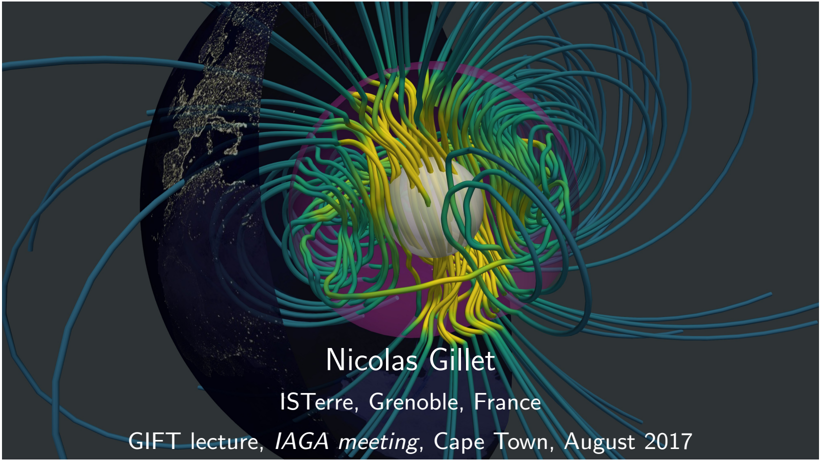
Understanding the geomagnetic field : a trip to the Earth's core



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GIFT lecture, *IAGA meeting*, Cape Town, August 2017

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cnrs

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Outlines

a geophysical introduction to deep Earth

the geomagnetic field, signature of a moving core

dynamics of the core, and insights from observations

discussion

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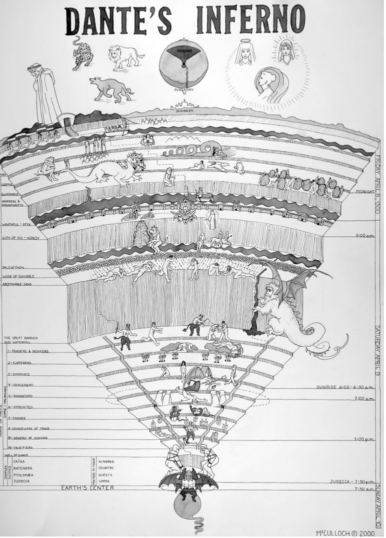
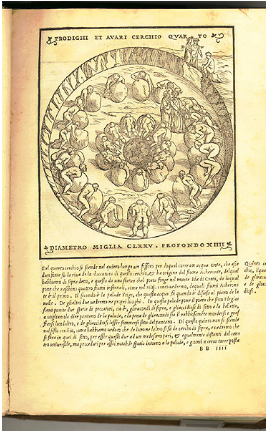
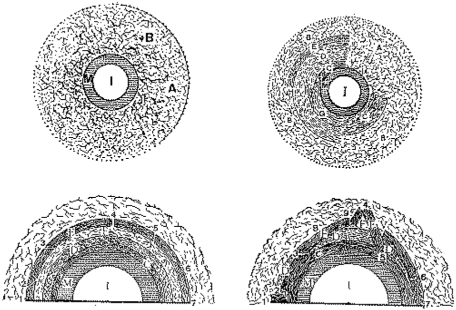
old news from the core : Dante's inferno (1315)

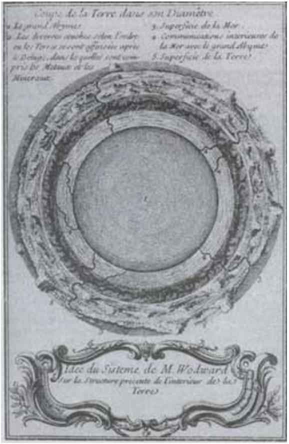




first physical models



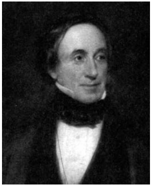
- an old sun (Descartes, 1644)
- a fluid Earth

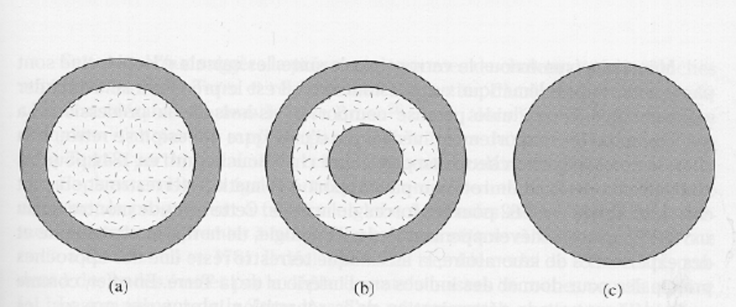


Woodward (1695)

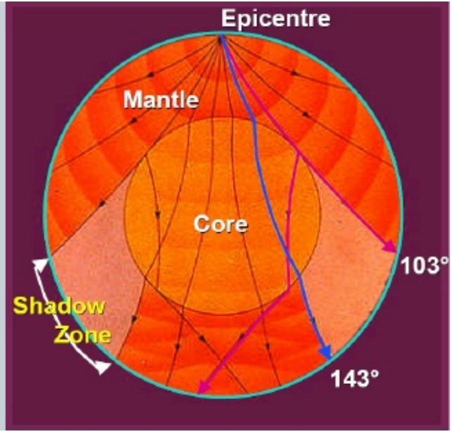
Hopkins' hypotheses (XIXth century)

- melting temperature increases with pressure
  $\longrightarrow$ thus with depth !
- is the Earth molten or not ?
  $\longrightarrow$ competition pression / temperature





early XXth century seismology



- two kinds of body waves :
  - sound wave "P"
  - shear waves "S" (do not propagate within fluids)
- shadow zone with no P waves (Oldham, 1906)

$\Rightarrow$ liquid core of radius $r \simeq 3500$ km

discovery of a solid inner core

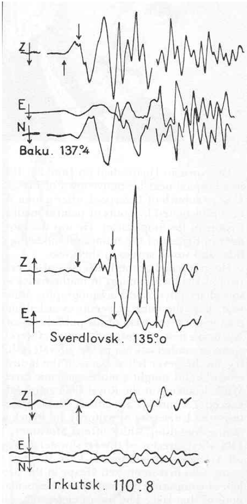
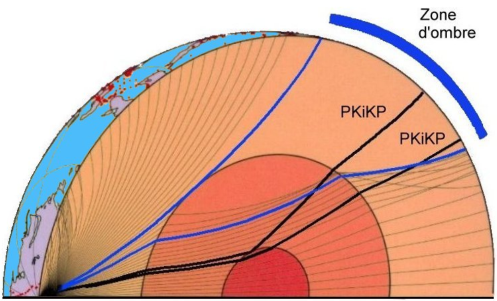


Fig. 5. Seismograms of the New Zealand earthquake of June 16, 1929, showing that the unexplained phases are well recorded on the vertical component [*Lehmann*, 1936].



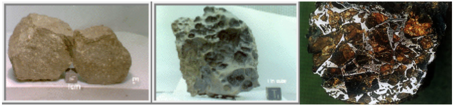
- unexplained phases in the shadow zone

⇒ solid inner core of radius $r \simeq 1200$ km (Lehmann, 1936)

- in any cases : a static picture of the core

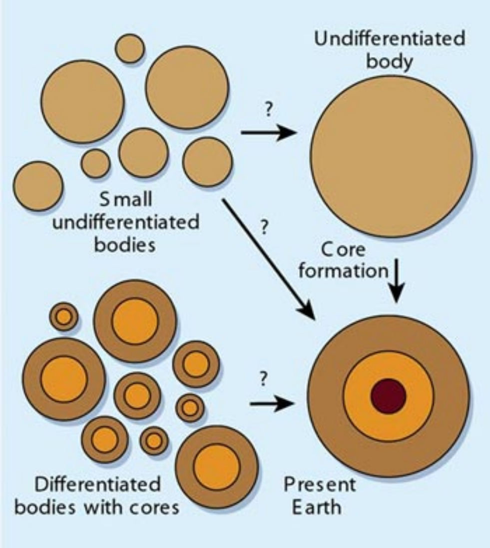
core formation and composition

- seismology
- geodesy (gravity field)
- accretion of planets ~4.5 Gyr ago
- chemistry of meteorites



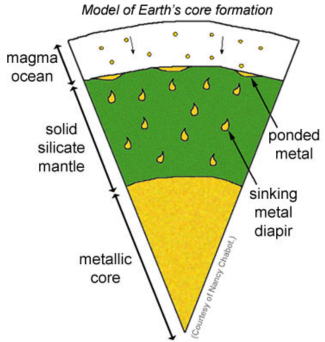
core composition = initial Earth – mantle

- Iron (85%) + light elements (Si, S, Ni, O...)



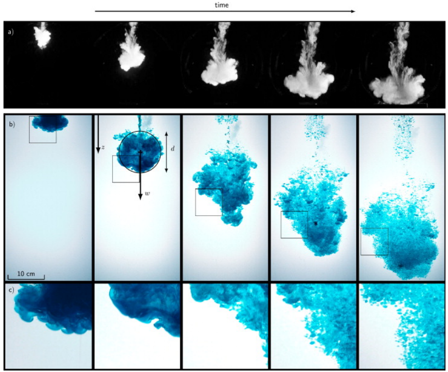
core formation and magma ocean

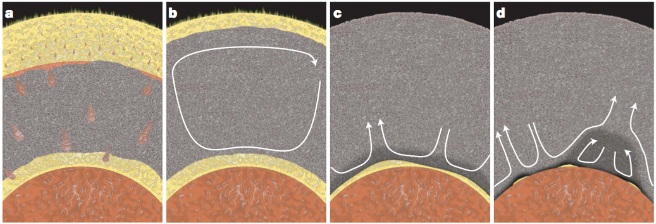
Stevenson's model



experimental studies show turbulent mixing

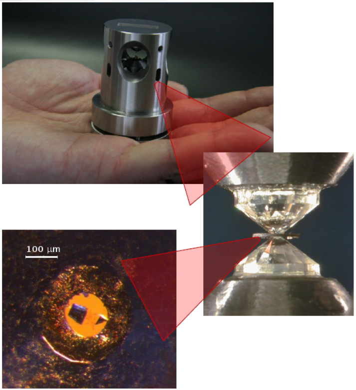
(Deguen et al, 2014)



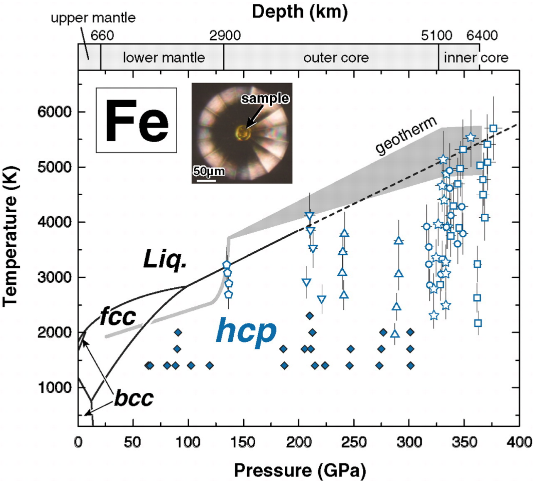


(Labrosse et al, 2007)

high T,P iron phase diagram



Diamond anvil cells
S. Merkel, Univ. Lille 1



Tateno et al (2010)

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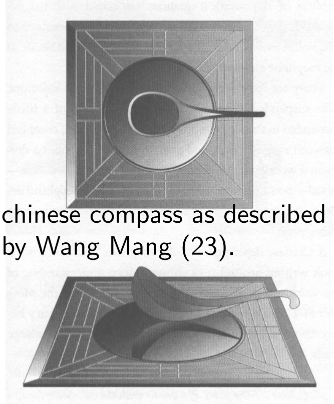
Discovery of the geomagnetic field

- orientation of some natural stones (towards the South) known by Chineses more than 2000 yrs ago

  no articfact, only recorded, used for navigation

- first scientific description by P. Peregrinus (letter to R. Bacon, 1269)

  idea of a dipole, oriented towards the North



chinese compass as described by Wang Mang (23).

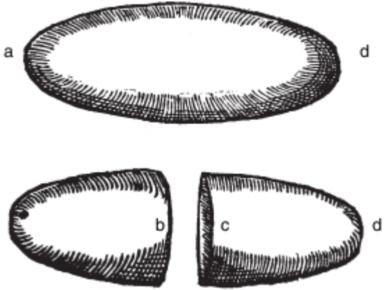
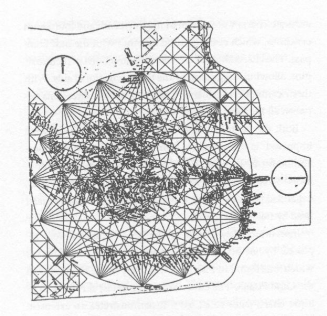


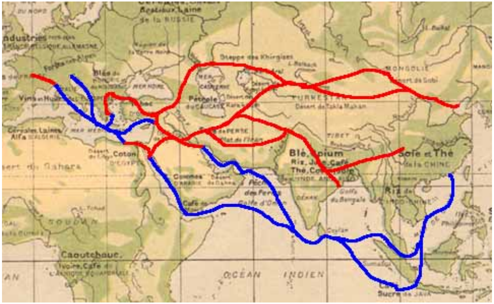
Figure 6 Experiment of cutting lodestone to show the appearance of magnetic pole at the new edges as described in *De Magnete*.

transmission to Europe ?

- first use for navigation by Italians :
  Carta Pisana (1275) of the Eastern Mediterranean sea



The Carta Pisana



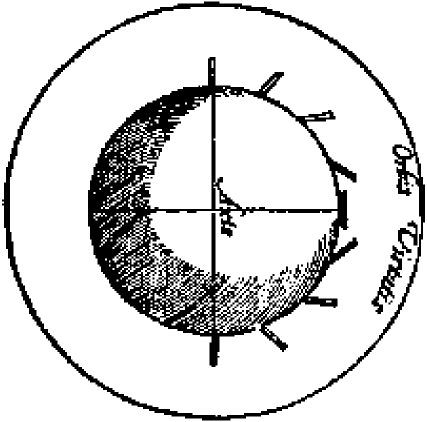
- first mentioned in 1375 by Arabians (who control the silk road)

... blind transmission ? independent discovery ?

- funny enough, only in French and Chinese is the word "love" used to name magnets (but with South/North conventions reversed !)

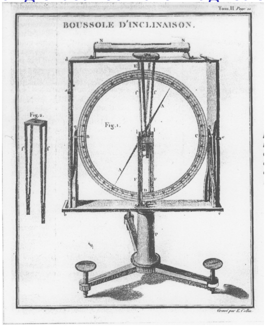
William Gilbert : De Magnete (1600)

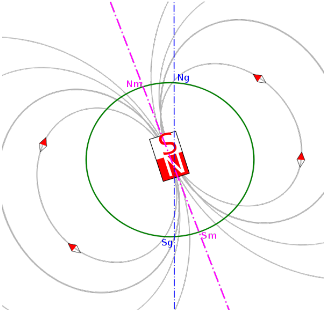
"Magnus magnet ipse est globus terrestris"

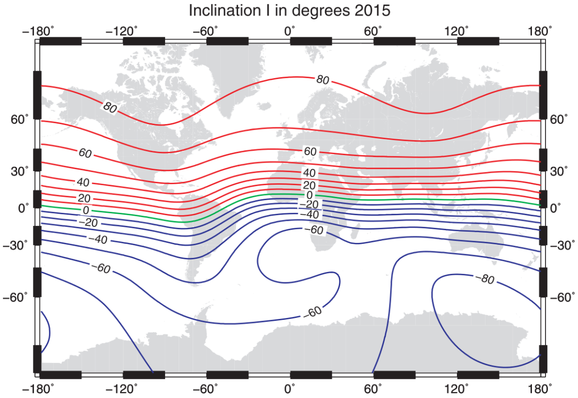


inclination : primarily sensitive to latitude

angle between the magnetic field and the horitontal plane





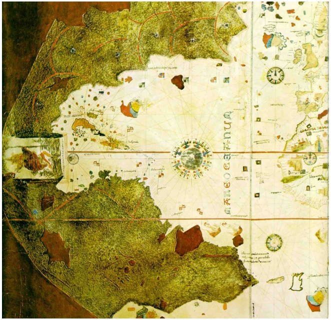


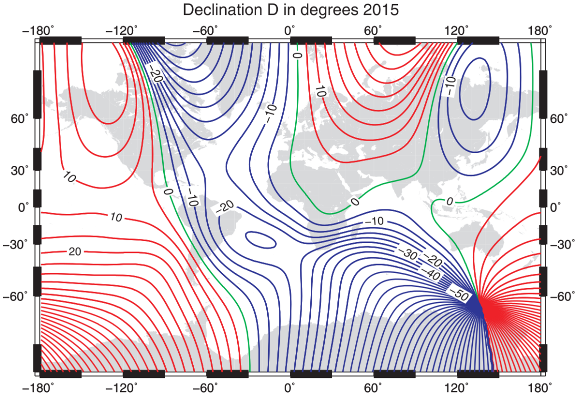
IGRF model (Thébault et al, 2015)

declination : sensitive to longitude

angle between the geographic and geomagnetic Norths

map by De las Casas





IGRF model (Thébault et al, 2015)

- first described with the discovery of America (although probably already known by Dutches)
- Kaap Agulhas : $I = 0$ as observed by Bartolomeu Dias in 1500 !

a time varying field

- 1580, London (William Borough) : $D = 11.5°$ E
- 1622, Depforth (Edmund Gunter) : $D = 6.15°$ E
  ... time variation then suspected
- 1635, Depforth (Henri Gélibrand) : $D \simeq 4°$ E

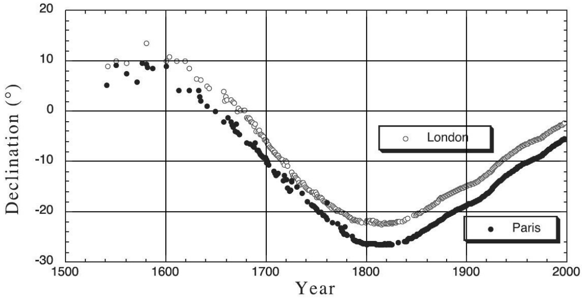


Figure 5. Reconstructed series of direct measurements of declination in Paris and London from the mid sixteenth century to the present [see *Alexandrescu et al.*, 1996, 1997].

no GPS ! which position on the oceans ?

- magnetic measurements on board : a strategic issue for the positioning in longitude
- motivated missions through the Atlantic ocean to measure the declination

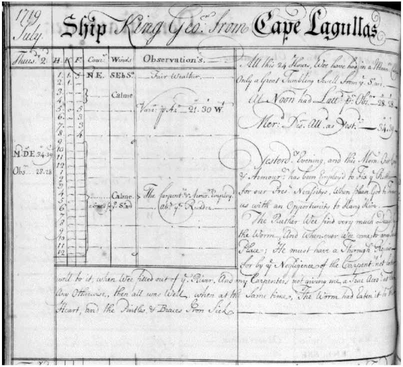
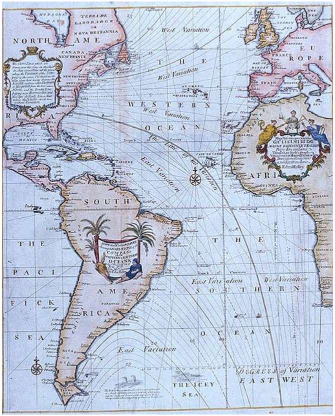


Figure 6. Excerpt from the log of the *King George* on 2 July 1719. Note the azimuth observation of magnetic declination around five o'clock in the afternoon and the recording of meridian distance rather than longitude. By permission of The British Library (source: IOBL L/MAR/B 402 B).

- summarized into historical compilations

(Jonkers et al, 2003)

- bad luck : almost E–W in the Northern Atlantic



the declination map by Halley (1701)

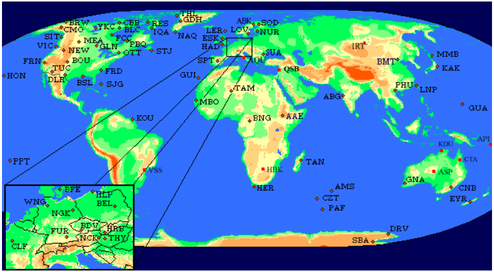
Von Humboldt, Gauss...

- trip to Americas (1798–1804)
- relative intensity measurements

- first absolute intensity measurements (1832)
- 1 Gauss $= 10^{-4}$ T
- Earth $\simeq$ tilted dipole (12.3° at that time)
- mainly of internal source (spherical harmonics)
- first observatory

ground-based observatories

INTERMAGNET network



Chambon-la-Forêt

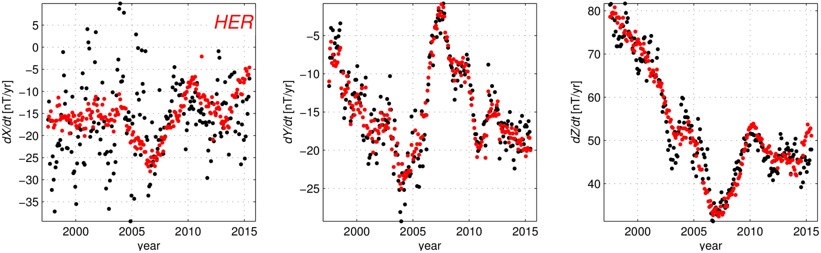
Apia

Tristan d'Acuña

Dumont d'Urville

geomagnetic secular variation

- rate of change of the magnetic field at the Hermanus observatory



- induction equation (Maxwell+Ohm's laws) within the fluid core :

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

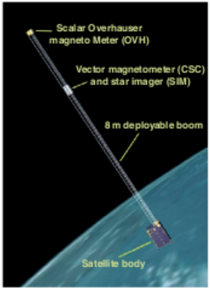
secular variation	electro-motive force (source)	magnetic diffusion (sink)

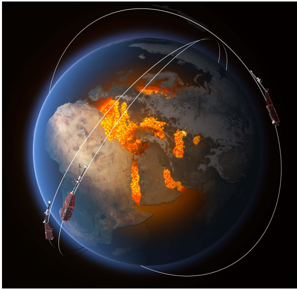
- time changes of the magnetic field (**B**) carry information on motions (**u**) within the outer core ! !

an era of magnetic satellites

continuous since 1999

- Pogo (USA) 1960's
- Magsat (USA) 1980
- Oersted (Denmark) 1999–2013
- Champ (Germany) 2000–2010

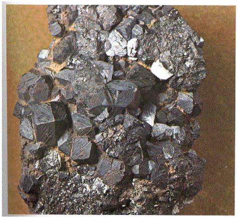



- Swarm (ESA, since Nov. 2013) : constellation of 3 satellites
- after Swarm ?

ancient field : remanent magnetization of rocks

naturally magnetized minerals

Magnetite
Fe3O4

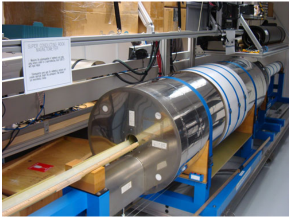


record the field last time they cooled down below the Currie temperature

coring

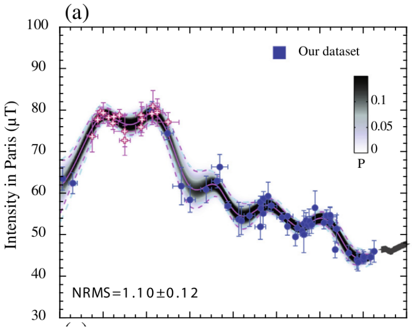
orientering

sampling

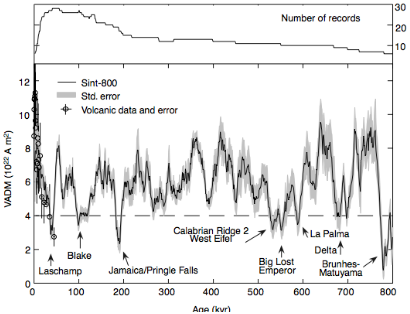


lab measurements

archeo- and paleo-magnetism

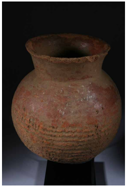


(Genevey et al, 2016)

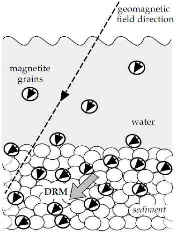


Valet et al

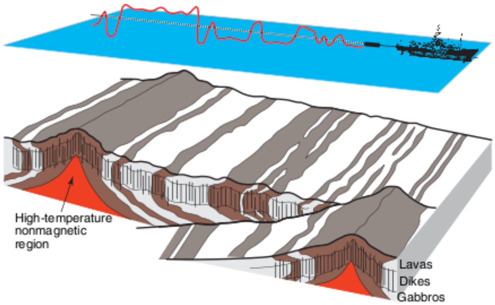
- Archeomagnetism :
  - past millenia
  - human artifacts (kilns, potteries...)



- Paleomagnetism
  - past millions yrs
  - lavas, ocean bottom lake sediments

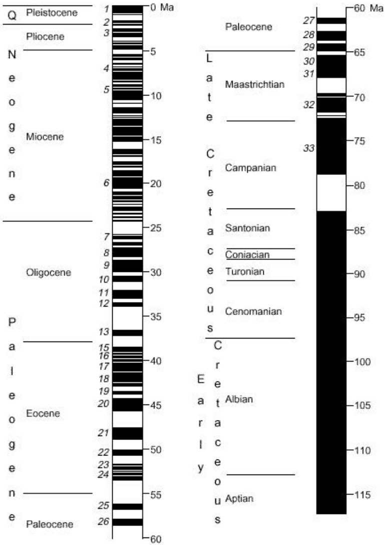


geomagnetic poles inversions



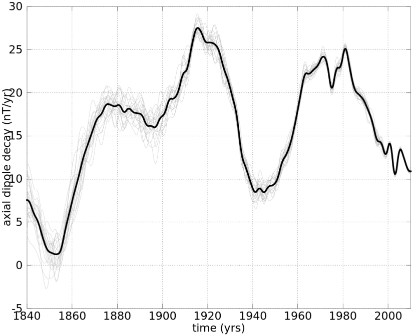
Johnson et al (1997)

- ancient : as old as about 4 Gyr !
  (Tarduno et al, 2010)
- mainly dipolar
- inversions every 100,000 yr to 1 Myr, unpredictable



geomagnetic dipole decay over the observatory era

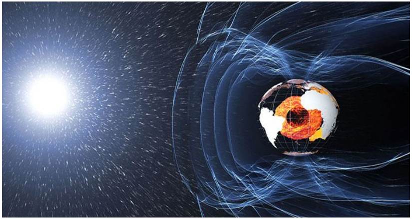
- at least since 1840, at an average rate of 15 nT/yr in average
- lost about 10% of its intensity in 180 yrs
- nothing exceptionnal (occurred many times in the past millenia)
- strongly changing rate of change : may raise again soon, who knows ?
- not necessary suggests a coming reversal



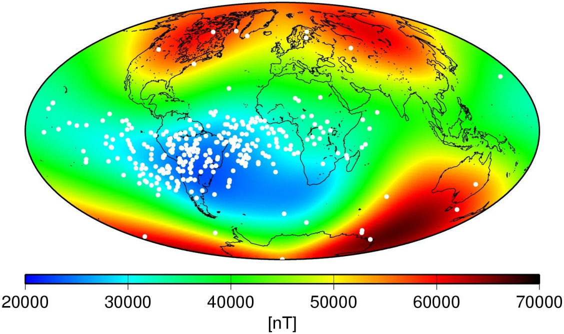
COV-OBS field model (Gillet et al, 2013)

impact of the South Atlantic anomaly

te geomagnetic field is more than a simple dipole !

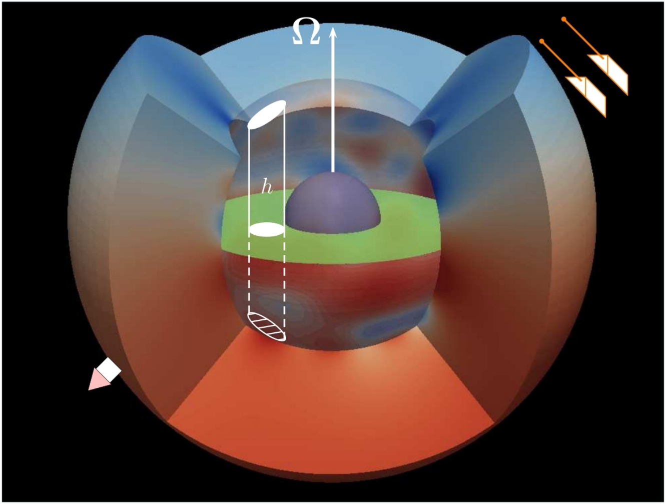


electrical anomalies of the Topex-Poseidon satellite



a step towards the core

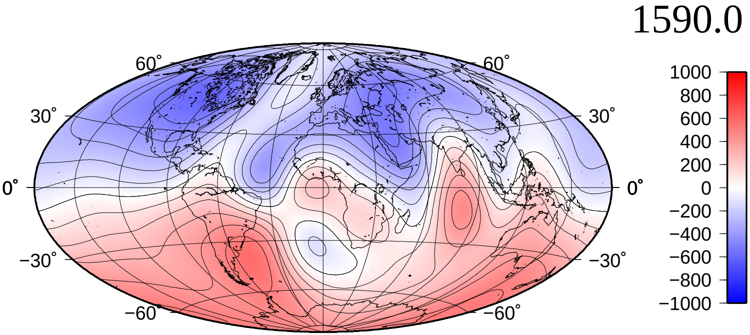
downward continuation through an electically insulating mantle



Courtesy : A. Fournier

the radial magnetic field at the core surface

here the radial componengt B_r (in nT)



gufm1 field model (Jackson et al, 2000)

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global picture

- accretion process (4.5 Gyr ago) :
  gravitational energy transorfmed into heat
- since then : despite radio-active heat production in the mantle, secular cooling (slowly gives back heat to the Univers)

$\Rightarrow$ heat extraction from the (solid) mantle through convection

$\Rightarrow$ heat extraction from the (liquid) core : likely convection

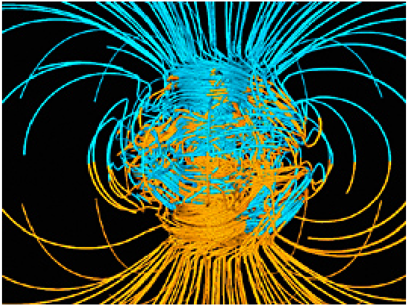
- NB : core convection still an open question (possibility of an stratified upper layer)
- core motions may also be mechanical forced (precession, tides...)

$\Rightarrow$ in any case : motions within the metallic core

... self-sustained natural dynamo (cf induction equation)

dynamo effect

- kinematic dynamo effect :
  - given a motion $\mathbf{u}$, can the induction equation produce a magnetic field from a seed perturbation ?
  - a theoretical issue since the 1940's
- dynamo effect (Larmor, 1919) :
  account for a feed back from the generated magnetic field on the flow (Lorentz force)
  - an experimental challenge taken in 1999 (Karlsruhe, Riga)
  - a numerical challenge taken in 1997 (Glatzmaier & Roberts)



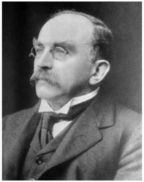
fluid mechanics & electromagnetism

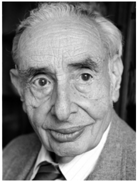
- classical physics :
  - Maxwell's equations (electromagnetism)
  - Navier-Stokes equations (fluis mechanics)
- particularity : rapidly rotating system (cf. ocean, atmosphere)


Oersted


Ampère


Maxwell


Larmor


Elsasser


Alfvén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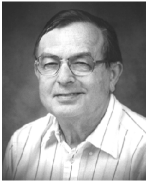

Roberts

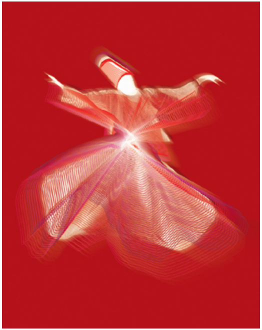
Taylor, Braginski, Moffat...

Coriolis force and fluids

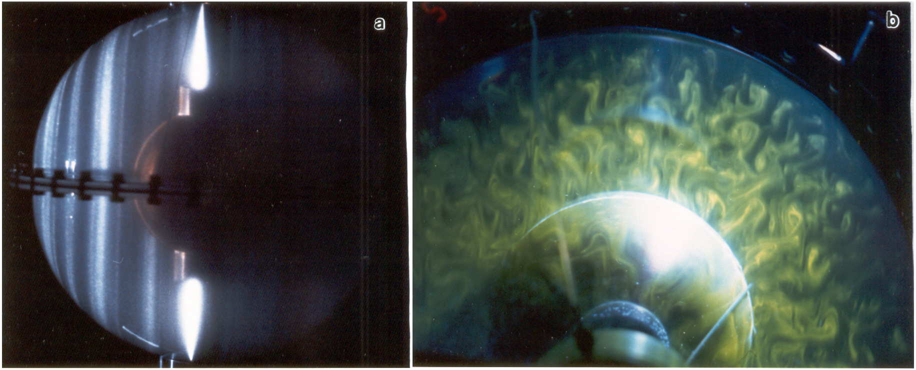
non rotating

credit : GFD Lab/MIT

rotating



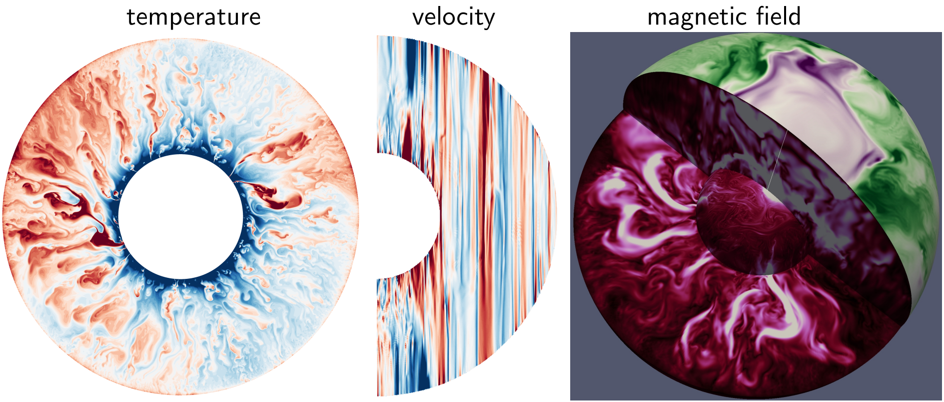
rapidly rotating convection



experiment in water (courtesy : P. Cardin)

state of the art numerical simulations

Schaeffer et al (2017)



+ Earth-like morphology (mainly dipolar field)
+ produces polarity reversals

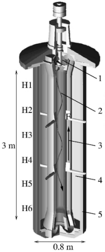
- still too dissipative !
- do not yet mimic rapid variations
- the closer to Earth's parameters, the less reversals occur...

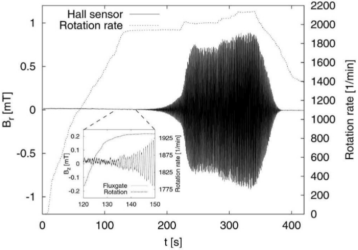
alternative : laboratory experiments

- very hard : magnetic field diffuses 10^5 times faster than momentum !
- necessary condition : $R_m = UL/\eta > O(10)$
  take $L = 1$ m, with best available $\eta \simeq 1$ m^2/s (liquid sodium)

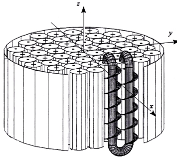
$\Rightarrow$ $U \simeq 10$m/s ! !

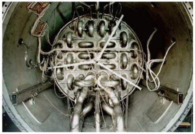
Riga (Gailitis et al, 1999)





Karlsruhe (Müller et al, 1999)

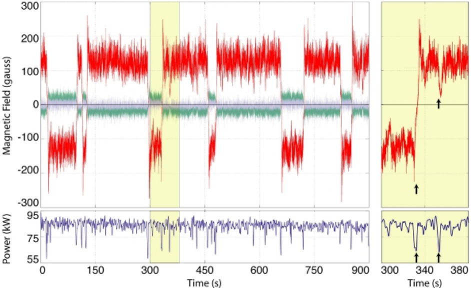




+ realistic physical parameters : turbulent motions
- no global rotation
- strongly constrained flow
- weak field intensity
  weak feed-back from the Lorentz force

Von Karman Sodium experiment

Cadarache, 2006 (CEA Saclay, ENS Paris & Lyon)

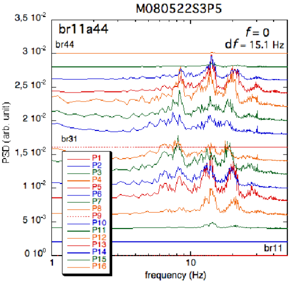


- less constrained flow
- complex dynamical regimes : inversions, intermittence...
- but ! requires ferromagnetic propellers to enhance induction !
  (not properly speaking a dynamo)

Derviche Tourneur Sodium experiment

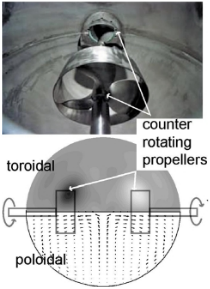
ISTerre, Grenoble

- rapidly rotating sphere
- rotating inner sphere (Couette flow)
- imposed magnetic field (this is not a dynamo)
- isolated waves and turbulent effects (help understand fundamental physical processes)



other running experiments

Madison (Forest et al)



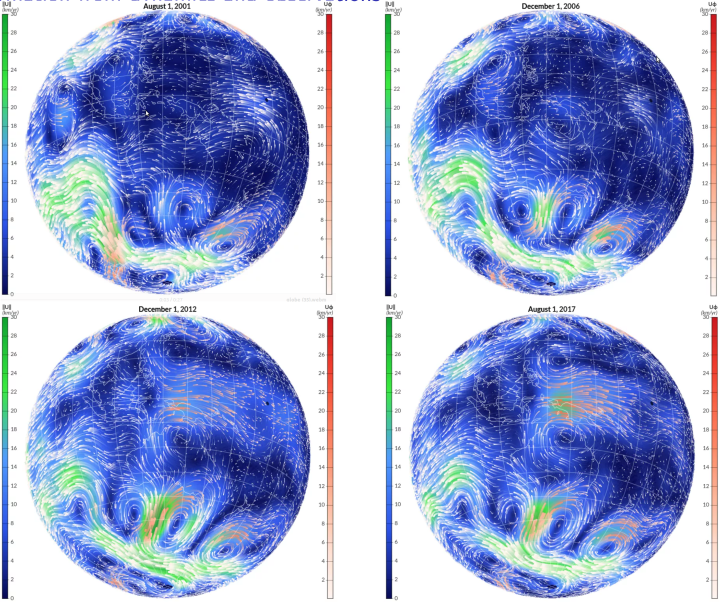
- 1 m diameter sphere (plasma)
- contra-rotating propellers (like VKS)
- no dynamo yet, transient induced field observed

Maryland (Lathrop et al)

- 3 m diameter rotating sphere filled with sodium ! !
- rotating inner sphere (Couette flow, like DTS)
- induced fields, but no dynamo observed
- currently modify the inner sphere roughness

towards an outer core meteorology...

mixing information from dynamics and observations

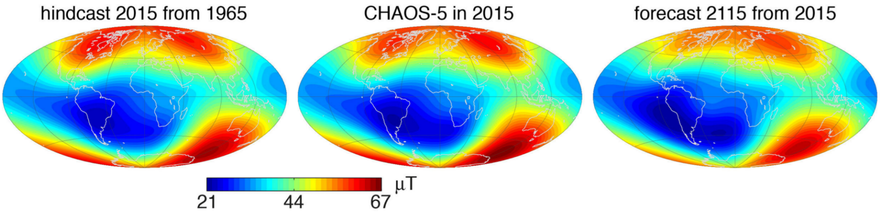


addapted from Barrois et al (2017)

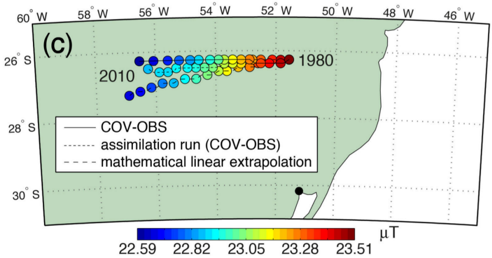
predictions for the South Atlantic Anomaly

from geodynamo models 'driven' by observations (Aubert, 2015)

- field intensity at the Earth's surface



- central position of the SAA

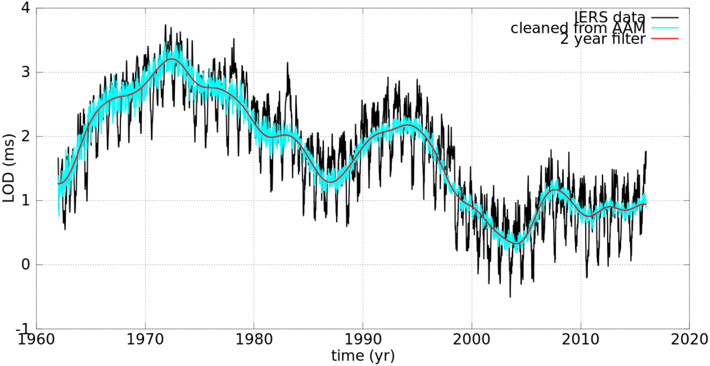


- on its way... still many progresses to do
- improve models of core turbulence (small length-scales)

length-of-day changes

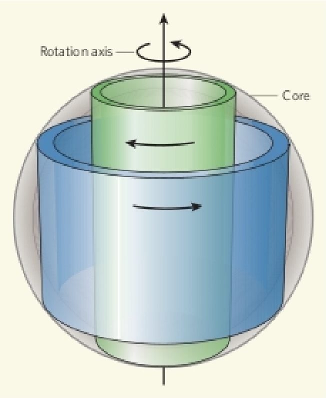
VLBI station (credit : USNO)

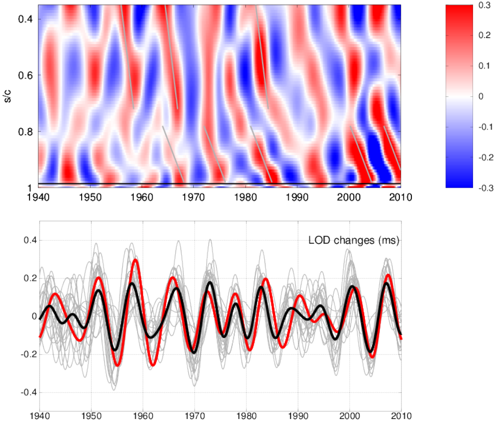
- angular momentum changes of the system core + mantle + atmosphere...
  - rapid variations : atmospheric winds
  - slow changes : core motions (Jault, 1988)



diving into the core with torsional Alfvén waves

1st described theoretically by Braginski in 1970





(Gillet et al, 2015)

- compare geodetic (observed) length-of-day changes with predictions from core flows (reconstructed from magnetic records)
- explain independent data with waves crossing the core in 4 yrs

$\Rightarrow$ the magnetic field in the core (invisible directly) must be at least 3 mT, 10 times stronger than at the core surface !

Outlines

a geophysical introduction to deep Earth

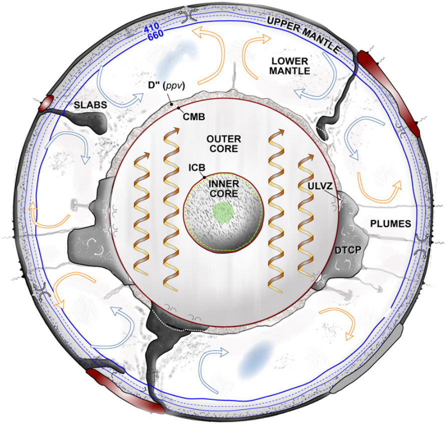
the geomagnetic field, signature of a moving core

dynamics of the core, and insights from observations

discussion

the Earth, a thermodynamic machinery (1)

- heat extraction from the core controlled by mantle convection
  - … characteristic times : 200–500 million years
- … possibly controles core dynamics ?
- … signature in magnetized rocks ? (see changes in the rate of polarity reversals)



courtesy : E. Garnero

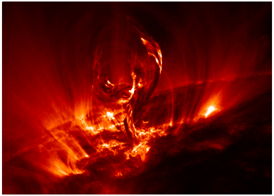
control mantle ⟶ magnetic field

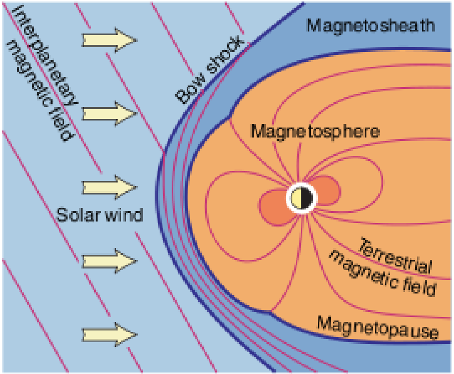
the Earth, a thermodynamic machinery (2)

- solar wind interaction with the Earth's dynamo field
- NB : the Earth's field...
  - does not properly speaking 'protects' from high energy particules
  - but modulates the Sun-Earth interaction

... atmospheric erosion slown down ?

- ... modulates mantle chemistry ?
  - e.g. recycling of water in the mantle
- ... decrease of the mantle viscosity
- ... affects the mantle convection

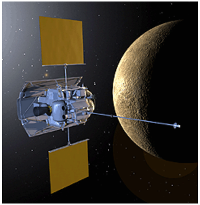




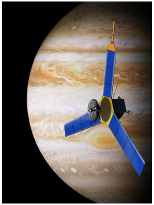
controle magnetic field $\longrightarrow$ mantle

the zoo of planetary dynamos : exploration

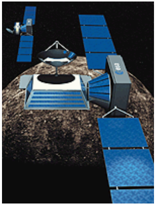
- *Pioneer* : Jupiter (1973)
- *Mariner* : Mercury (1975)
  no field detected on Venus !
- *Voyager* : Jupiter (1979), Saturn (1980), Uranus (1986), Neptune (1989)
- *Galileo* : Jupiter (1995) and its moons (Ganymede, Io, Calisto)
- *Mars Global Surveyor* (1997)
  dead dynamo on Mars !



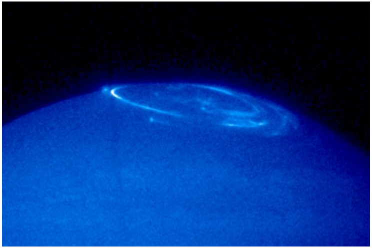
Messenger
Mercury
2007...

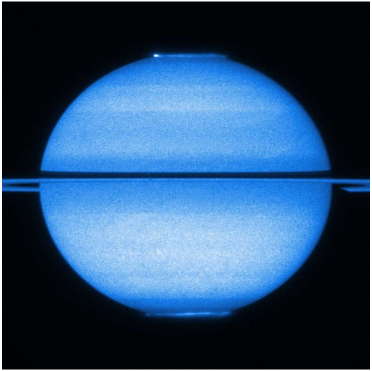


Juno
Jupiter
2016



Bepi-Colombo
Mercury
2019

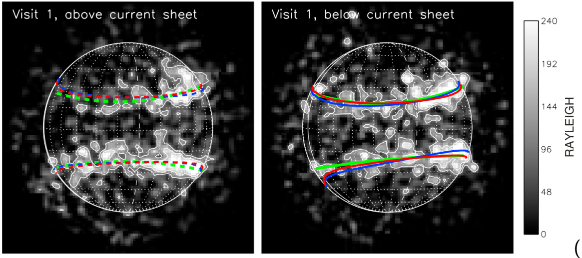




auroras on Jupiter and Saturn

the zoo of terrestrial dynamos : so many questions

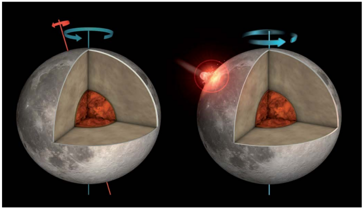
- why Venus seems to have no dynamo ?
  - similar to the Earth (in size and rotation rate)
  - apparently no mantle convection ? different mantle rheology ?
- why is Mercury's field so weak ?
  - small planet but relatively large core
  - different forcing ? (2 rotations in 3 revolution... strong tides)
- how Ganymede does sustain its dynamo ?
  - small planet, and our Moon has lost its dynamo long ago
  - other forcing, e.g. Jovian's tides ?

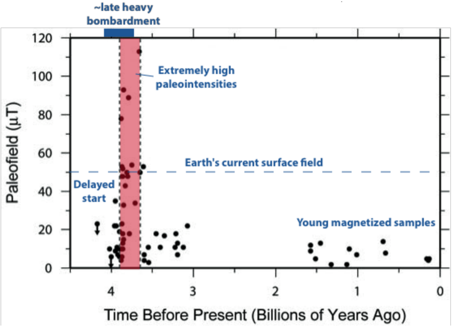


(Saur et al, 2014)

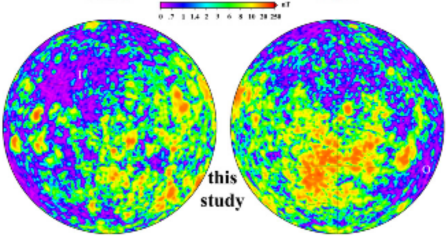
the Lunar dynamo

- unlikely of convective origin
- dynamo energy from impacts, precession ?
- very large field during its dynamo era, why ?





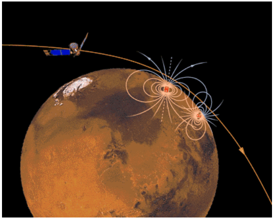
(wieczorek et al, 2006)

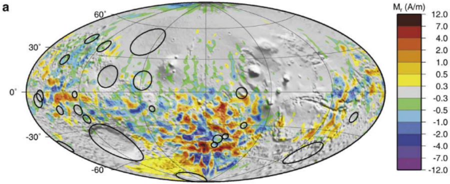


(Purucker, 2008)

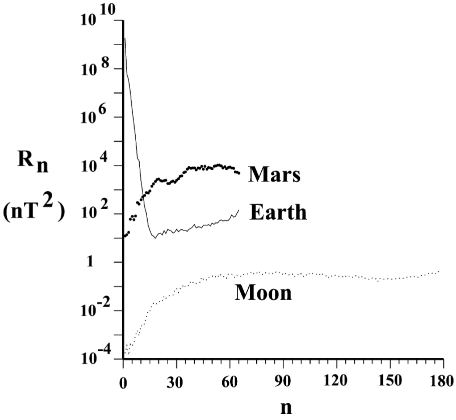
Mars' dynamo

- why is Mars's crustal field so intense ?
- has the core frozen too fast ? (smaller planet)

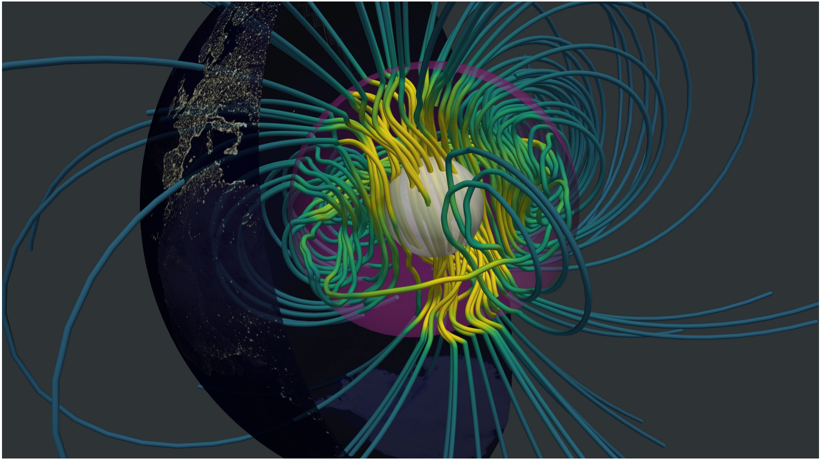




(Langlais et al, 2003)



(Purucker et al, 2008)



Thank you !