the earth to poſſeſs by our experiment: or $\frac{4}{15}$, or between $\frac{1}{3}$ and $\frac{1}{4}$ of the whole magnitude will be metal; and conſequently $\frac{20}{31}$, or nearly $\frac{2}{3}$ of the diameter of the earth, is the central or metalline part.

MEAN DENSITIES OF CELESTIAL BODIES

- No longer a hollow Earth, but a metallic core could be expected to be a permanent magnet.

Knowing then the mean denſity of the earth in compariſon with water, and the denſities of all the planets relatively to the earth, we can now aſſign the proportions of the denſities of all of them as compared to water, after the manner of a common table of ſpecific gravities. And the numbers expreſſing their relative denſities, in reſpect of water, will be as below, ſuppoſing the denſities of the planets, as compared to each other, to be as laid down in Mr. DE LA LANDE's aſtronomy.

Water . . .	1
The Sun . .	$1\frac{2}{15}$
Mercury . .	$9\frac{1}{6}$
Venus . . .	$5\frac{11}{15}$
The earth . .	$4\frac{1}{2}$
Mars	$3\frac{2}{7}$
The Moon . .	$3\frac{1}{11}$
Jupiter . . .	$1\frac{1}{24}$
Saturn . . .	$\frac{13}{32}$

C. Hutton, Phil. Trans. R. Soc., 68, 689–788 (1778)

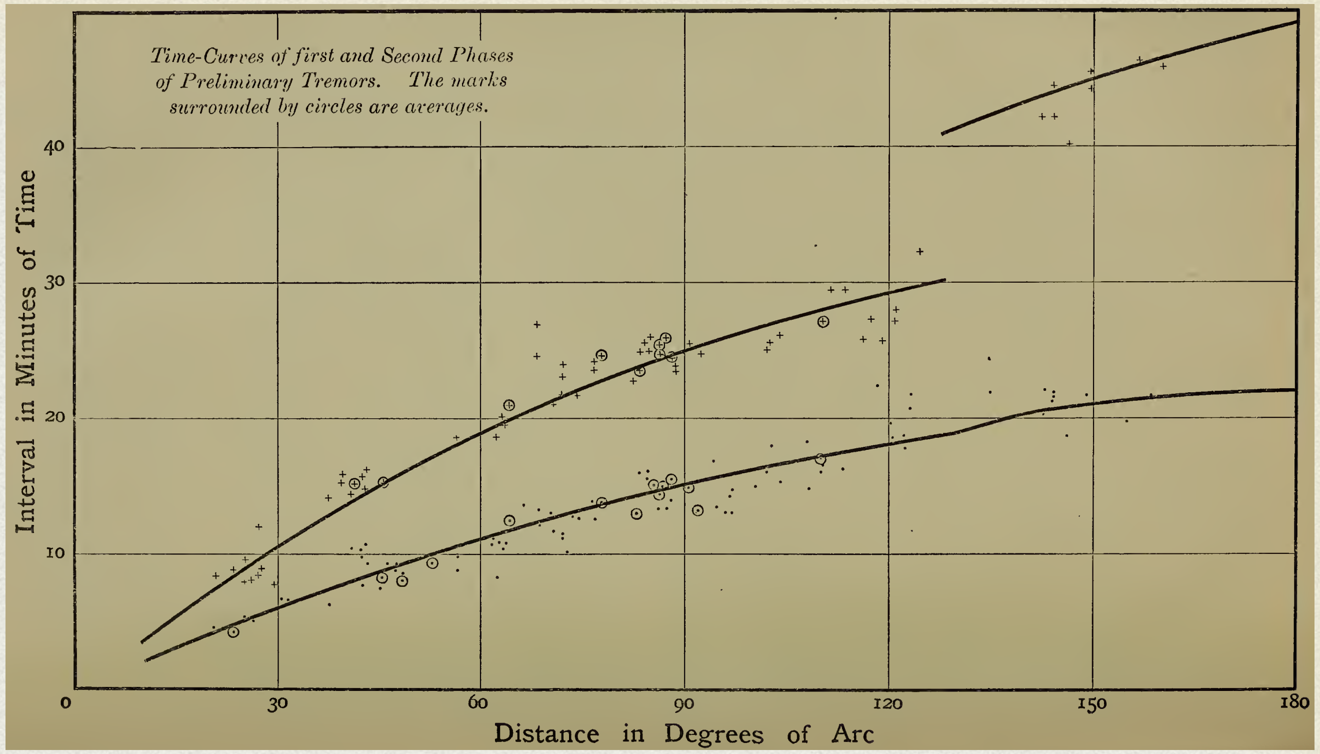
THE DYNAMO HYPOTHESIS

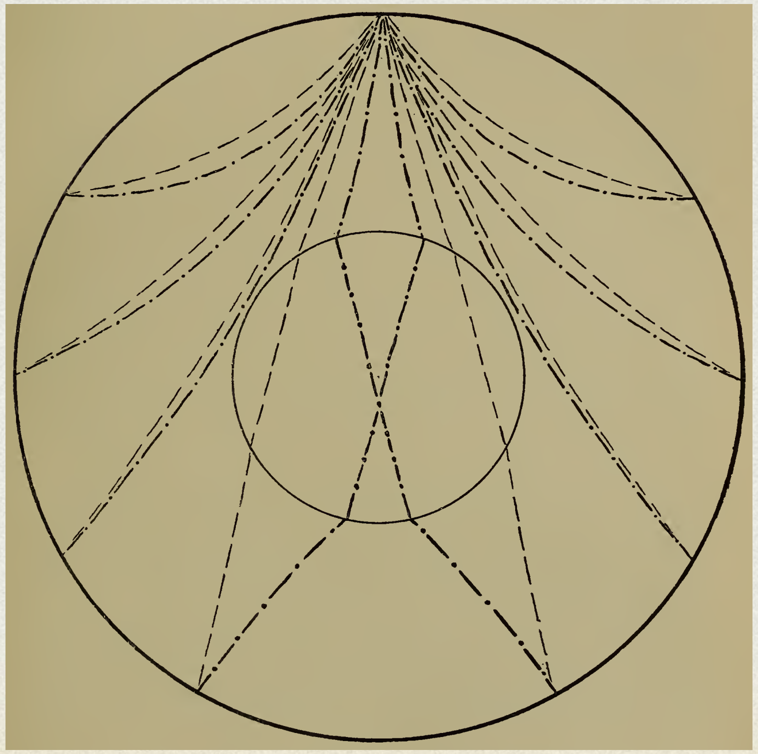
- Discovery of Curie temperature (1895) meant that a hot ($T > 1000$ K) Earth's interior cannot support permanent magnetic field.

- The dynamo hypothesis, that magnetic fields within the Earth (and the Sun) are supported by electric currents was proposed by Joseph Larmor (1919).

SEISMIC WAVES FIRST STUDIES

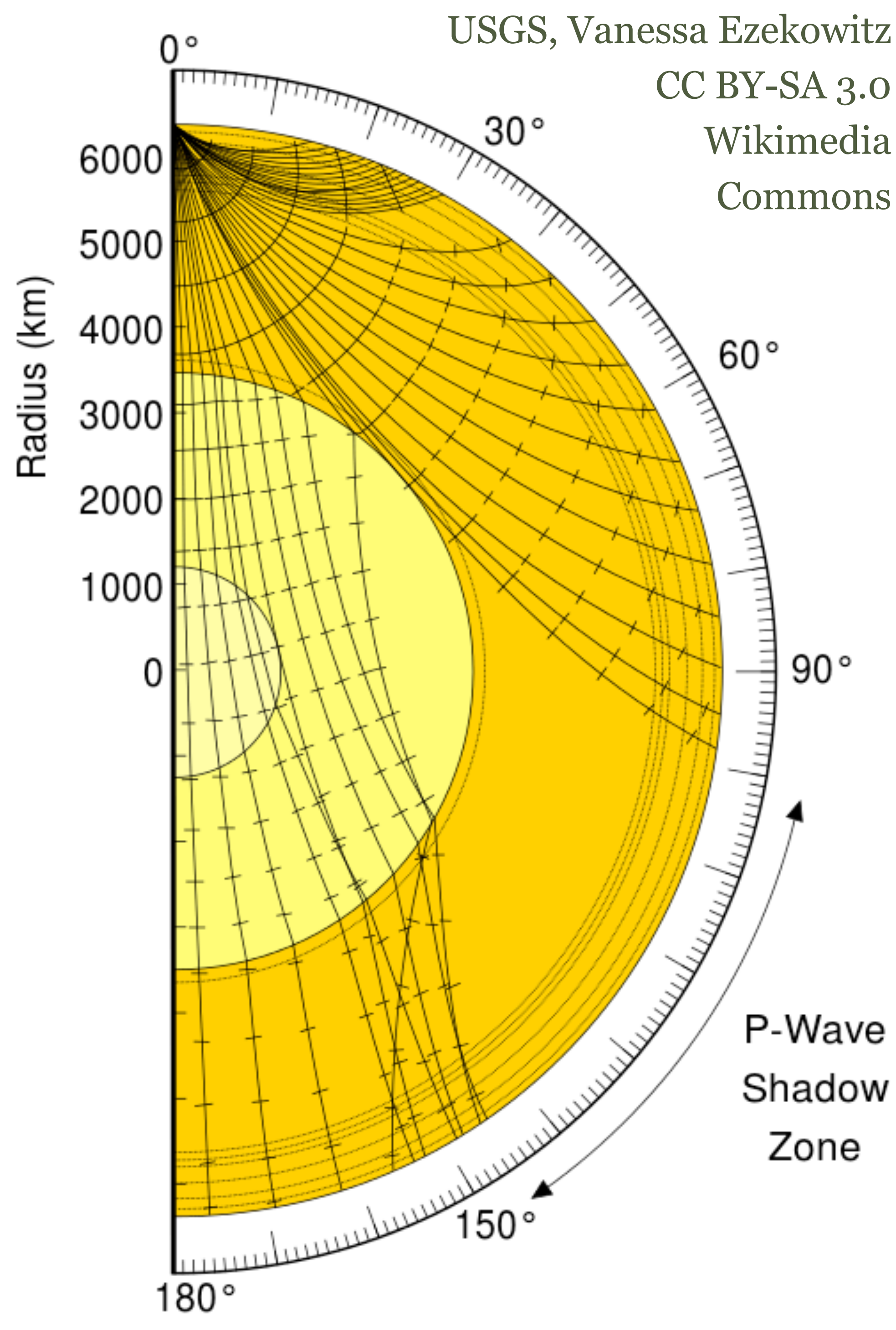
- 1906: Richard Oldham detected two types of seismic waves: primary and secondary
- 1912: Beno Gutenberg measures the depth of the core-mantle discontinuity at 2900 km
- 1926: Harold Jeffreys demonstrates that the core is liquid
- 1936: Inge Lehmann discovers the inner solid core

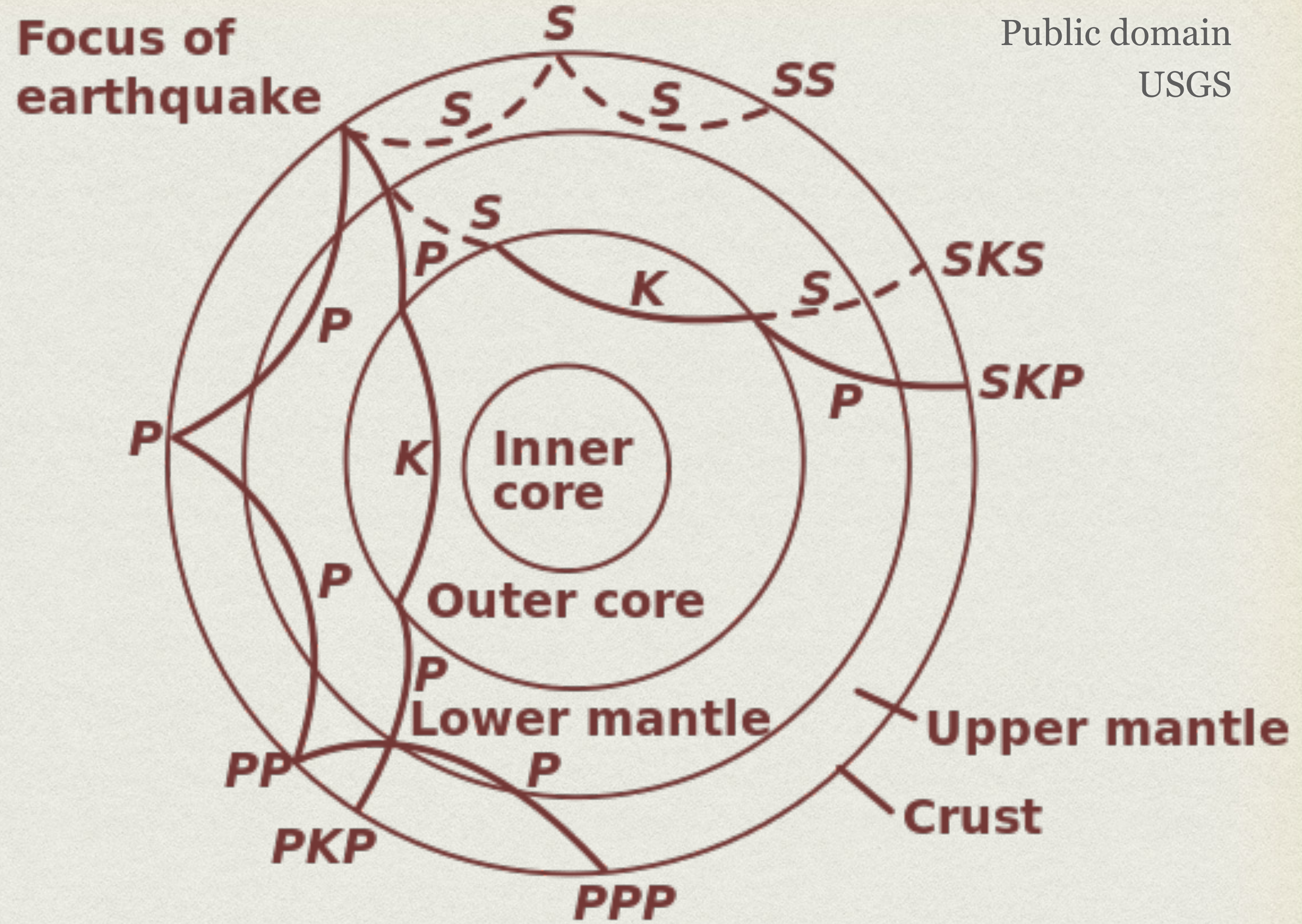




Oldham (1906)

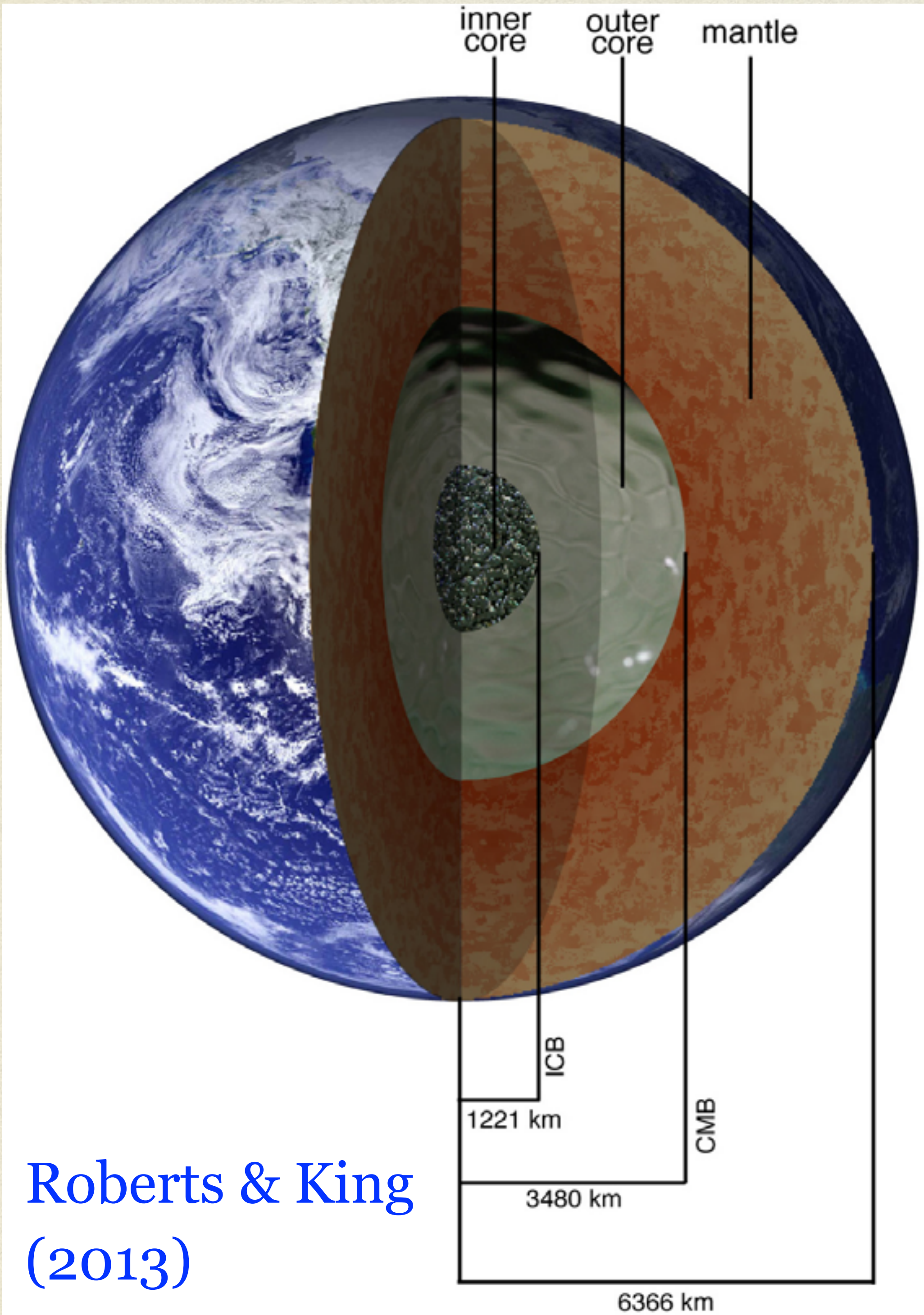
SEISMIC WAVES: MODERN VIEW



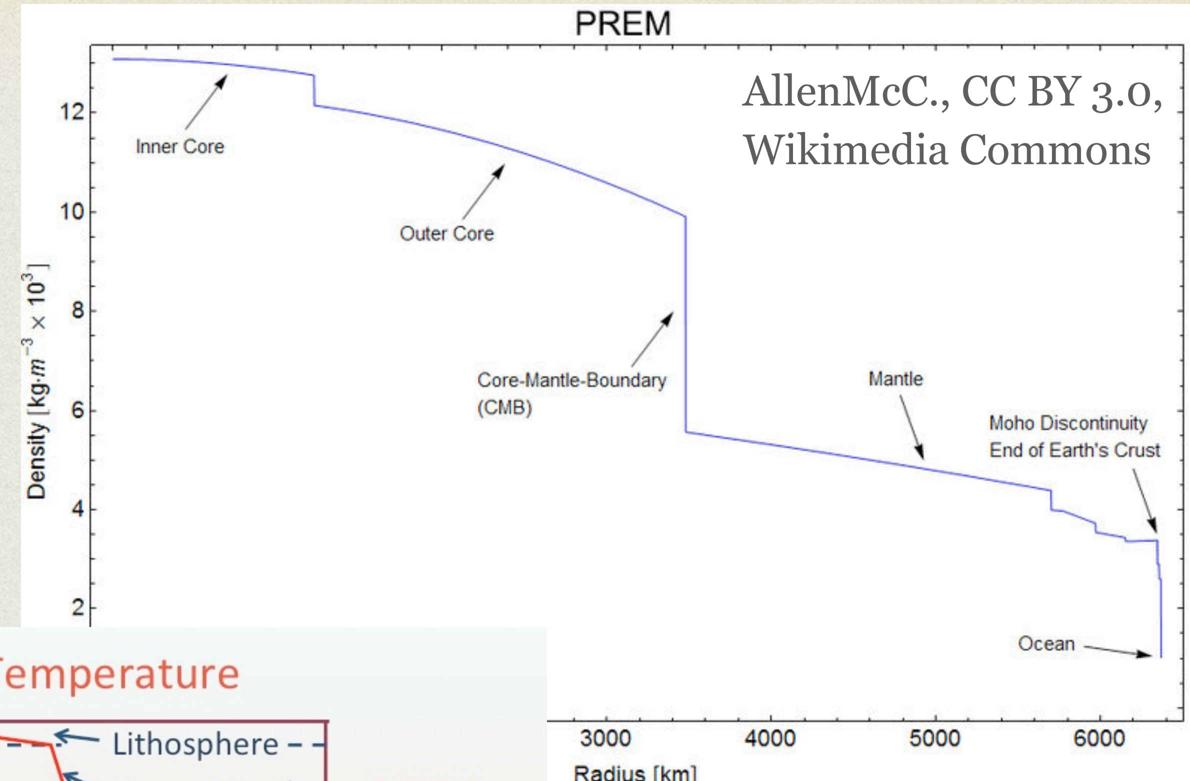


P - primary/pressure/longitudinal (faster)
S - secondary/shear/transverse (slower)
K - pressure wave in the outer core

INTERNAL STRUCTURE OF THE EARTH



Roberts & King (2013)



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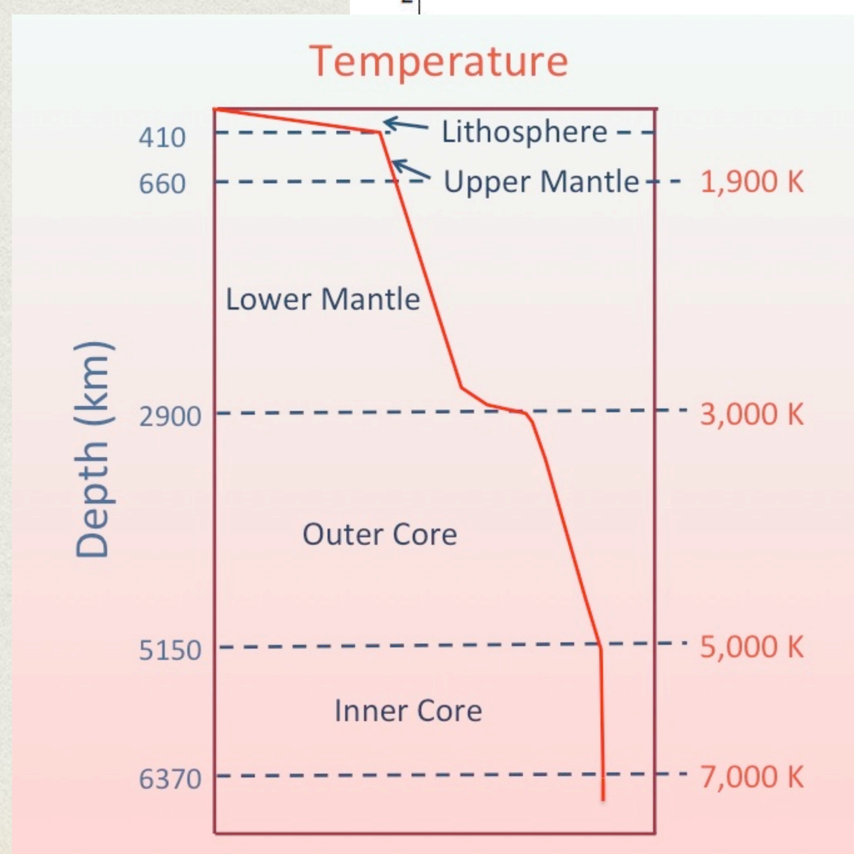

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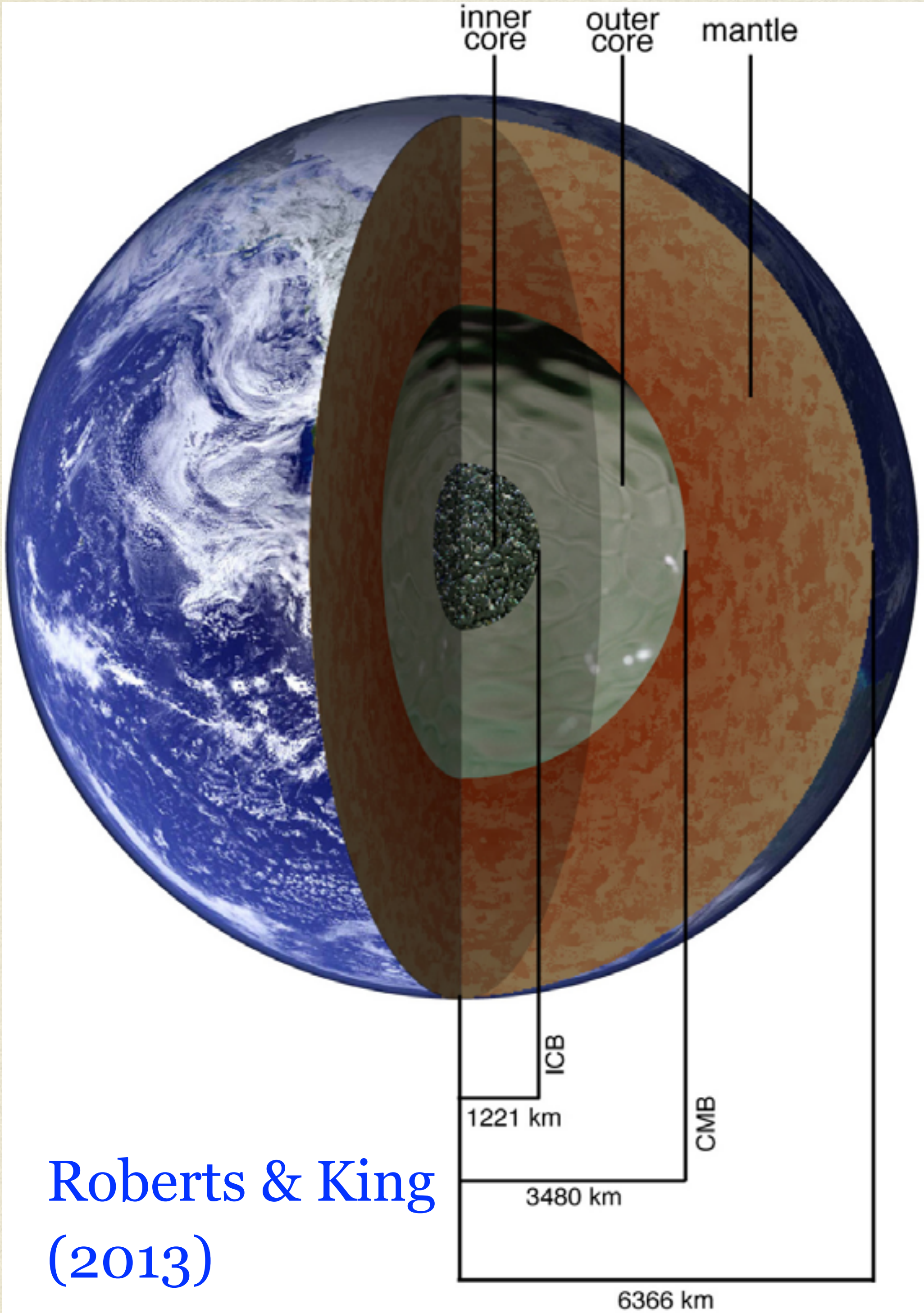
INTERNAL STRUCTURE OF THE EARTH



Roberts & King (2013)

- crust: solid, locally ferromagnetic
- mantle:
  - solid, unmagnetized
  - convectively unstable
  - extremely slow convection ($\sim 3\,\mathrm{cm\,yr^{-1}}$, $\sim 10^8\,\mathrm{yr}$)
- outer core (3480 km):
  - liquid (does not transmit S-waves; Jeffreys 1926)
  - kinematic viscosity comparable to that of water
  - convection driven by inner heat (and light elements)
- inner core (Lehmann 1936; 1220 km):
  - solid, unmagnetized
  - slowly grows due to cooling
  - age highly uncertain: 0.5-4 Gyr
  - density jump by 6%
  - higher iron/nickel abundance
  - differential rotation $\lesssim 1^\circ/\mathrm{yr}$

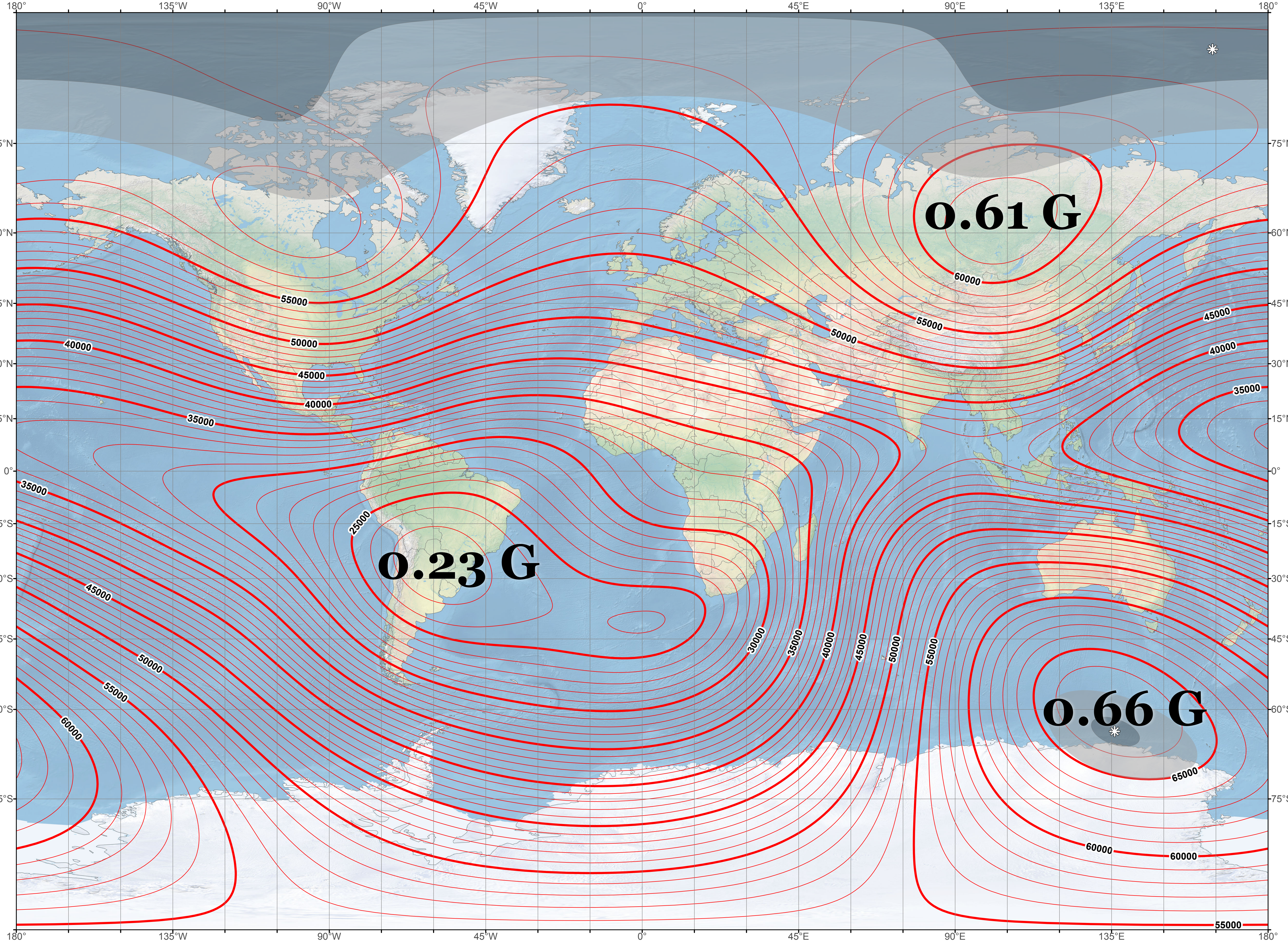
PARAMETERS OF THE EARTH'S INTERIOR

- mantle:
  - dynamic viscosity $\mu \sim 10^{23}\,\mathrm{Pa\,s} \sim 10^{24}\,\mathrm{g\,cm^{-1}\,s^{-1}}$
  - kinematic viscosity $\nu = \mu/\rho \sim 10^{23}\,\mathrm{cm^2\,s^{-1}}$
  - convective velocity $\mathrm{v} \sim 10^{-7}\,\mathrm{cm\,s^{-1}} \sim 3\,\mathrm{cm\,yr^{-1}}$
  - dynamical time scale $\tau_{\mathrm{dyn}} = \Delta R/\mathrm{v} \sim 10^8\,\mathrm{yr}$
  - Reynolds number $\mathrm{Re} = \mathrm{v}\,\Delta R/\nu \sim 3 \times 10^{-22} \ll 1$

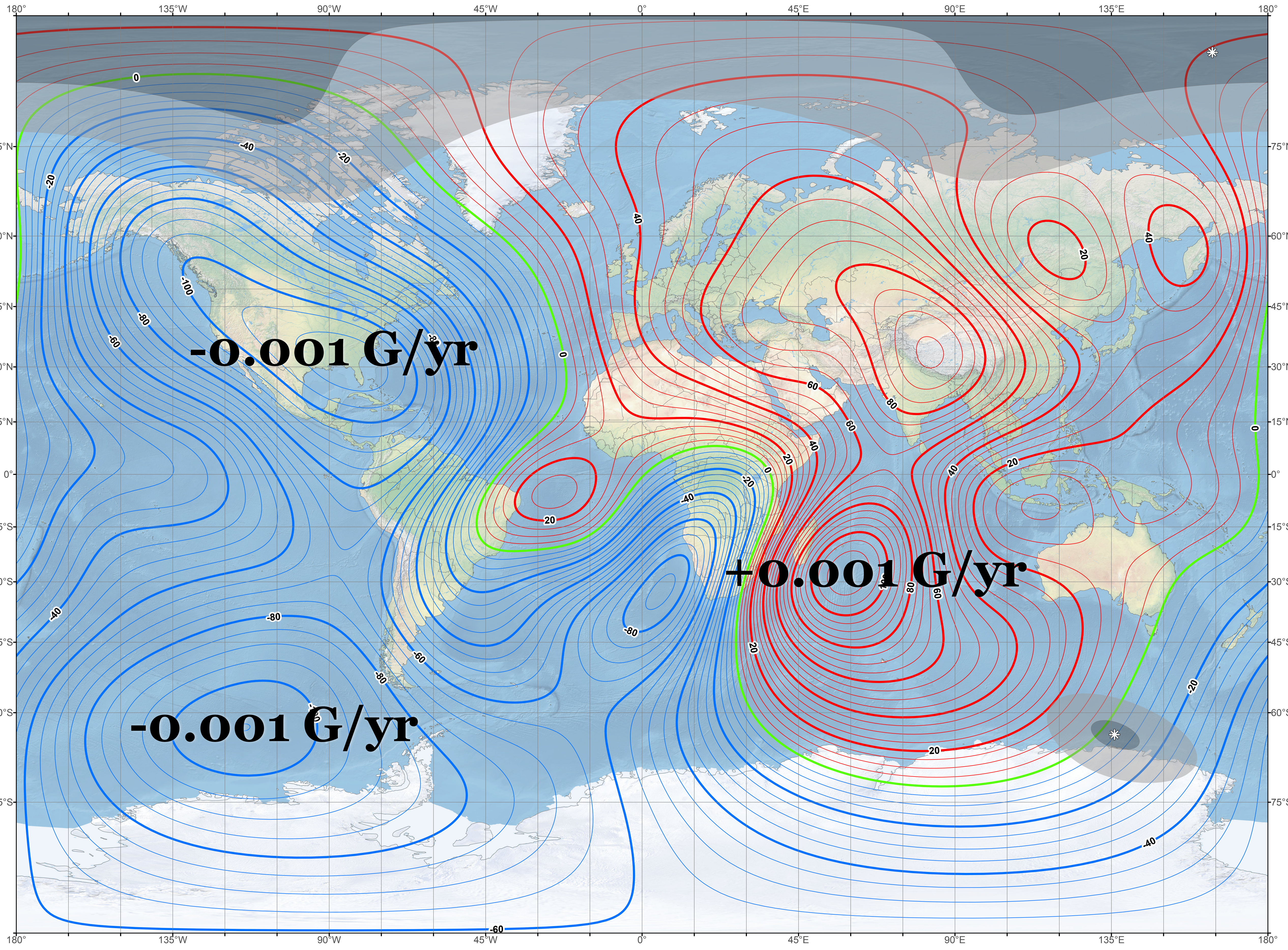
- outer core:
  - mean magnetic field strength $B \sim 2.5\,\mathrm{mT} = 25\,\mathrm{G}$
  - convective velocity $\mathrm{v} \sim 0.04\,\mathrm{cm\,s^{-1}} \sim 1\,\mathrm{in\,min^{-1}}$
  - dynamical time scale $\tau_{\mathrm{dyn}} = \Delta R/\mathrm{v} \sim 200\,\mathrm{yr}$
  - Alfvén velocity $\mathrm{v_A} = B/\sqrt{4\pi\rho} \sim 2.2\,\mathrm{cm\,s^{-1}} \gg \mathrm{v}$
  - magnetic/kinetic energy ratio $u_{\mathrm{B}}/u_{\mathrm{kin}} = (B^2/8\pi)/(\rho \mathrm{v}^2/2) \sim 3 \times 10^3 \ll 1$
  - kinematic viscosity $\nu \sim 10^{-2}\,\mathrm{cm^2\,s^{-1}}$
  - Reynolds number $\mathrm{Re} = \mathrm{v}\,\Delta R/\nu \sim 10^9 \gg 1$
  - magnetic diffusivity $\eta \sim 7 \times 10^3\,\mathrm{cm^2\,s^{-1}} \gg \nu$
  - diffusive decay time scale $\tau \sim R_{\mathrm{o}}^2/\pi^2\eta \sim 6 \times 10^4\,\mathrm{yr} \gg \tau_{\mathrm{dyn}}$

- inner core:
  - kinematic viscosity $\nu \sim 10^{18}\,\mathrm{cm^2\,s^{-1}}$

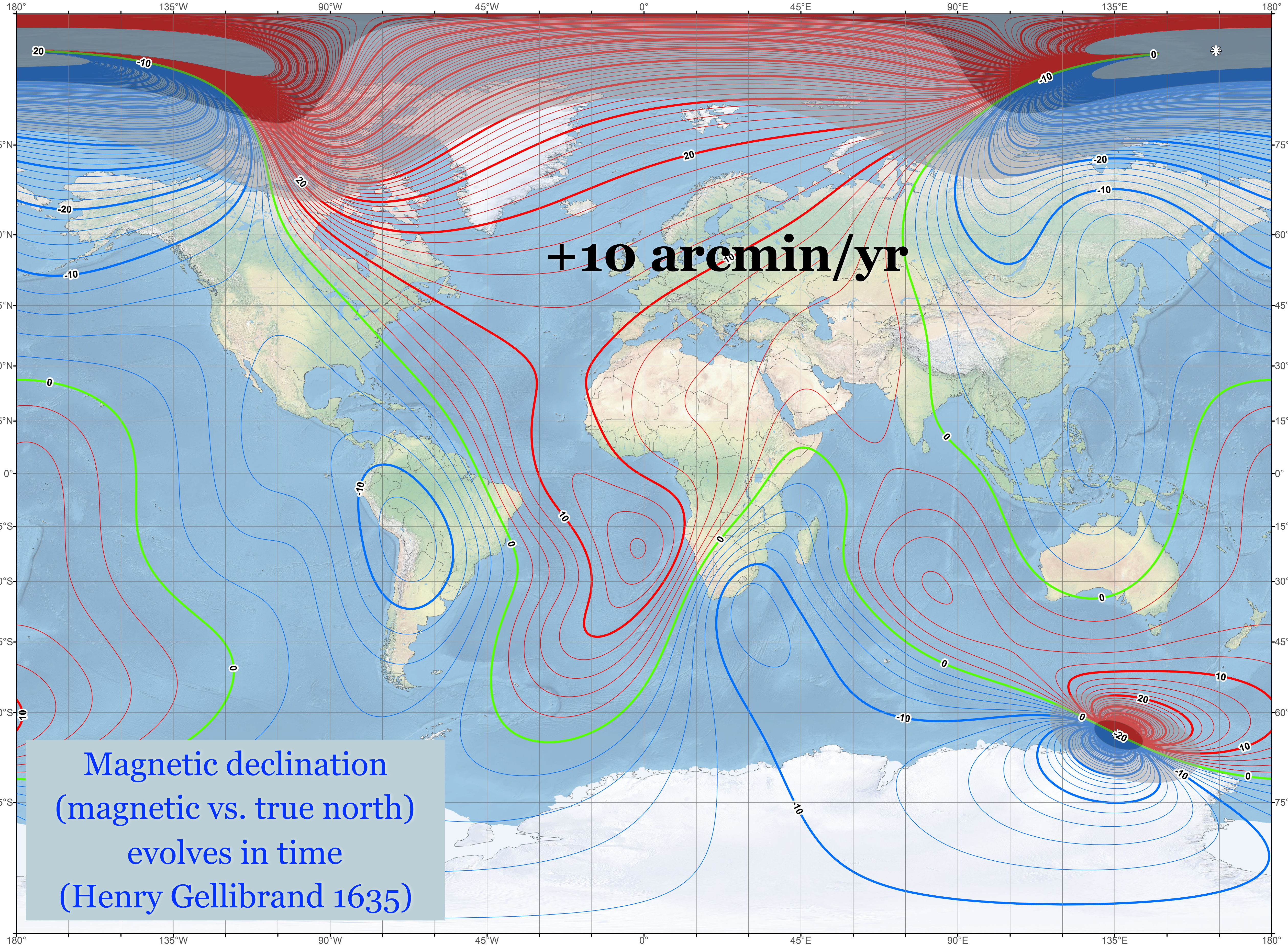
US/UK World Magnetic Model - Epoch 2020.0
Main Field Total Intensity (F)



US/UK World Magnetic Model - Epoch 2020.0
Annual Change Total Intensity (F)



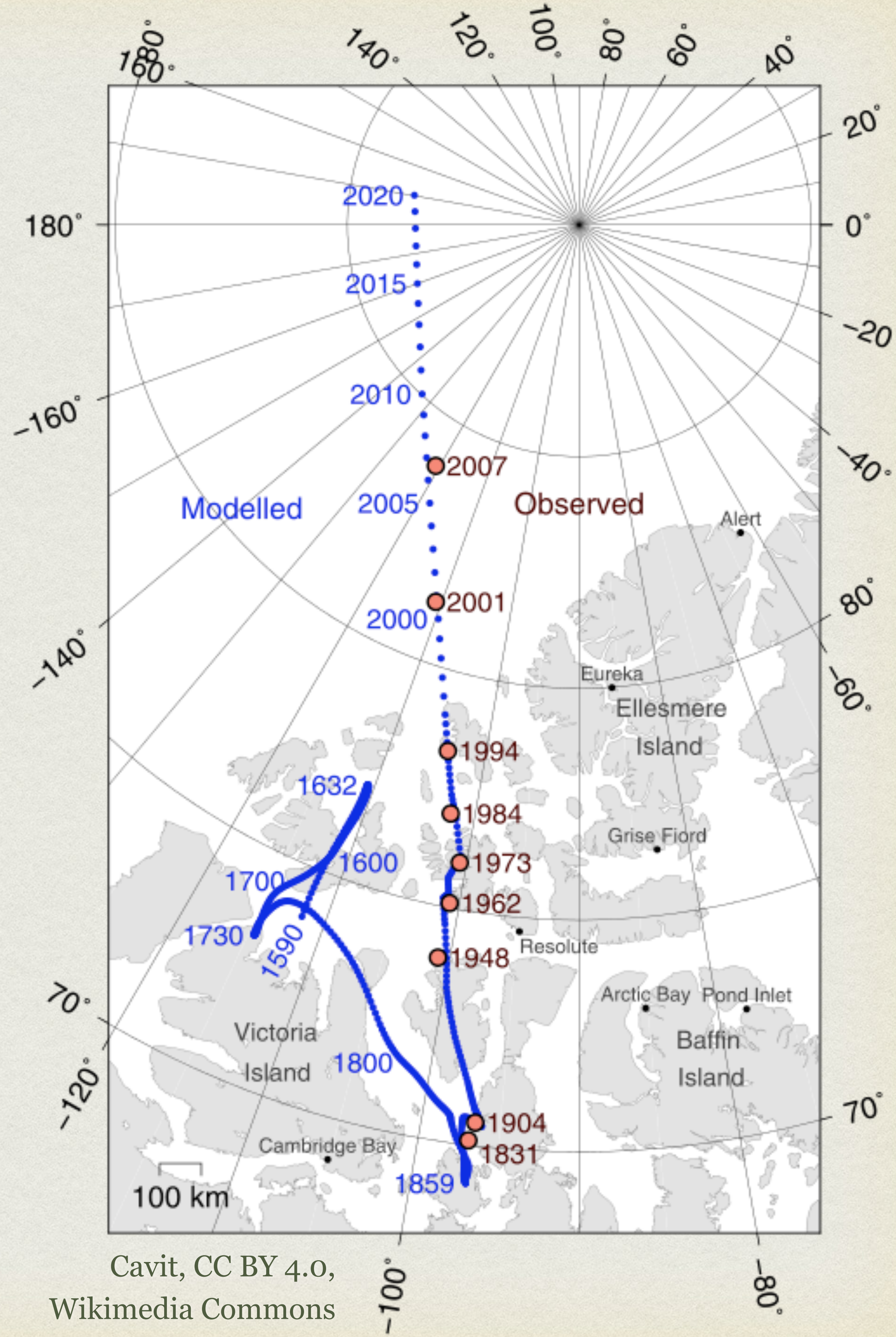
US/UK World Magnetic Model - Epoch 2020.0
Annual change declination (D)



MAGNETIC POLE SHIFT

- north magnetic pole has been shifting by $\sim 50\,\mathrm{km\,yr^{-1}}$ over the past 2 decades

- magnetic dipole moment has been decreasing by 5% per century (faster than diffusive decay)



POWER SPECTRUM OF THE GEOMAGNETIC FIELD

- surface magnetic field projected onto the core-mantle boundary (CMB)
- magnetic curtain for $l > 13$ hides the core field by cool ($T < T_{\text{Curie}}$) magnetized crust

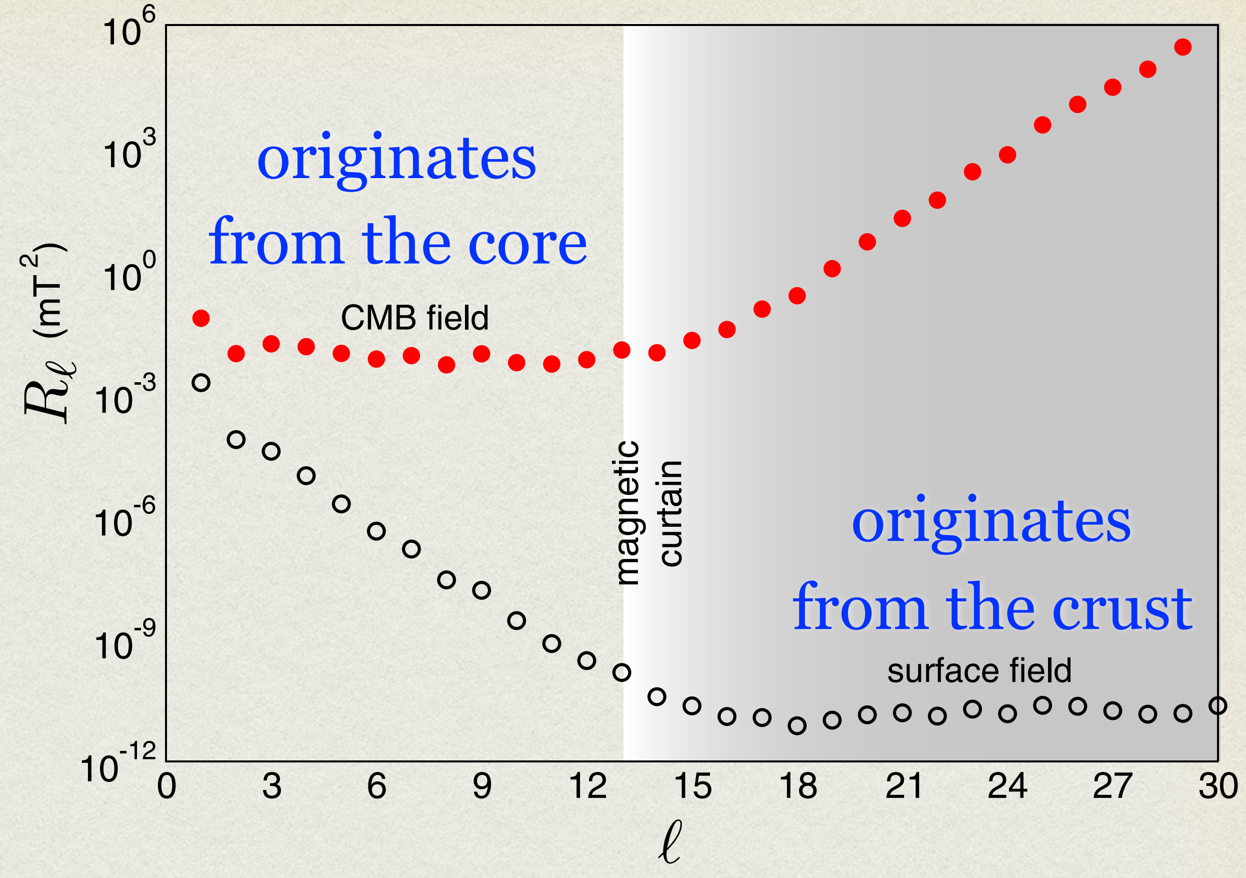


Figure 3. A Mauersberger–Lowes spectrum for geomagnetic field intensity as a function of harmonic degree; see (8*a*). Gauss coefficients for data points are taken from the xCHAOS model of Olsen and Mandea (2008), derived from field measurements from satellite and ground-based observatories made between 1999 and 2007. Hollow symbols show the spectrum at Earth's surface, $R_\ell(a)$; solid symbols show it at the CMB, $R_\ell(r_o)$. The shading illustrates where information about the core is hidden behind the magnetic curtain, the edge of which is indicated.

Roberts & King (2013)

PROJECTING THE SURFACE FIELD TO THE CORE BOUNDARY

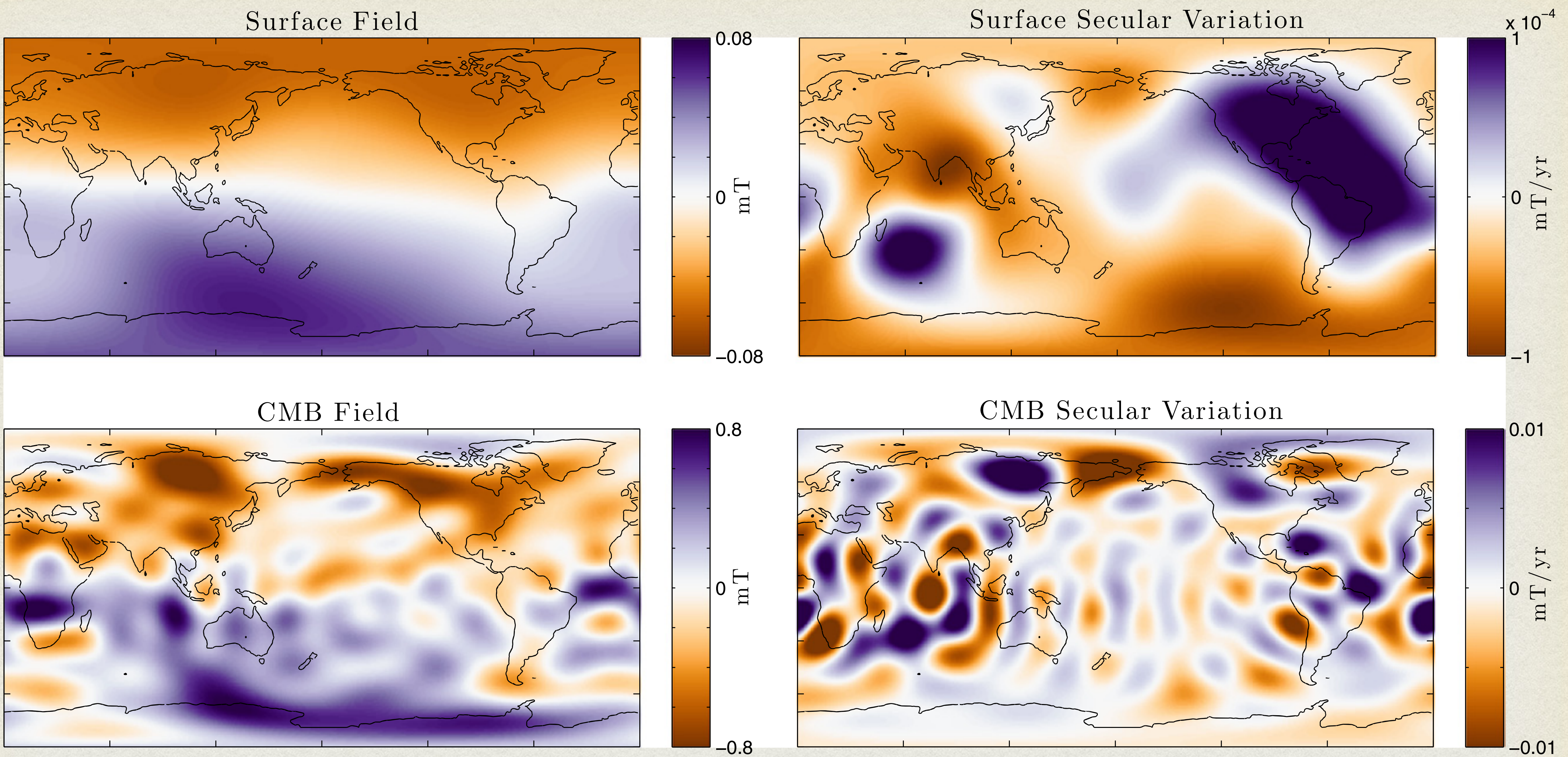


Figure 5. Radial magnetic field $\widehat{B}_r$ (left panels) and secular variation $\partial_t \widehat{B}_r$ (right panels) at Earth's surface (top panels) and the CMB (bottom panels). Data from observations in 2004 are taken from the xCHAOS model of Olsen and Mandea (2008) for $\ell \leqslant 13$.

this does not include any toroidal field component

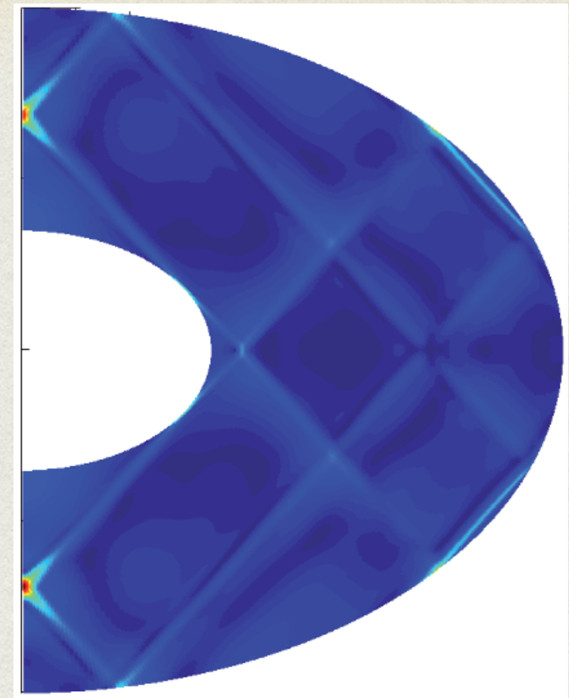
Roberts & King (2013)

TOTAL MAGNETIC FIELD FROM EARTH'S NUTATIONS

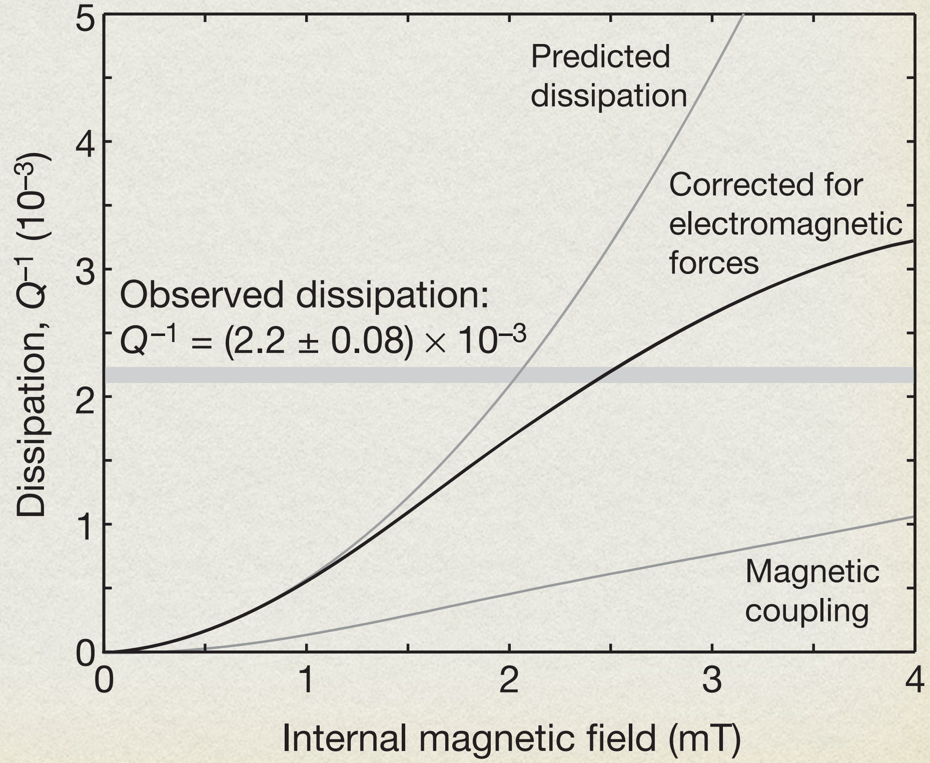
- Nutations are variations in the orientation of the Earth's rotation axis, caused by tidal forces from the Moon and Sun on slightly aspherical Earth structure ($\epsilon = 0.0025$ for the inner core).

- Phase delays are measured between the tidal forces and Earth's response. These allow to estimate the damping rate and total dissipation.

- The inferred dissipation rate can be explained by electric currents induced by magnetic field of total strength 2.5 mT = 25 G .



Buffett (2010)



PALEOMAGNETISM

Roberts & King (2013)

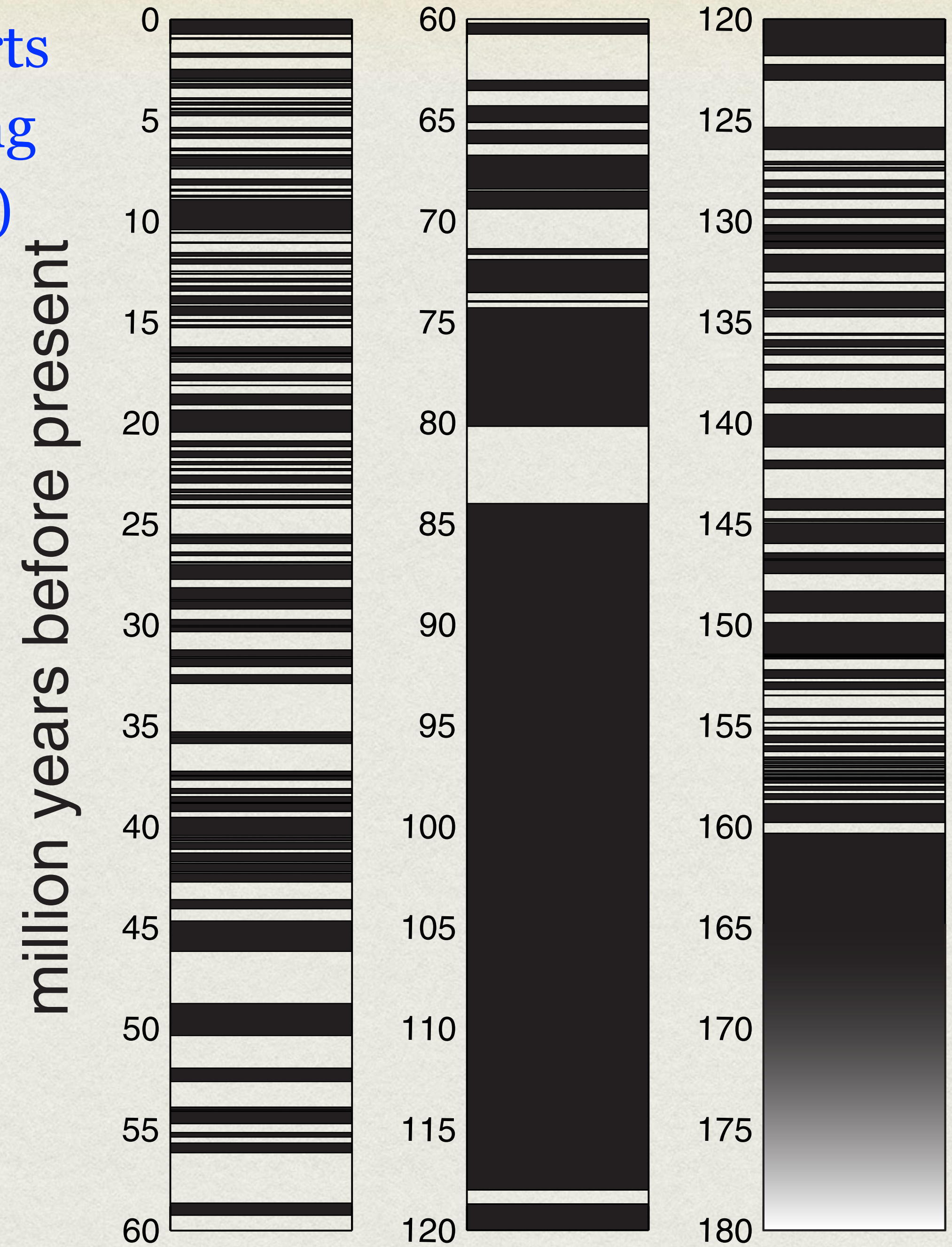
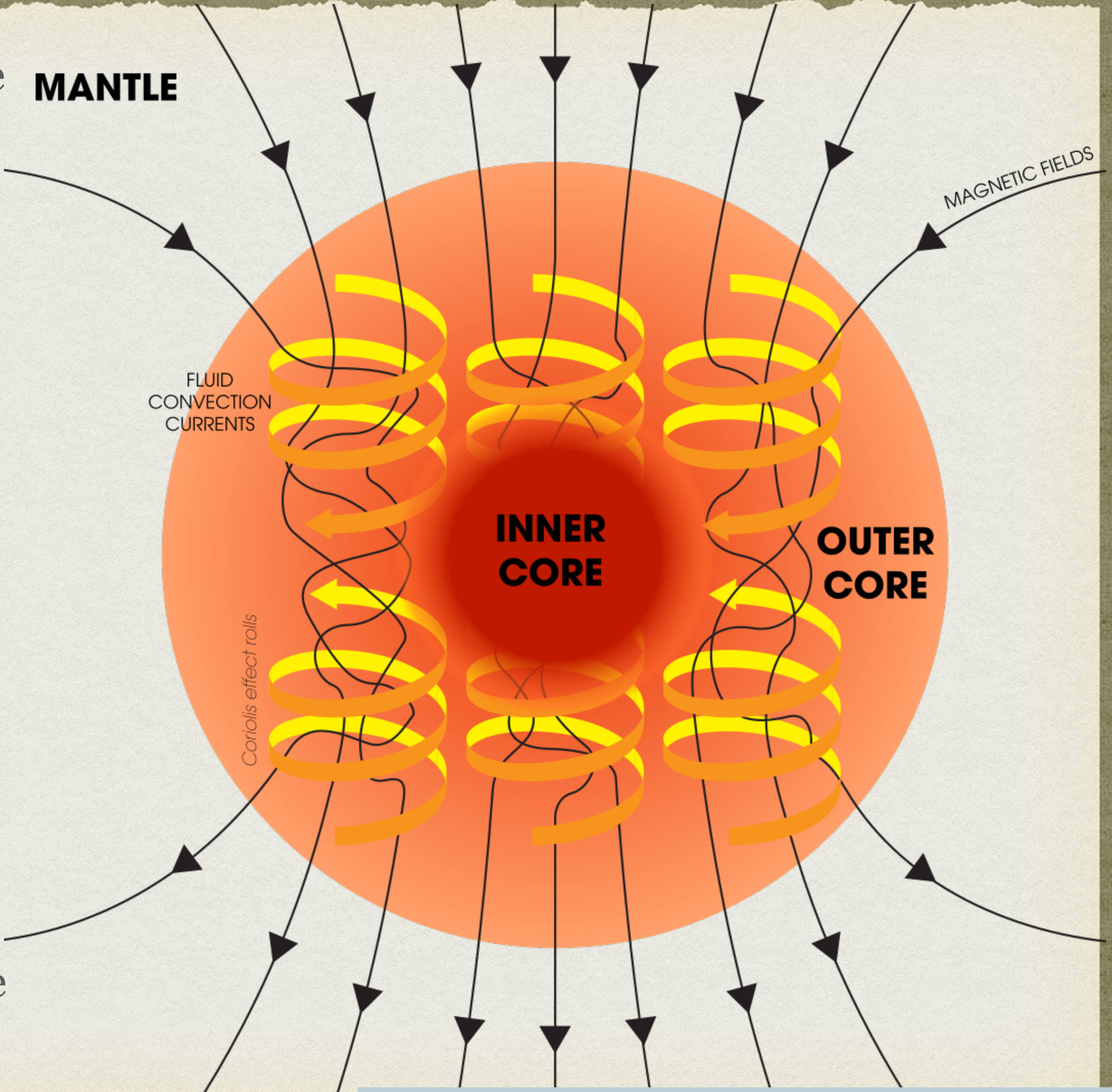


Figure 9. A timeline of geomagnetic polarity reversal occurrences. Data extracted from Kent and Gradstein (1986).

- local measurements of prehistoric magnetic field orientation confirm that the magnetic dipole has been preferentially aligned with the Earth's rotation axis
- rich record of polarity reversals, most recent at 0.78, 2.6, 3.6 Myr ago. Is one ongoing presently?
- a reversal may last 1-10 kyr.
- no statistical preference for either orientation

GEODYNAMO

- Earth's magnetic field decays on the time scale of ~50 kyr.
- A regeneration mechanism is necessary - the geodynamo.
- The geodynamo is supported by circulation of conducting matter, which is possible in the fluid outer core due to convection.
- Convection is enabled by a net heat flow from the core to the much cooler mantle.
- The Earth's rotation and Coriolis forces are important for shaping the core convection.



SUMMARY

- The strength of Earth's magnetic field is ~0.3 G on the surface and ~25 G in the core (including strong hidden toroidal component).
- It is dominated by dipole on the surface roughly aligned with the rotation axis, but has a flat spectrum at the core boundary.
- It shows complex variations on very different time scales, including secular magnetic pole wander and prehistoric polarity reversals.
- It is generated by dynamo in the liquid outer core, driven by convection due to gradients of temperature and chemical potential, augmented by rotation.