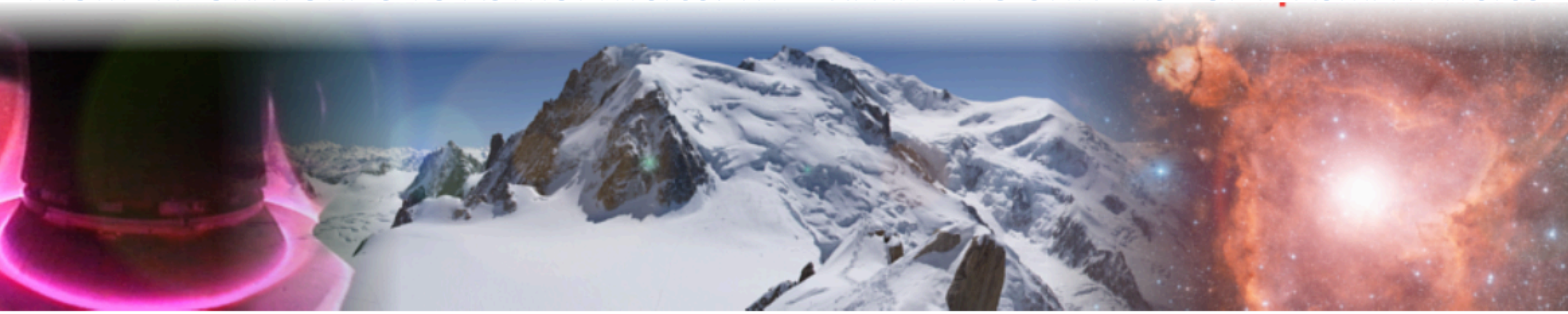
ÉCOLE DE PHYSIQUE des HOUCHES

UNIVERSITÉ Grenoble Alpes

FROM LABORATORIES TO ASTROPHYSICS: THE EXPANDING UNIVERSE OF PLASMA PHYSICS



Natural dynamos

Henri-Claude NATAF

ISTerre, Univ. Grenoble Alpes / CNRS

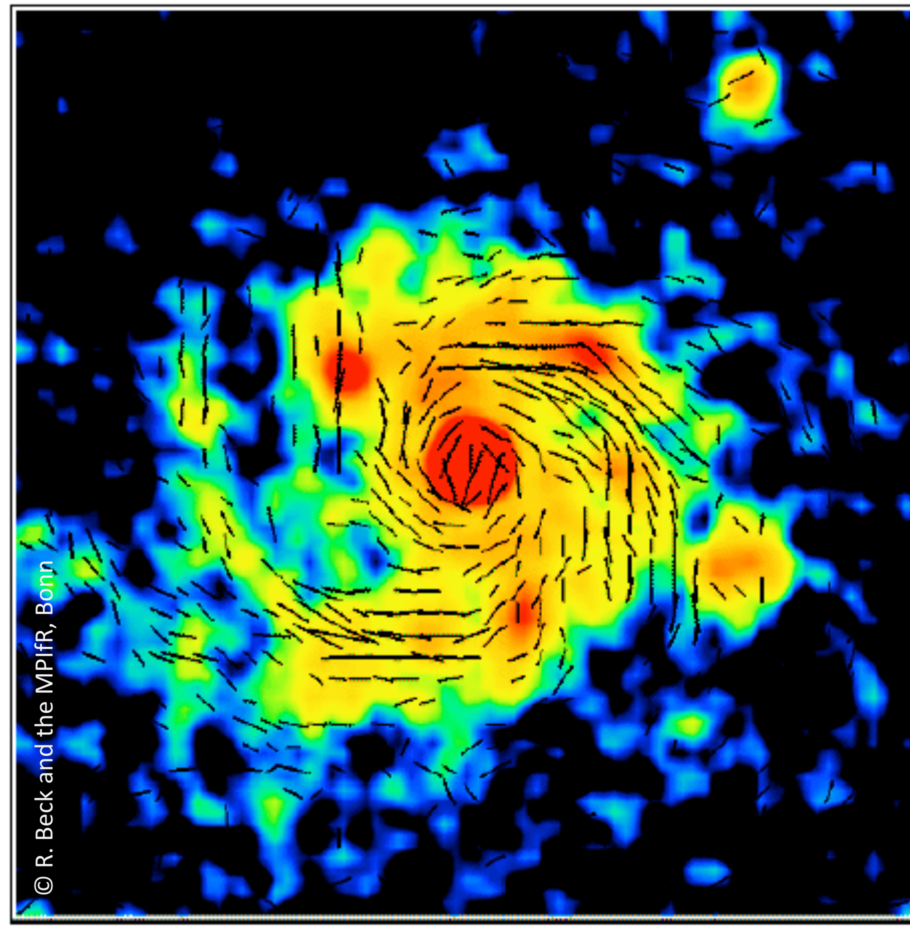
overview

- Dynamos all around!
- A tour of the solar system
- Back on Earth
  - Time-variation of the magnetic field
  - Mechanisms at work
  - A dive into the Earth's core
  - Exploring a geodynamo simulation

Dynamos all around!

- Galaxies and stars generate a magnetic field.

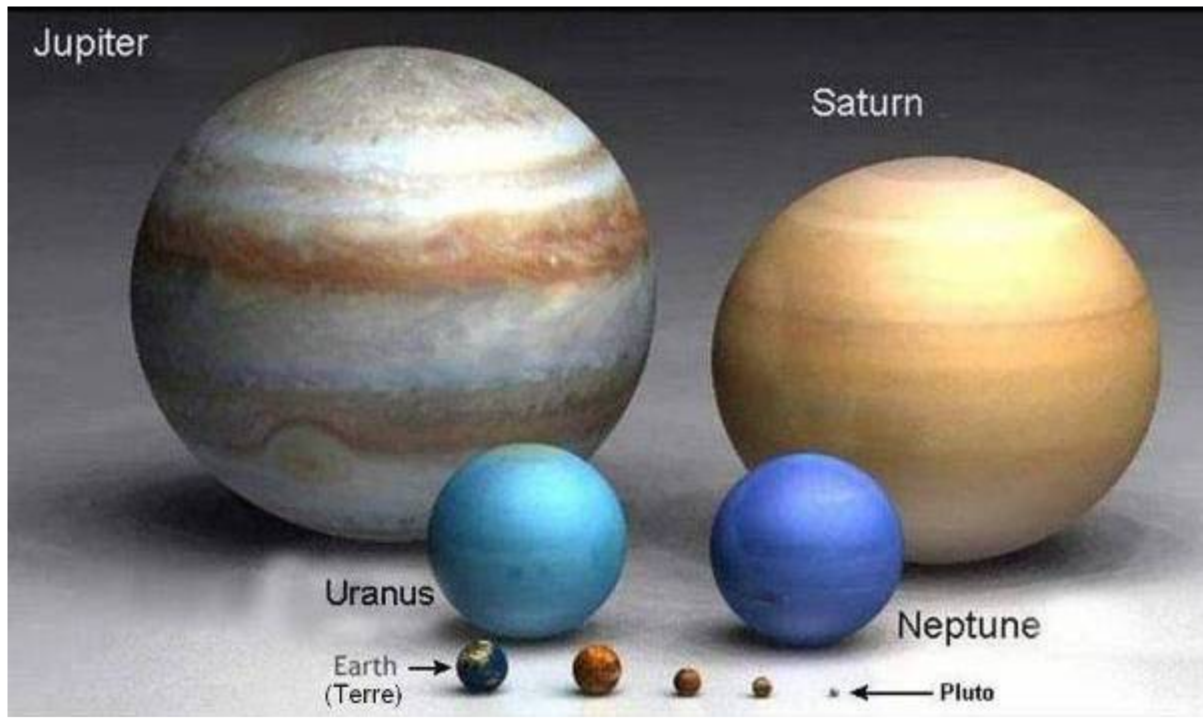
Dynamos all around!



from Fletcher, 2011

Dynamos all around!

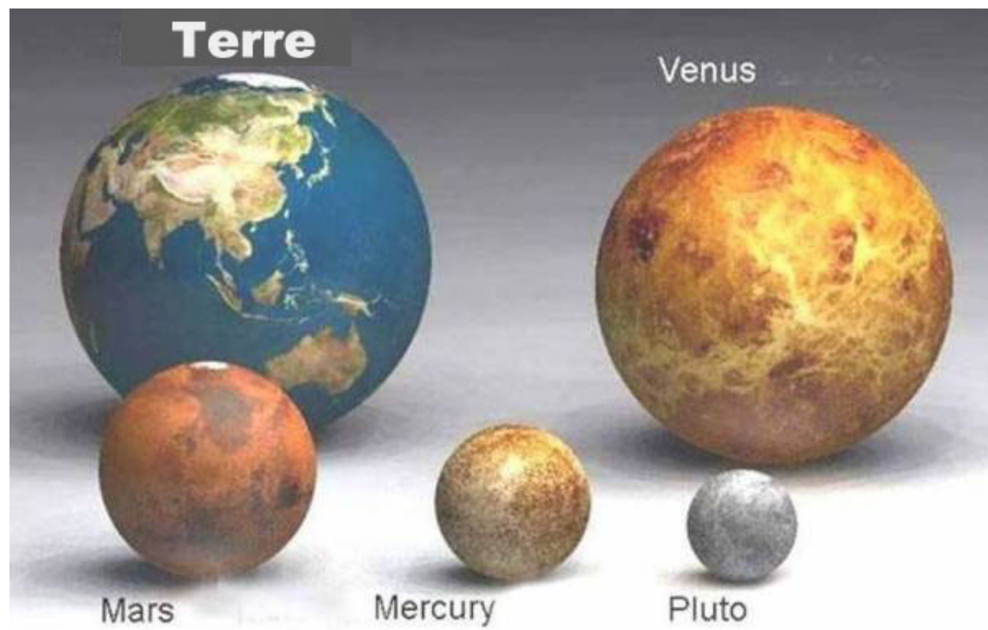
- Most planets* have or have had a dynamo-generated magnetic field:
  - ✓ Gas giants
  - ✓ Ice giants



*in the solar system

Dynamos all around!

- Most planets* have or have had a dynamo-generated magnetic field:
  - ✓ Gas giants
  - ✓ Ice giants
  - ✓ Terrestrial planets
  - + Several satellites



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*in the solar system

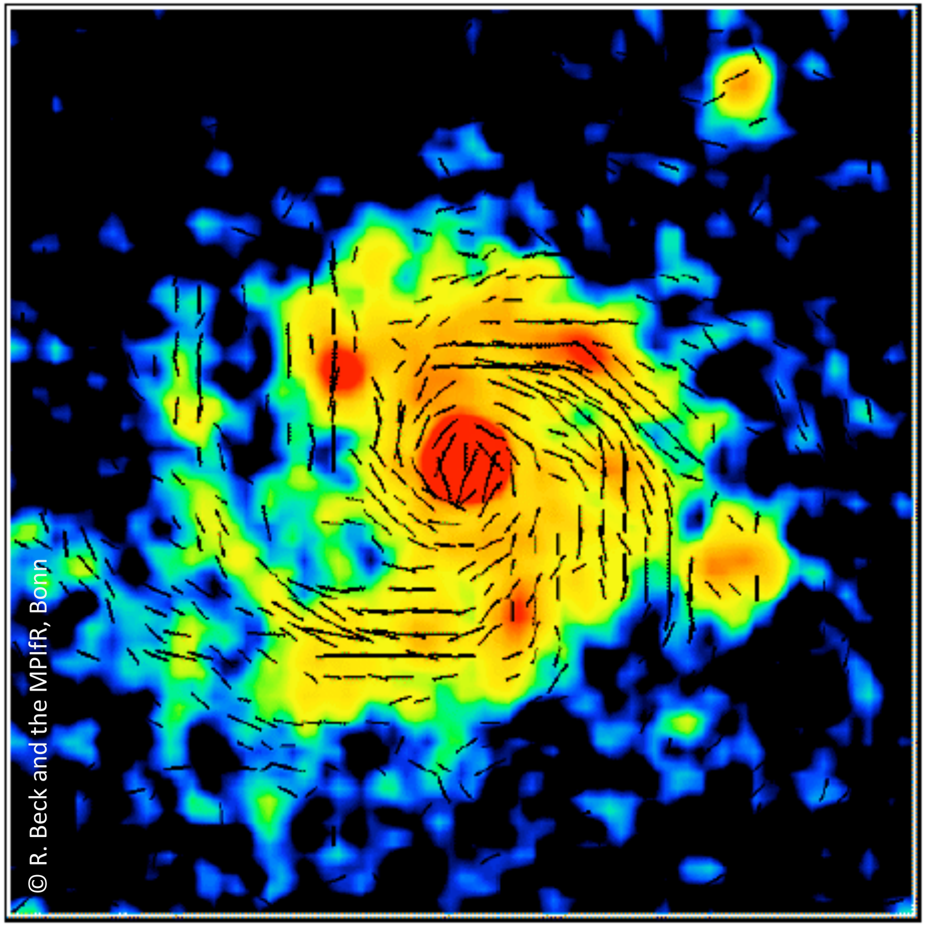
Dynamos all around!

- Different conductive fluids:
  - Plasmas
  - Metallic hydrogen ($\eta \sim 1\ m^2/s$)
  - Ionic water ($\eta \sim 100\ m^2/s$)
  - Metallic iron ($\eta \sim 1\ m^2/s$)
- Different energy sources:
  - Internal heat
  - Mechanical forcing
- Different dynamo mechanisms.

Galactic dynamos

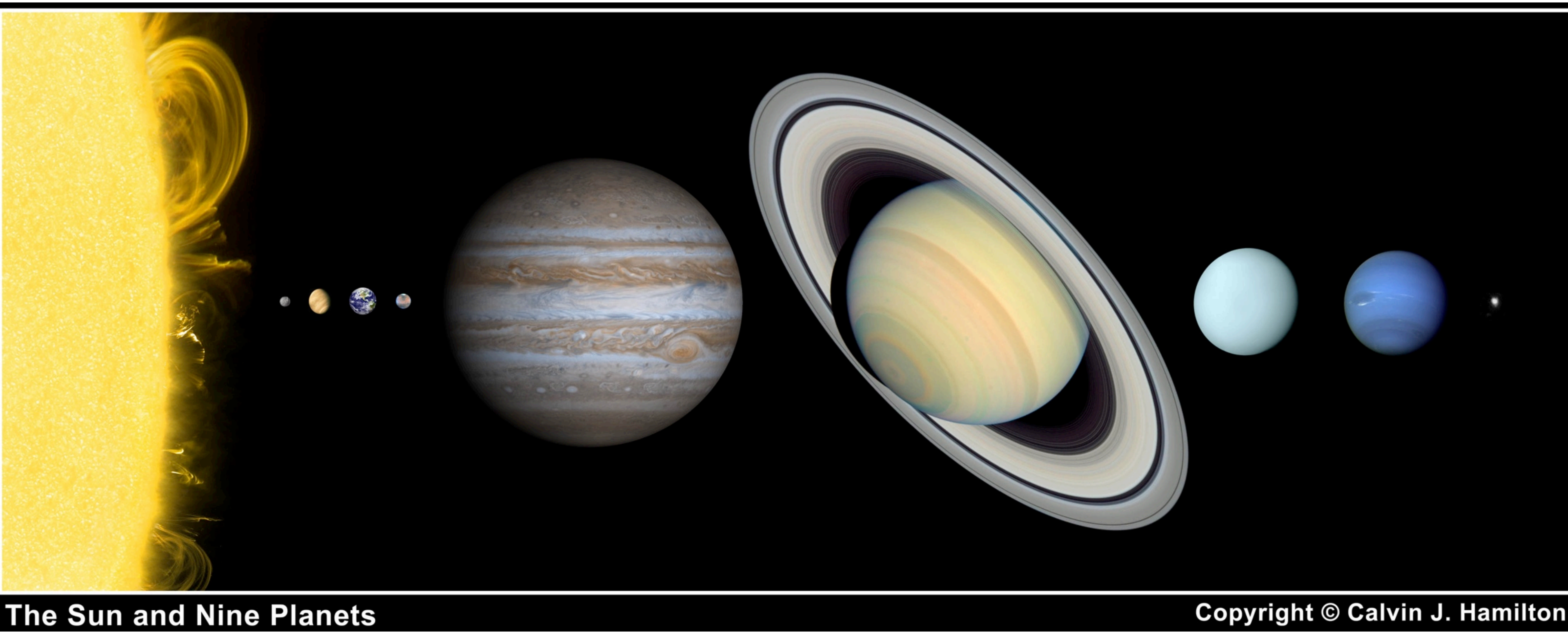
Fluid: plasma
B ~ 1 nT
Power: super-nova
mechanism: αω ?

Reversals: ?
Observation: ~100 galaxies



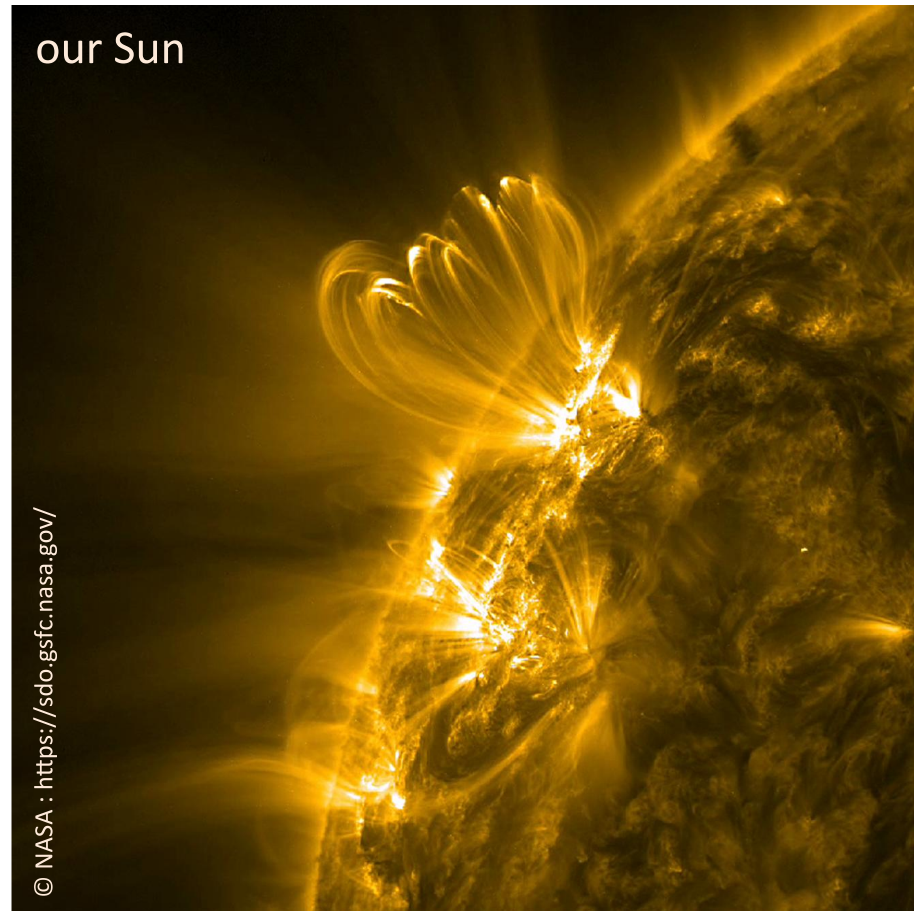
from Fletcher, 2011

A tour of the solar system

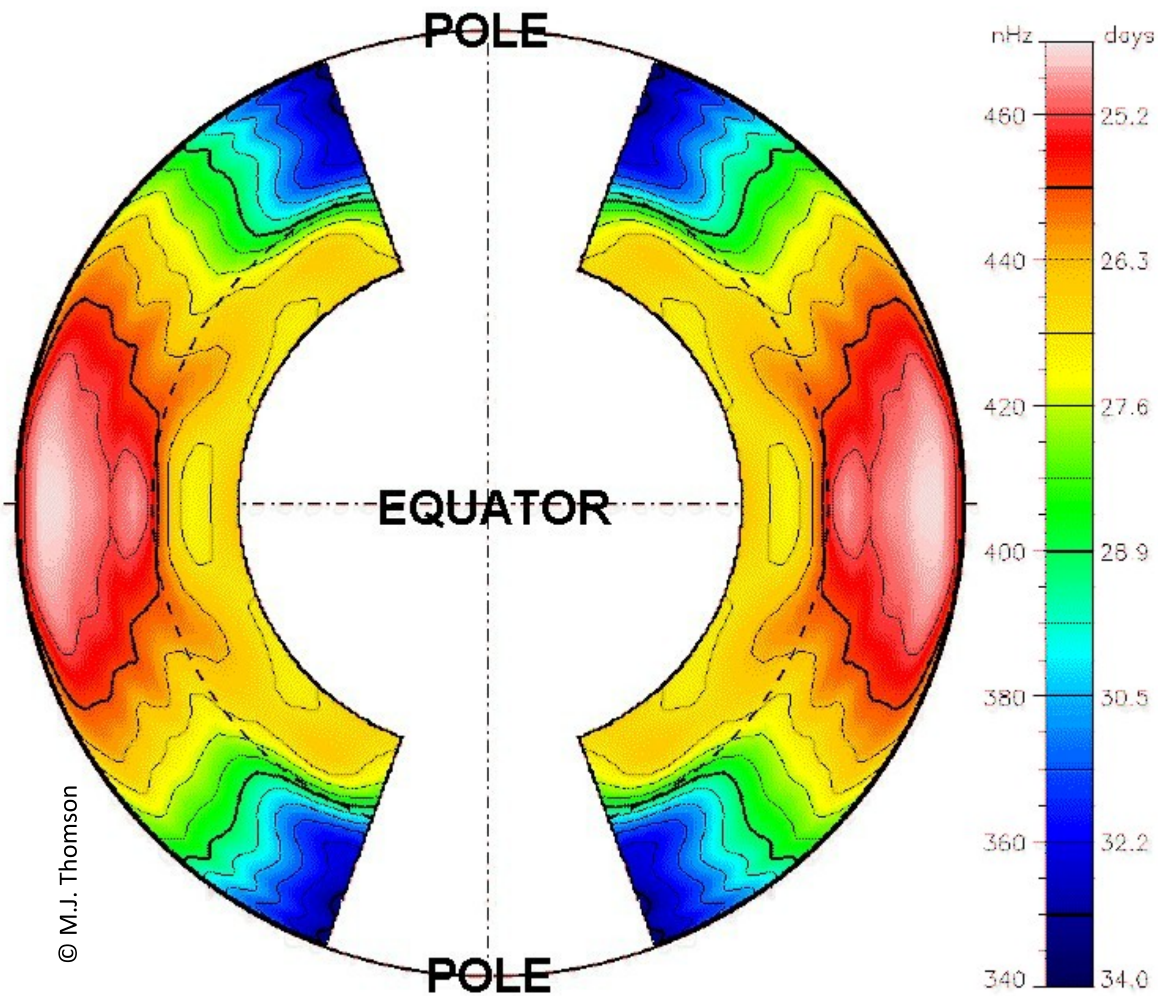


The Sun

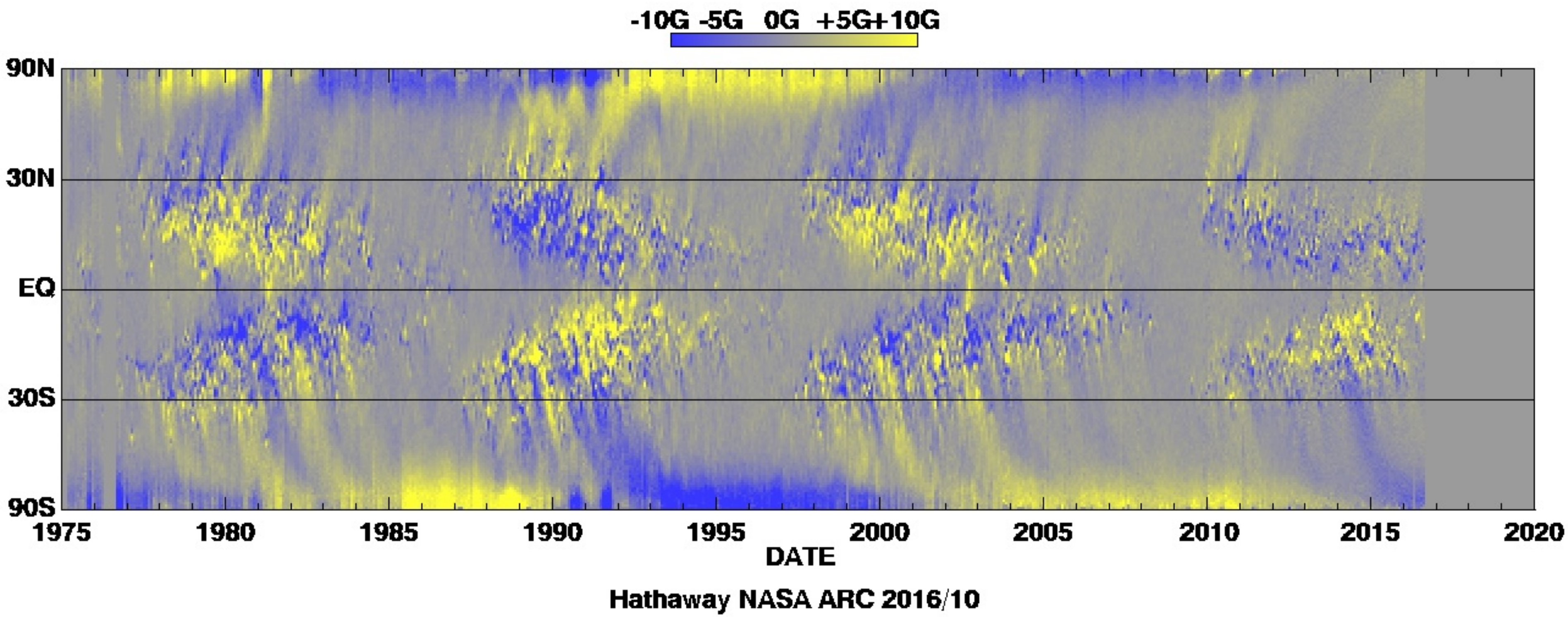
Fluid: plasma
B ~ 1-10^3 mT
Power: ~200 μW/kg
Mechanism: αω ?
Depth: shallow
Dipole + toroidal
Reversals: cyclic
Observation: ~400 y



The Sun

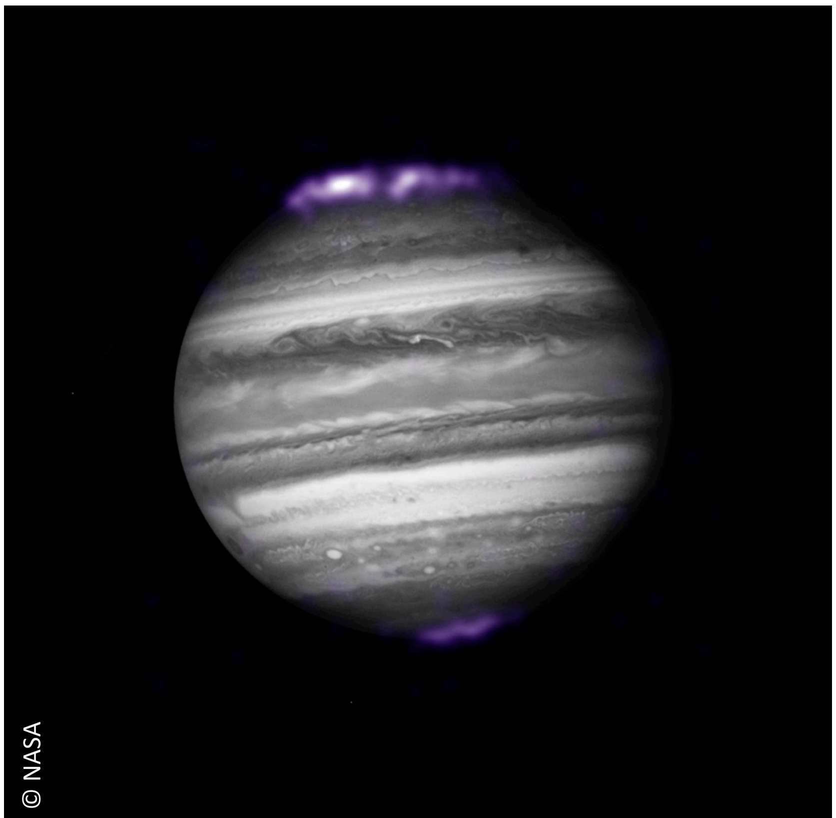

POLE
EQUATOR
POLE
nHz
days
460
25.2
440
26.3
420
27.6
400
28.9
380
30.5
360
32.2
340
34.0

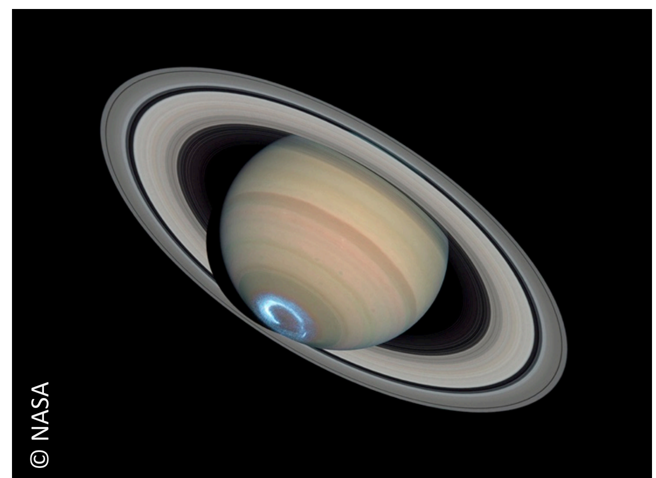
The Sun



https://solarscience.msfc.nasa.gov/dynamo.shtml

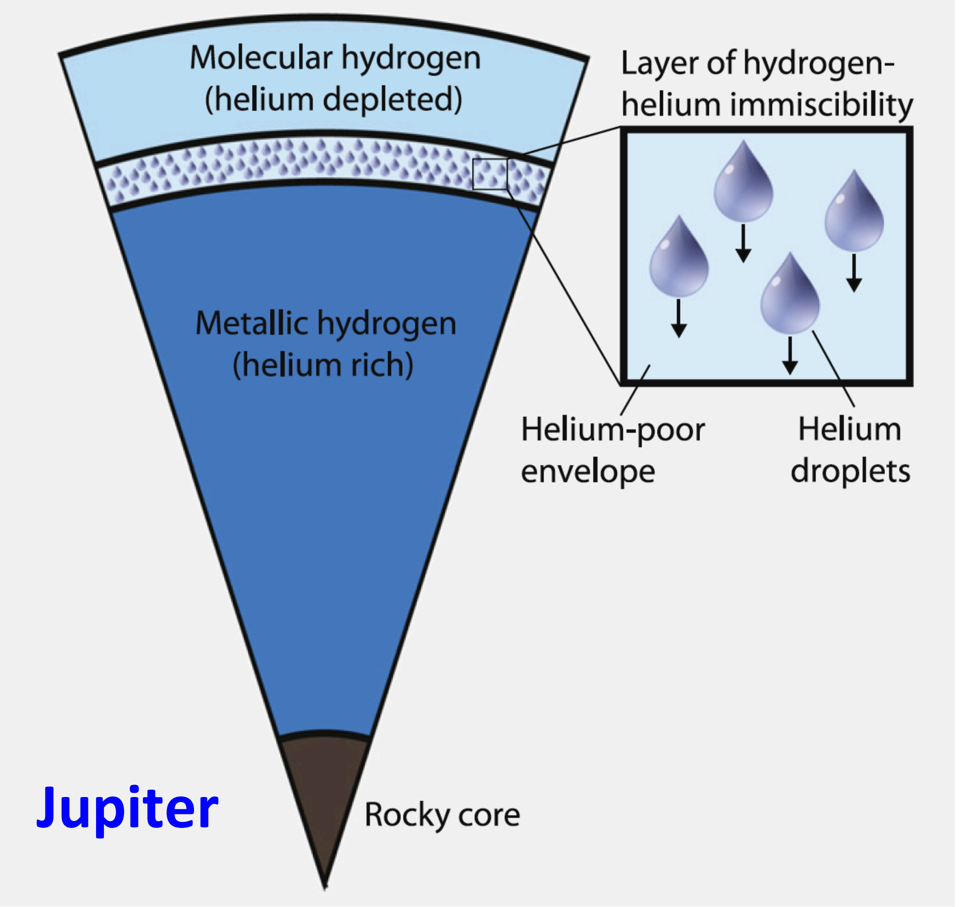
Jupiter and Saturn





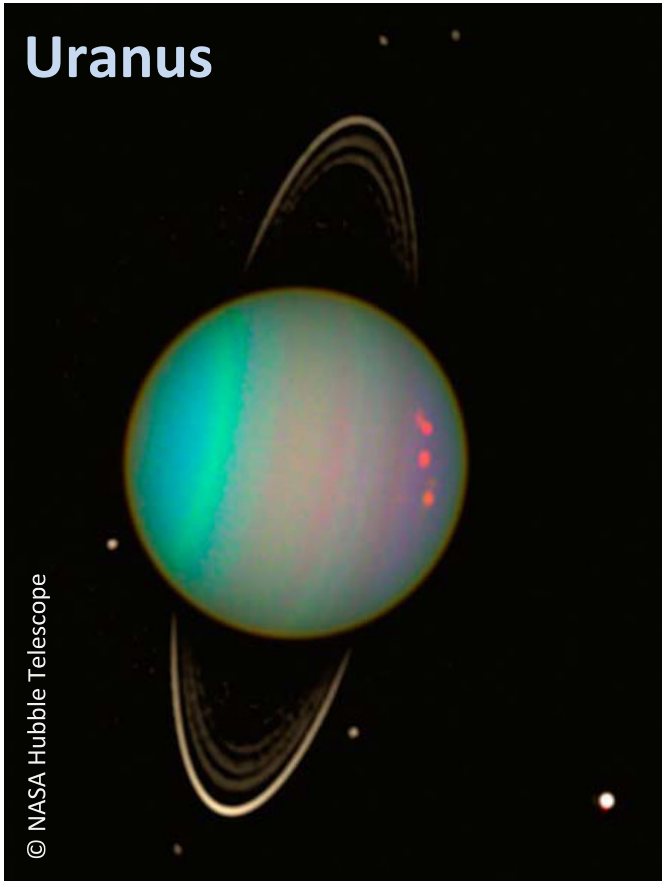
Jupiter and Saturn

Fluid: metallic hydrogen
B ~ 1.5 mT
Power: ~200 pW/kg
Mechanism:
Depth: deep
Dipole
Reversals: ?
Observation: 50 y



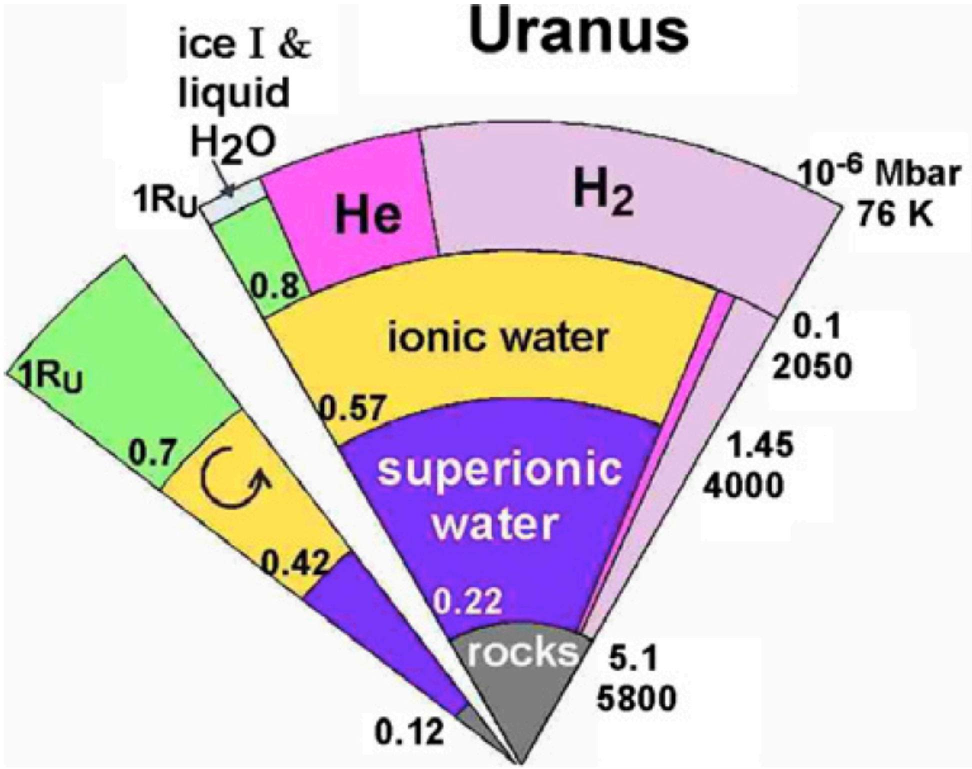
Hubbard & Militzer, 2016

Uranus and Neptune



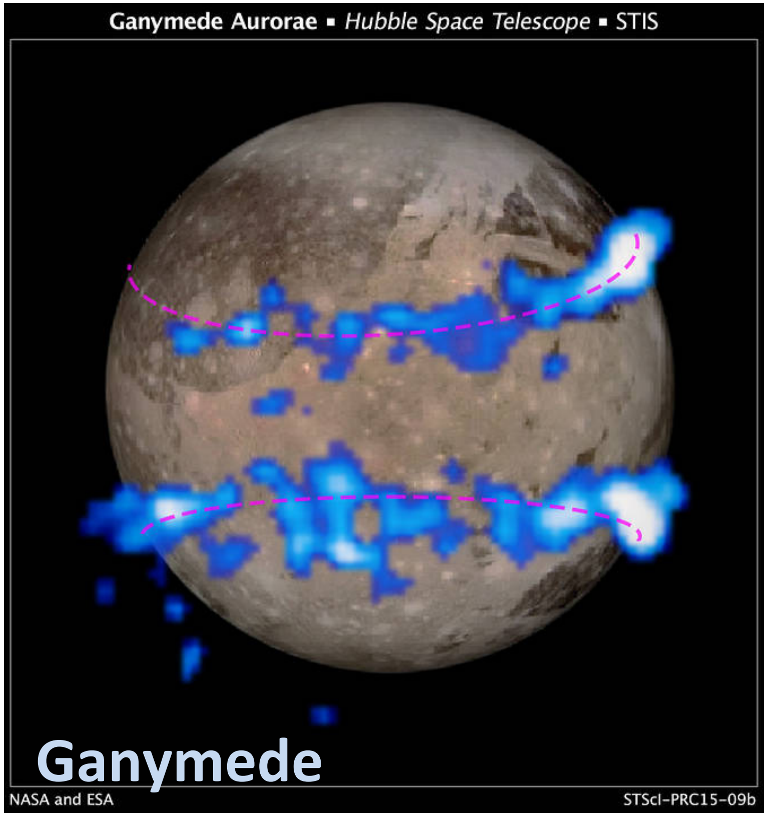
Uranus and Neptune

Fluid: ionic water
B ~ 0.1 mT
Power: ~? pW/kg
Mechanism:
Depth: intermediate
Non-dipole
Reversals: ?
Observation: 50 y



Redmer et al, 2011

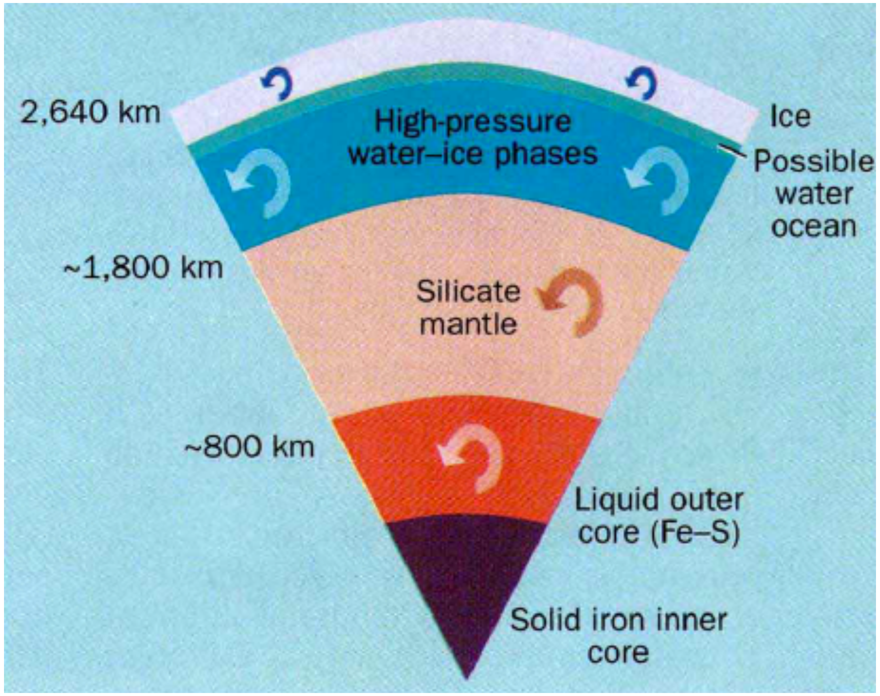
Ganymede



Saur et al, 2015

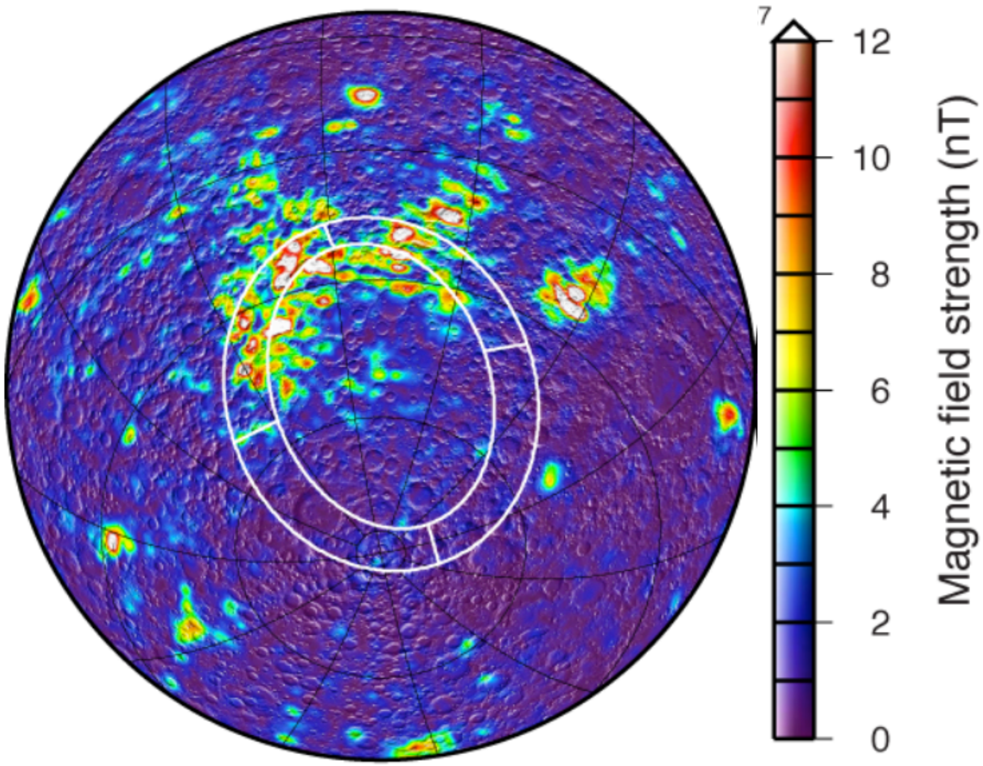
Ganymede

Fluid: metallic liquid iron
B ~ 0.01 mT
Power: ?
Mechanism:
Depth: deep
Dipole
Reversals: ?
Observation: 30 y



Stevenson, 1996

the Moon



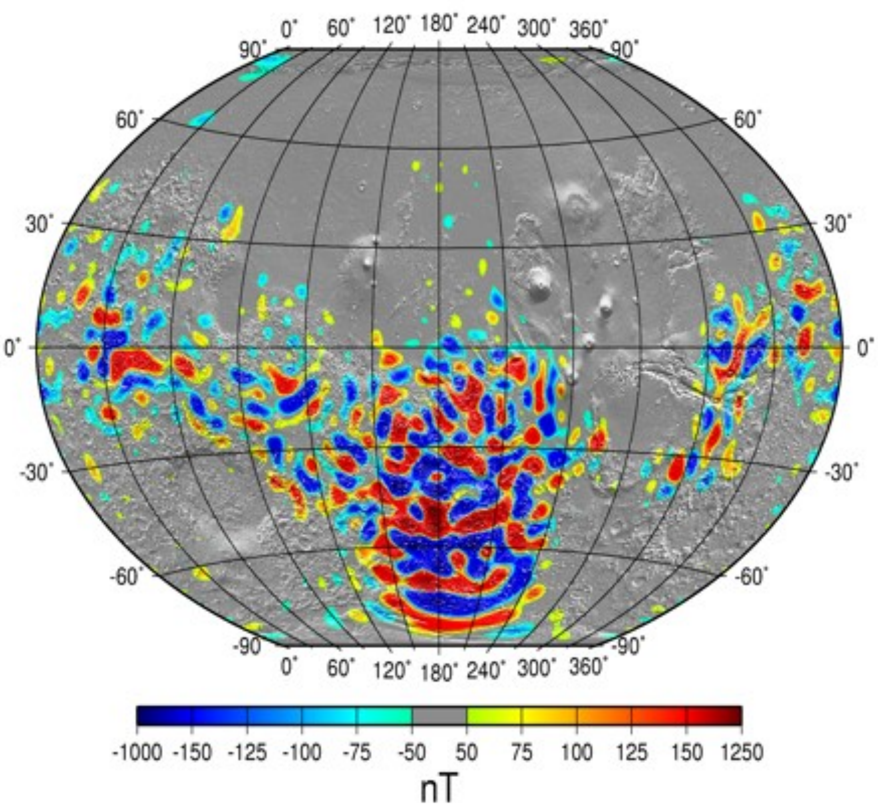
Fluid: metallic liquid iron
B ~ 1 μT
Power: impact or tides?
Mechanism: inertial turbulence
Depth: very deep
Dipole ?
Reversals ?
Observation: fossil 4 Gy !

Magnetic anomalies near the South Pole-Aitken basin

Wieczorek

Mars

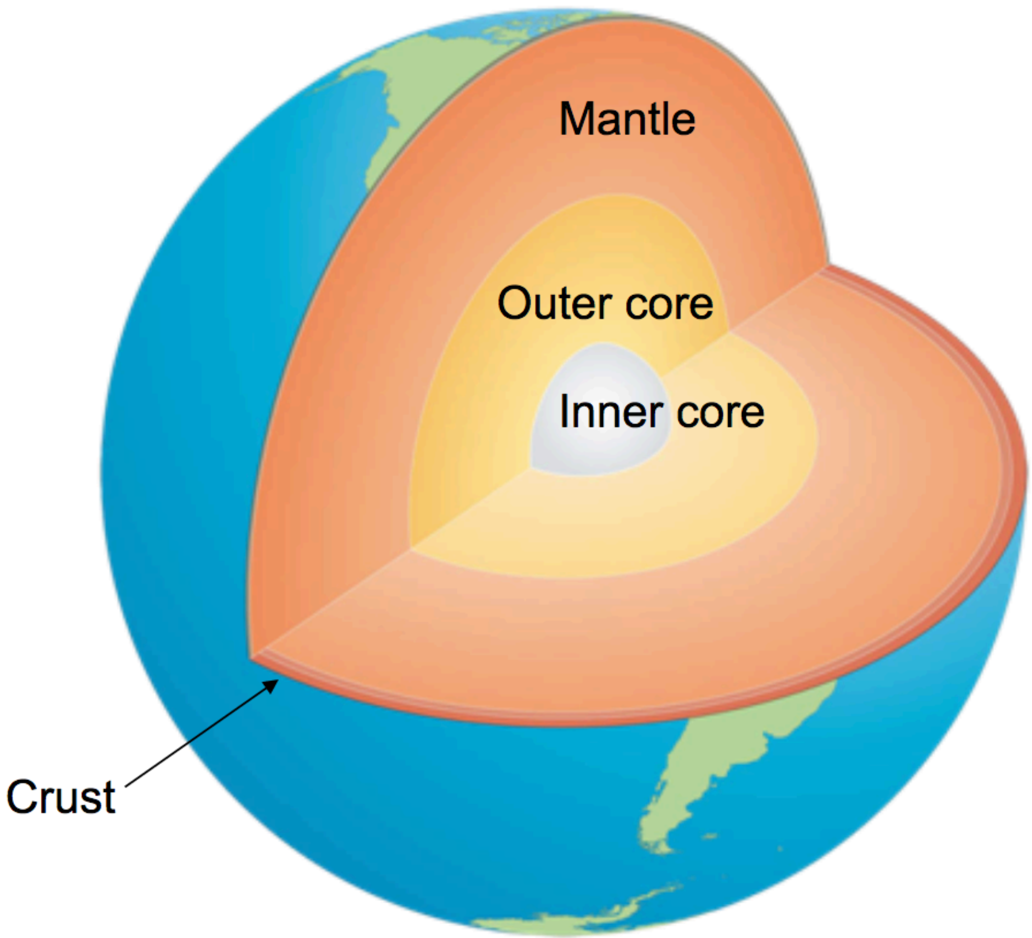
Radial magnetic field



Fluid: metallic liquid iron
B ~ 1 mT ?
Power: ~ ? pW/kg
Mechanism: ?
Depth: deep
Dipole ?
Reversals ?
Observation: fossil 4 Gy !

Back on Earth

Back on Earth



Fluid: metallic liquid iron
B ~ 0.05 mT
Power: ~6 pW/kg
Mechanism: see below…
Depth: deep
Dipole
Reversals: chaotic
Observation: 400 y and 400 My (3450 My ?)

Time-variation of the magnetic field

Magnetic declination at Paris since 1540

358 M. Alexandrescu et al. / Physics of the Earth and Planetary Interiors 98 (1996) 321–360

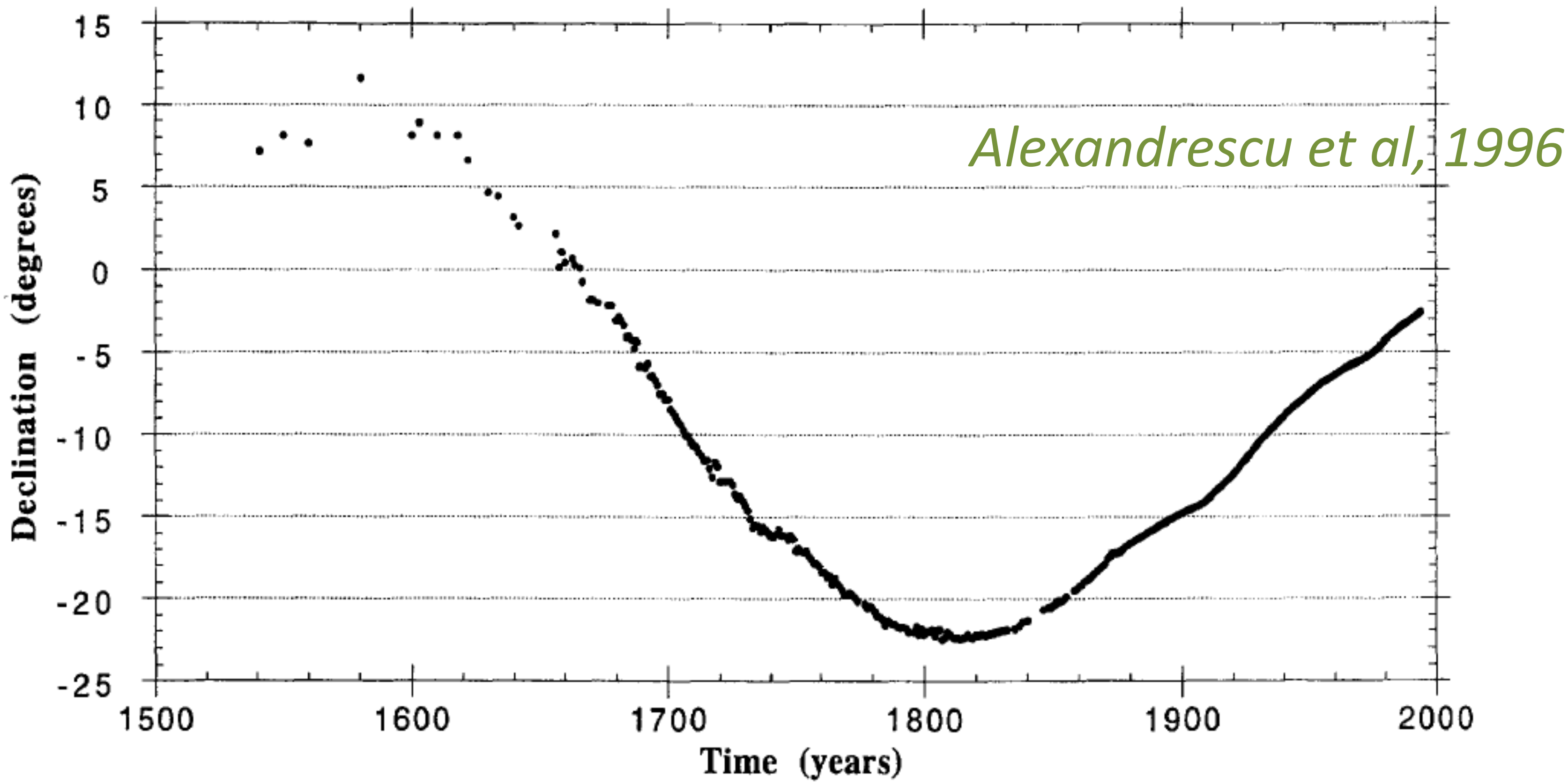


Fig. 10. Annual mean values of declination, 1541–1994, reduced to the Chambon-la-Forêt observatory.

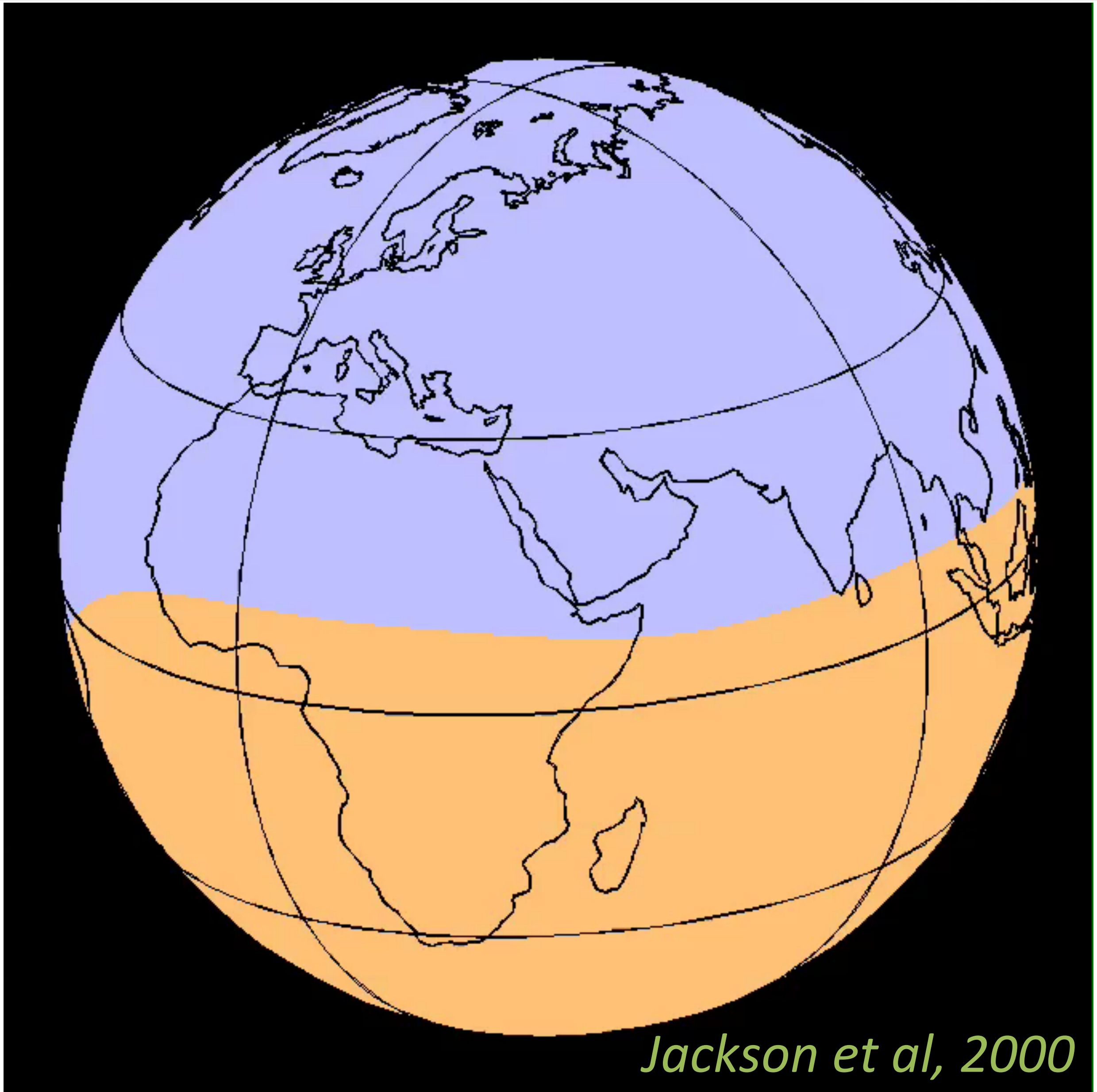
Downward continuation to the core-mantle boundary

- Considering the Earth's mantle as insulating, the rotational of the magnetic field vanishes and **B** derives from a scalar potential *V*:

  $\mathbf{B} = -\nabla V$ such that $\nabla^2 V = 0$

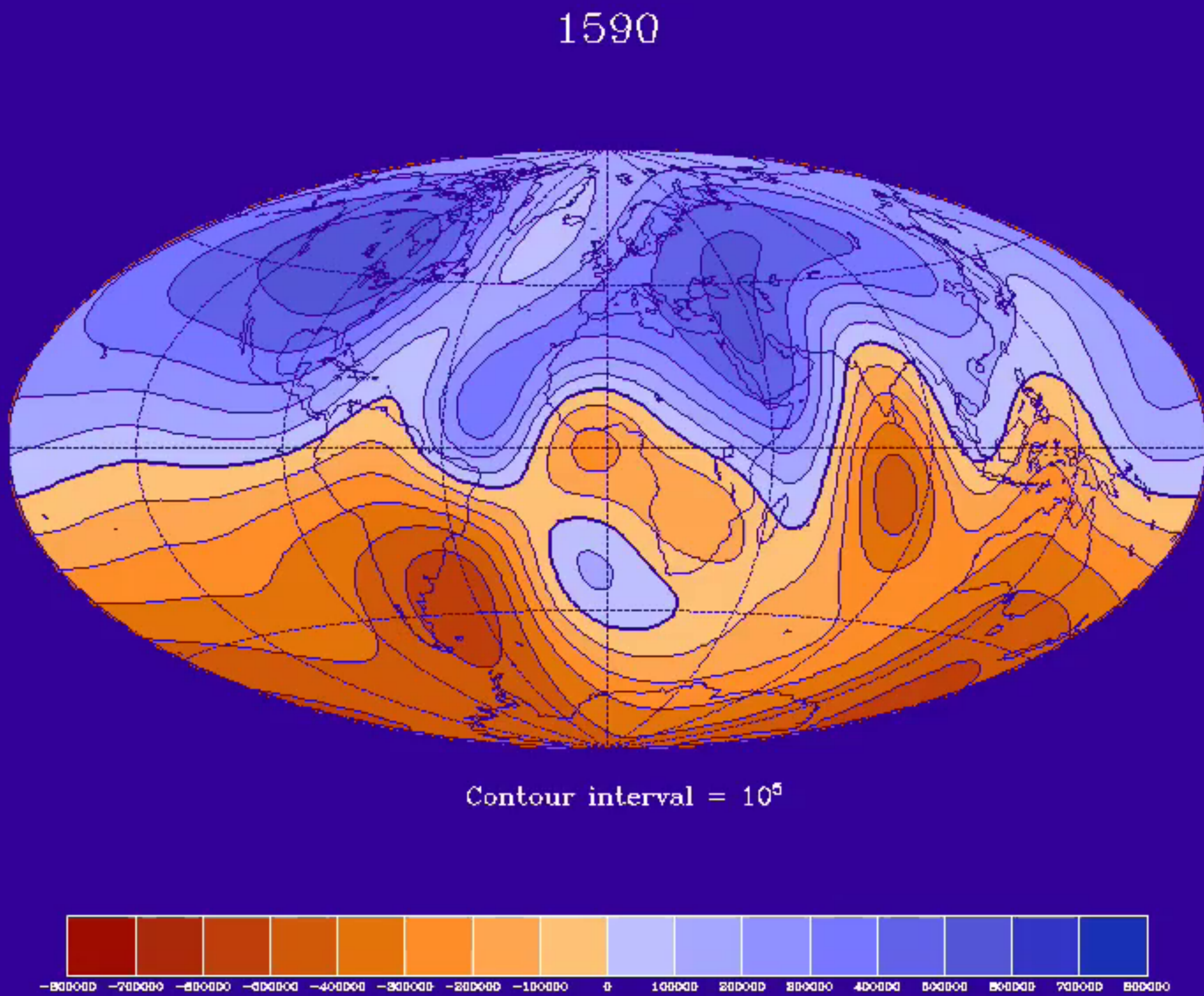
- In spherical geometry, the solutions of the Laplace equation are the spherical harmonics, yielding: $$V(r,\theta,\phi) = \sum_{l=1}^{\infty} \sum_{m=-l}^{l} c_l^m \left(\frac{r_p}{r}\right)^{l+1} Y_l^m(\theta,\phi)$$

http://jupiter.ethz.ch/~cfinlay/gufm1.html

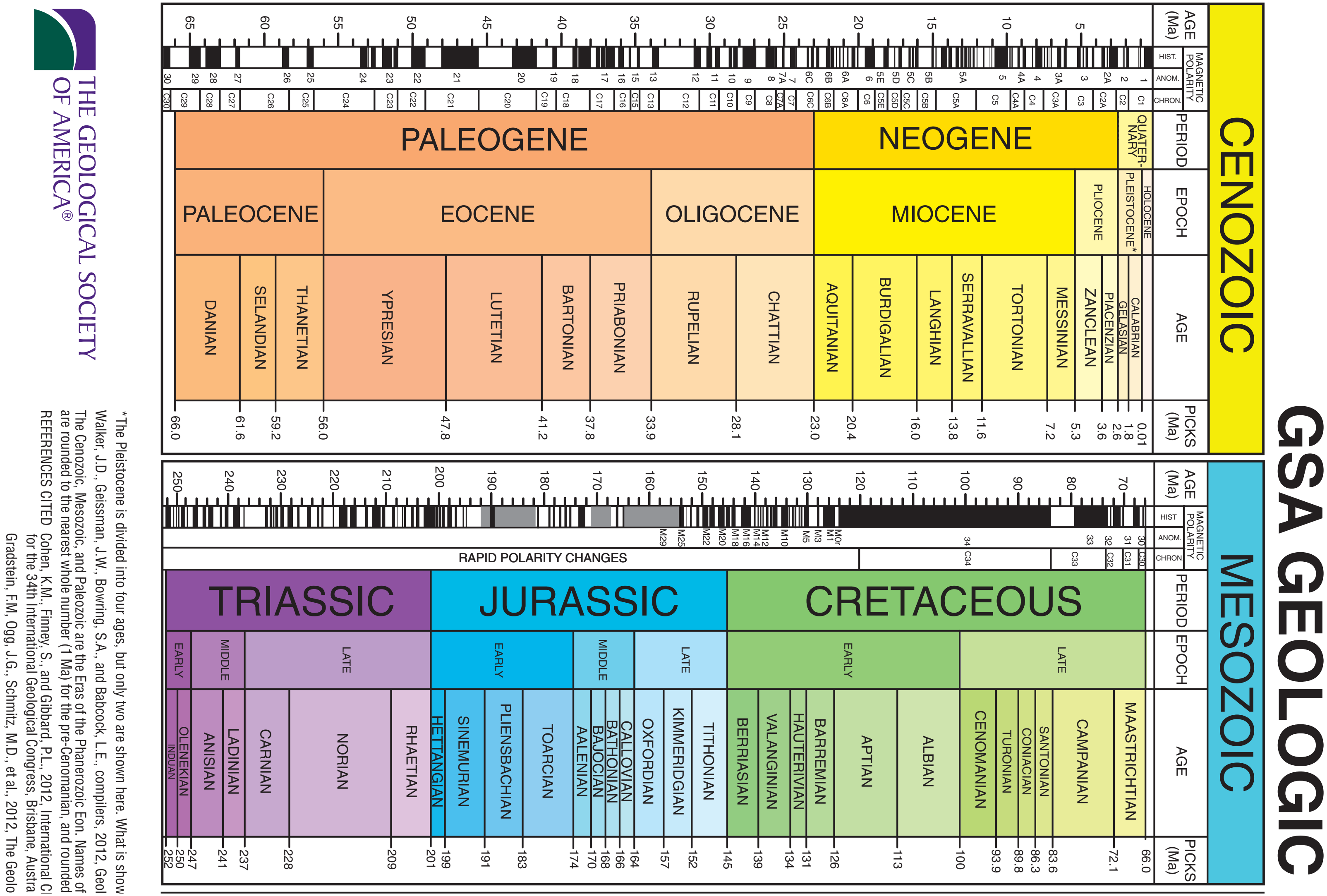


Jackson et al, 2000

Jackson et al, 2000



Magnetic reversals


GSA GEOLOGIC
THE GEOLOGICAL SOCIETY OF AMERICA®
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MESOZOIC
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HIST.
ANOM.
CHRON.
PERIOD
EPOCH
AGE
PICKS (Ma)
PALEOGENE
NEOGENE
QUATER-NARY
PALEOCENE
EOCENE
OLIGOCENE
MIOCENE
PLIOCENE
PLEISTOCENE*
HOLOCENE
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SELANDIAN
THANETIAN
YPRESIAN
LUTETIAN
BARTONIAN
PRIABONIAN
RUPELIAN
CHATTIAN
AQUITANIAN
BURDIGALIAN
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RAPID POLARITY CHANGES
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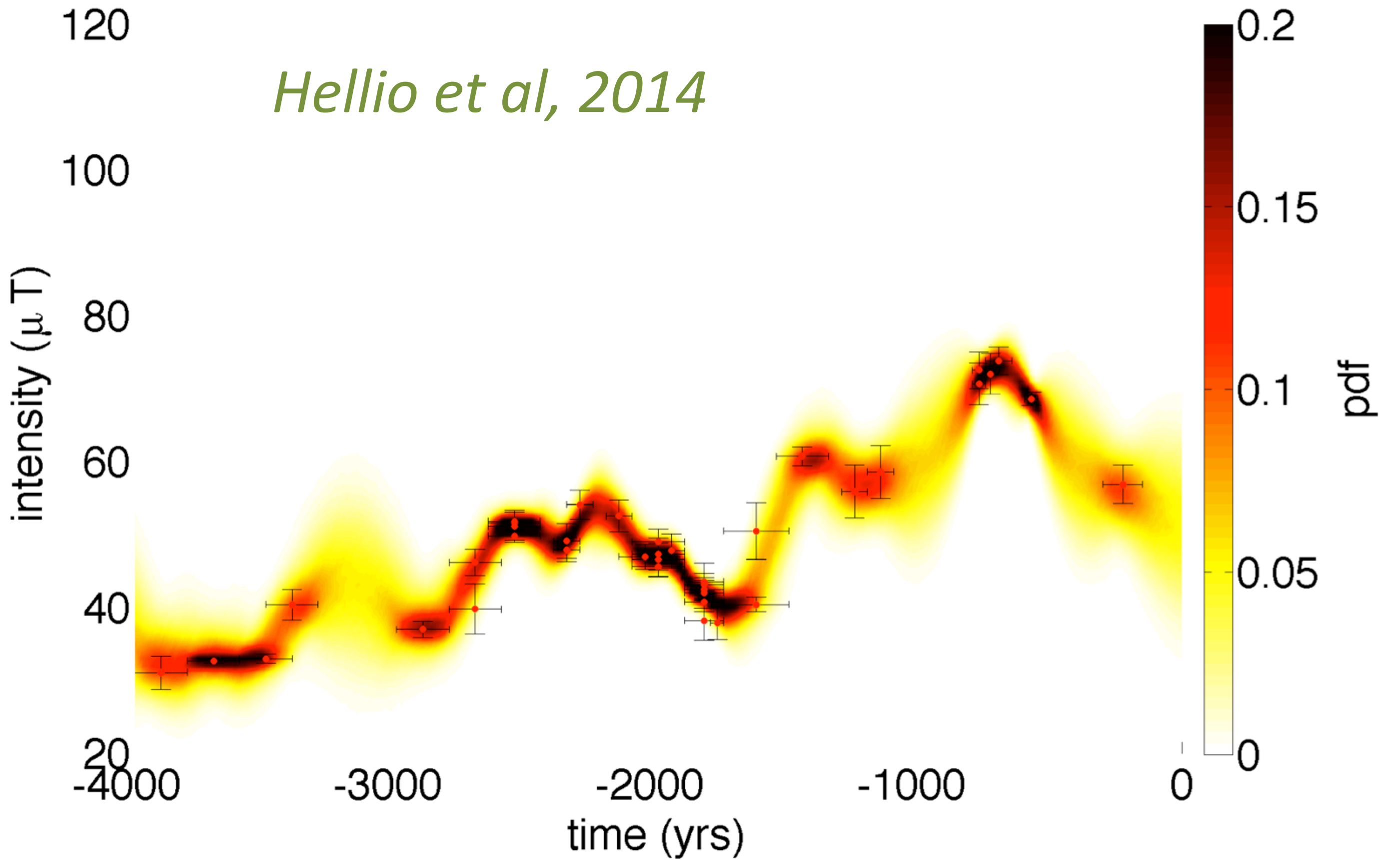
89.8
86.3
83.6
72.1
66.0
*The Pleistocene is divided into four ages, but only two are shown here. What is show
Walker, J.D., Geissman, J.W., Bowring, S.A., and Babcock, L.E., compilers, 2012, Geol
The Cenozoic, Mesozoic, and Paleozoic are the Eras of the Phanerozoic Eon. Names of
are rounded to the nearest whole number (1 Ma) for the pre-Cenomanian, and rounded
REFERENCES CITED Cohen, K.M., Finney, S., and Gibbard, P.L., 2012, International Cl
for the 34th International Geological Congress, Brisbane, Austra
Gradstein, F.M, Ogg, J.G., Schmitz, M.D., et al., 2012, The Geolo

- Chaotic reversals, hue? Do you find that elsewhere? Yes!

→ Come to the Journal Club this afternoon!

Archeointensity in Syria



Mechanisms at work

- Cornerstones:
  - αω-dynamo (~1960)
  - Busse columns-dynamo (~1970)
  - Numerical consistent geodynamo (~1995)
  - B-scaling laws: power vs magnetostrophy (~2000)
  - Success of the Quasi-Geostrophic approach (~2010)
  - Is convective power enough? (~2015)
  - The role of the 'tangent cylinder' (~2020)

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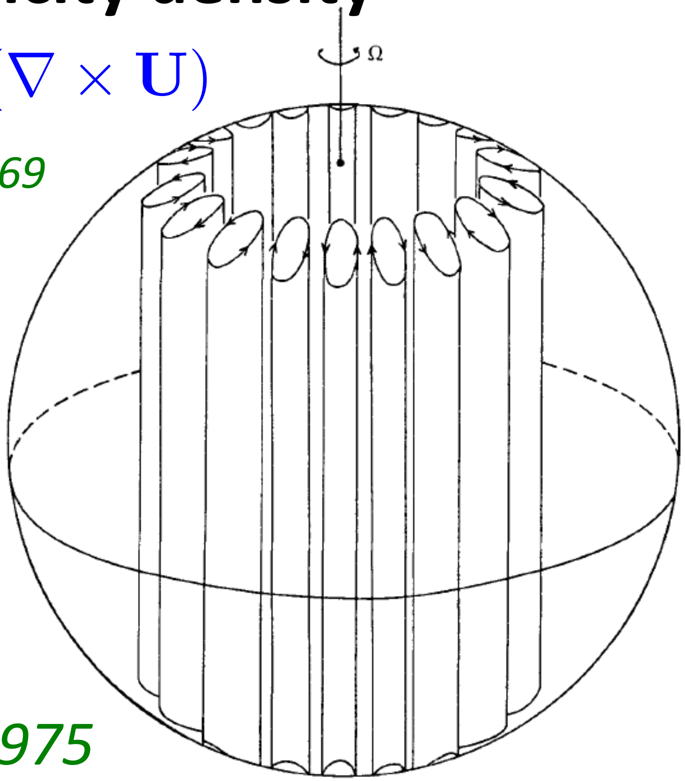
Column-scale helicity

Flow helicity density

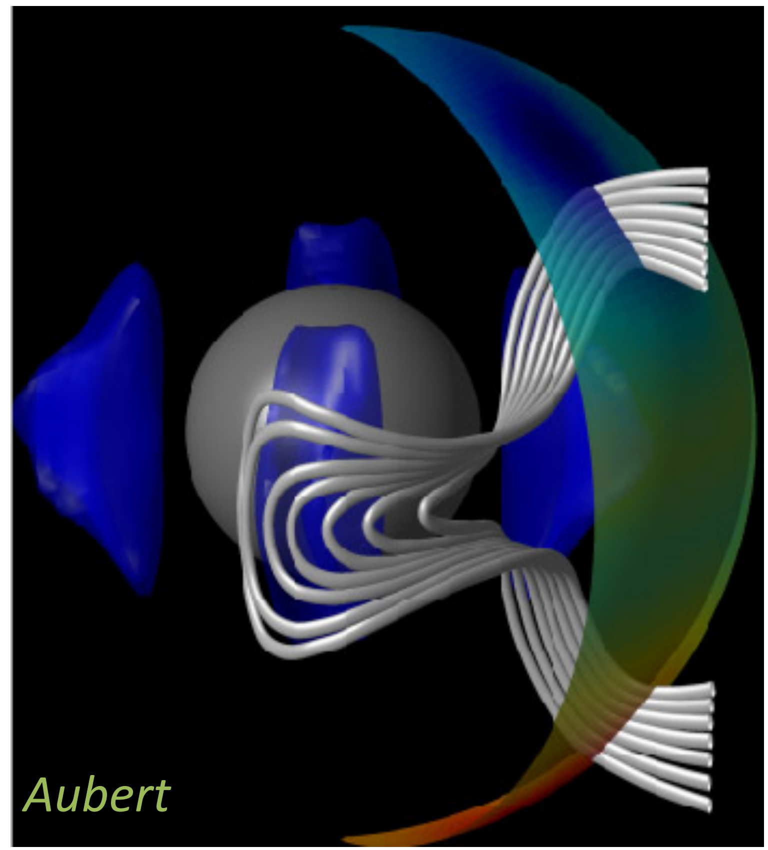
$$h = \mathbf{U} \cdot (\nabla \times \mathbf{U})$$

Moffatt, 1969



Busse, 1975

Fig. 1. Qualitative sketch of onset of convection in a fluid sphere according to the linear analysis in Paper I.



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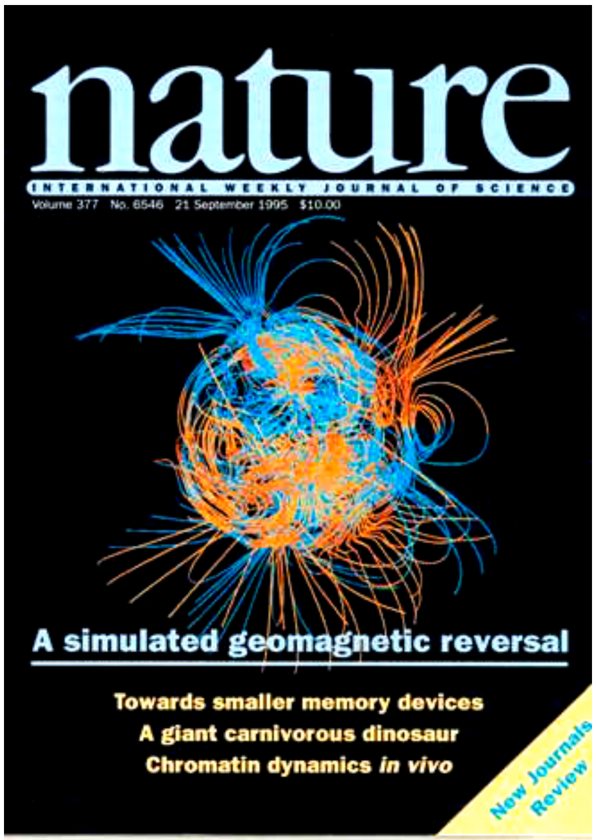
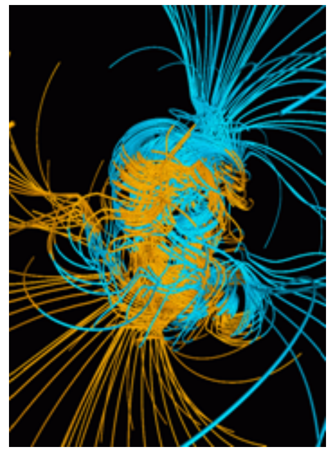
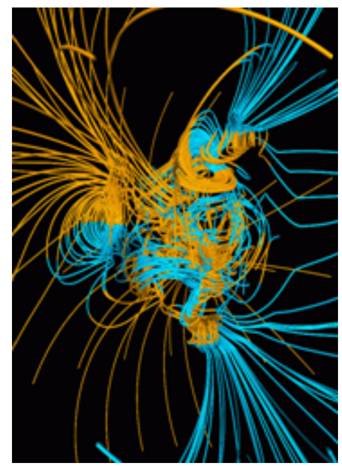
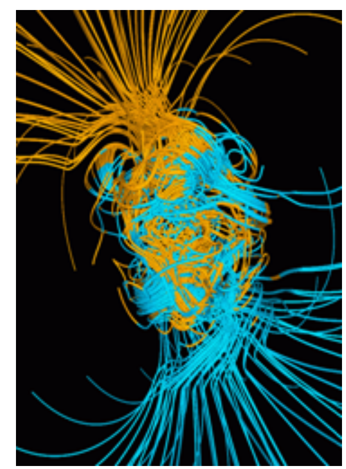
The first consistent convective numerical geodynamo

Glatzmaier & Roberts, 1995; 1997









it reverses!

Mechanisms at work

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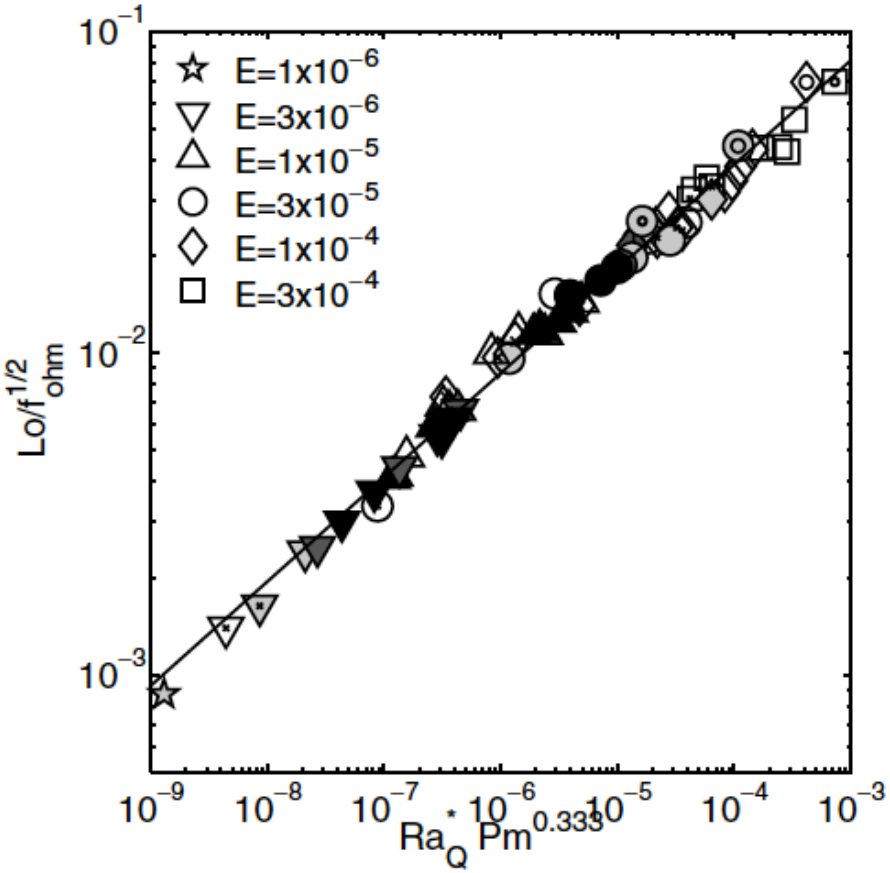

Christensen & Aubert, 2006

Magnetic intensity *B* limited by the available power *P*

$$B \sim \sqrt[3]{\frac{P}{M_{oc}} R_{oc}}$$

rather than by magnetostrophic equilibrium

$$B \sim \sqrt{\eta\Omega}$$

____

NB: *B* in Alfvén wave velocity units

Mechanisms at work

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A dive into the Earth core

Core flows

- One can use the time-variation of the observed magnetic field to obtain constraints on the velocity field at the surface of the core.
- Indeed, consider the induction equation:

$$\partial_t \mathbf{B} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \eta \Delta \mathbf{B}$$

At the core surface, its radial component yields:

$$\partial_t B_r = -\nabla_H \cdot (\mathbf{U_H} B_r) + \frac{\eta}{r} \nabla^2 (r B_r)$$

where the subscript $_H$ denotes horizontal component.

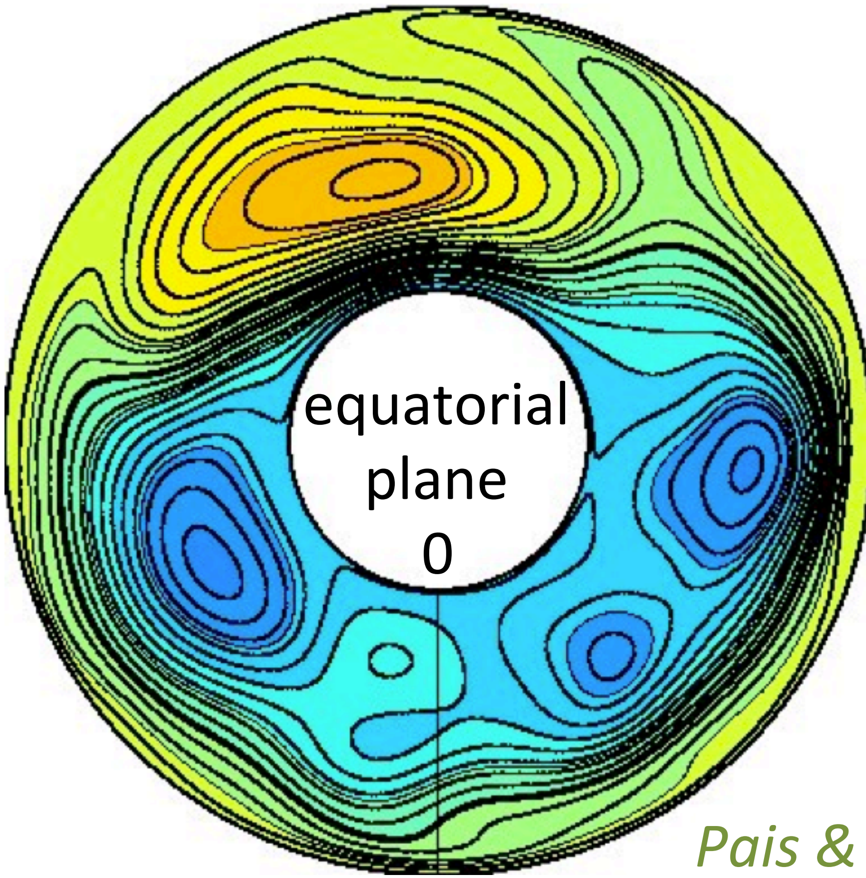
Considering short time-scales at which diffusion is negligible, one gets: $\partial_t B_r = -\nabla_H \cdot (\mathbf{U_H} B_r)$

Roberts & Scott, 1965

Core flows

- Under some assumptions, we can thus derive the flow **U** at the surface of the core from observations of B_r and its time-derivative.
- Because of the Earth rotation, we expect the flow within the core to be **quasi-geostrophic**. Hence, we can extend the core flow deduced at the surface into columns spanning the entire core.
- This yields the following result.

Discovering the flow inside the core: a large non-axial anti-cyclone



Equatorial section of the stream function from geomagnetic data (B_r and dB_r/dt) in year 2000.

Mean velocity ~15km/year

Pais & Jault, 2008

Torsional Alfvén waves

- On top of the long-term circulation of the previous slide, ***torsional waves*** have been detected, which travel across the core in about **4 years**.
- This places constraints on the intensity of the magnetic field hidden within the core (of about **3 mT**).

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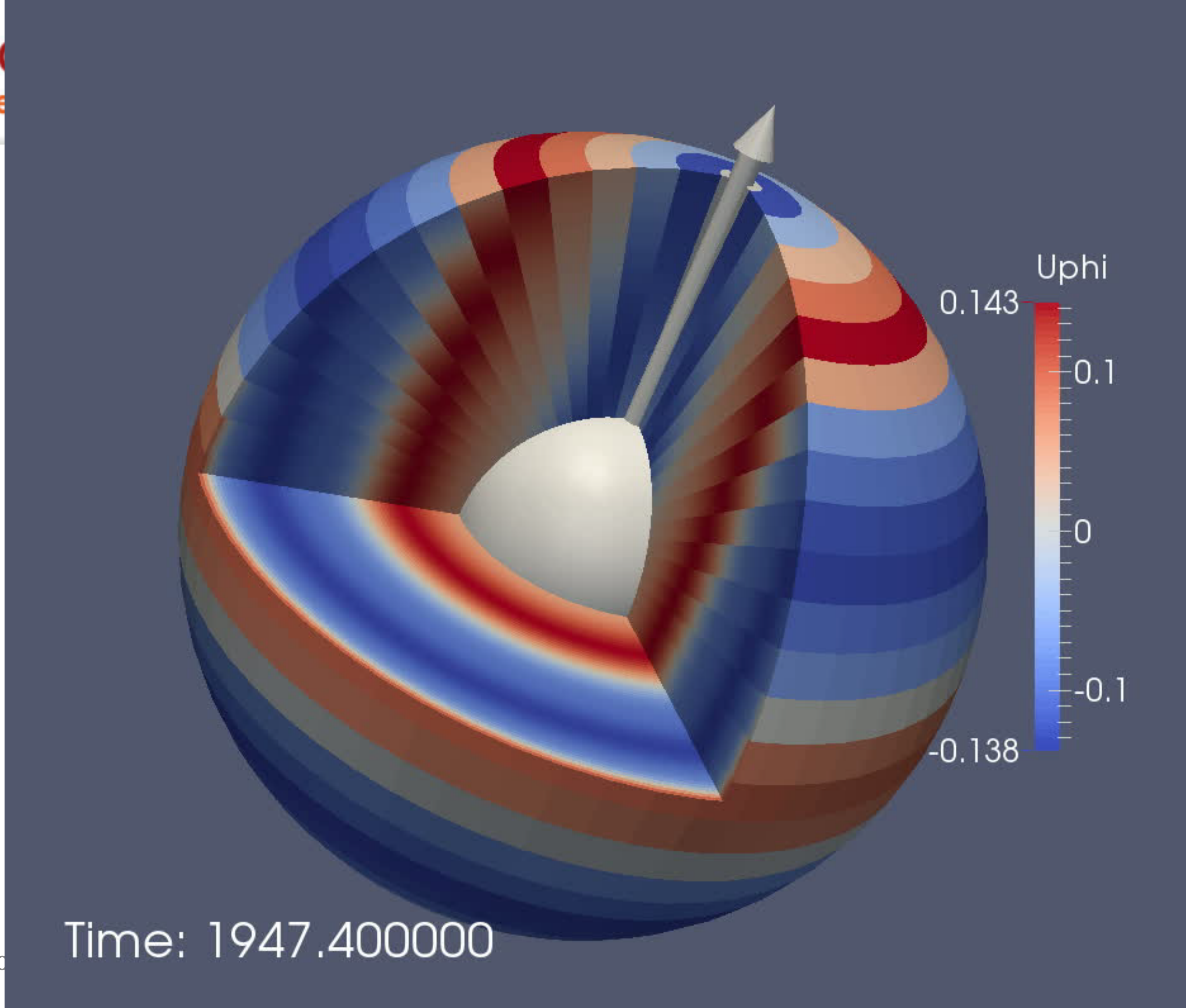
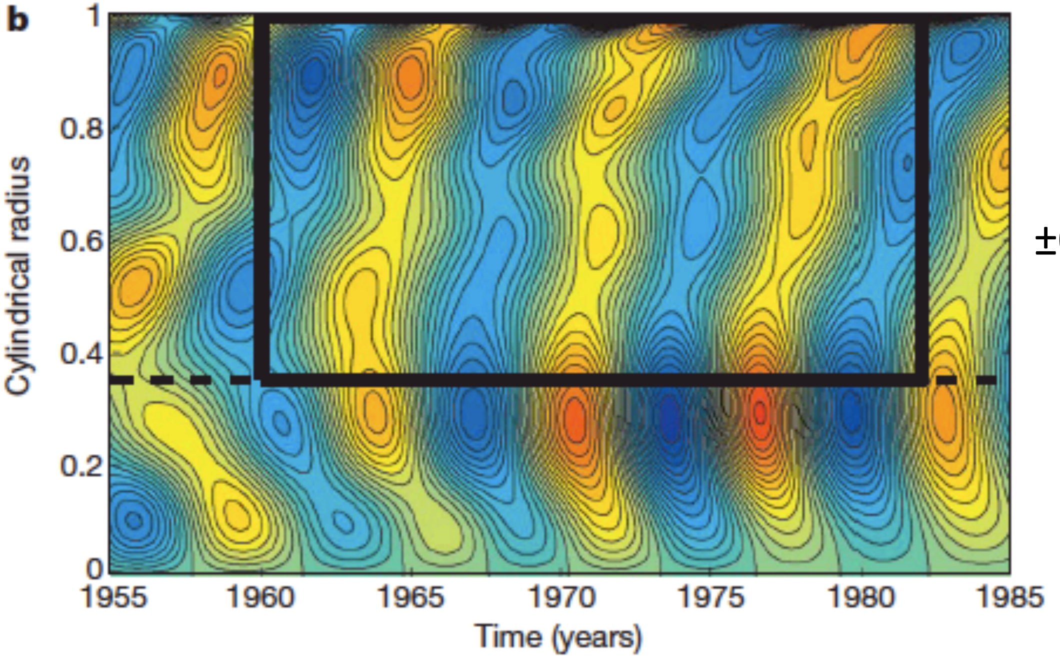


Torsional oscillations in the core (km/year), 1947-1977, from Gillet et al, Nature, 2010

- Sceptical? You would like a confirmation from another observable?

→ Come to the Journal Club this afternoon!

- Alfvén waves that jerk the Earth !



±0.4km/year

$$V_A = \frac{B}{\sqrt{\rho \mu_0}}$$

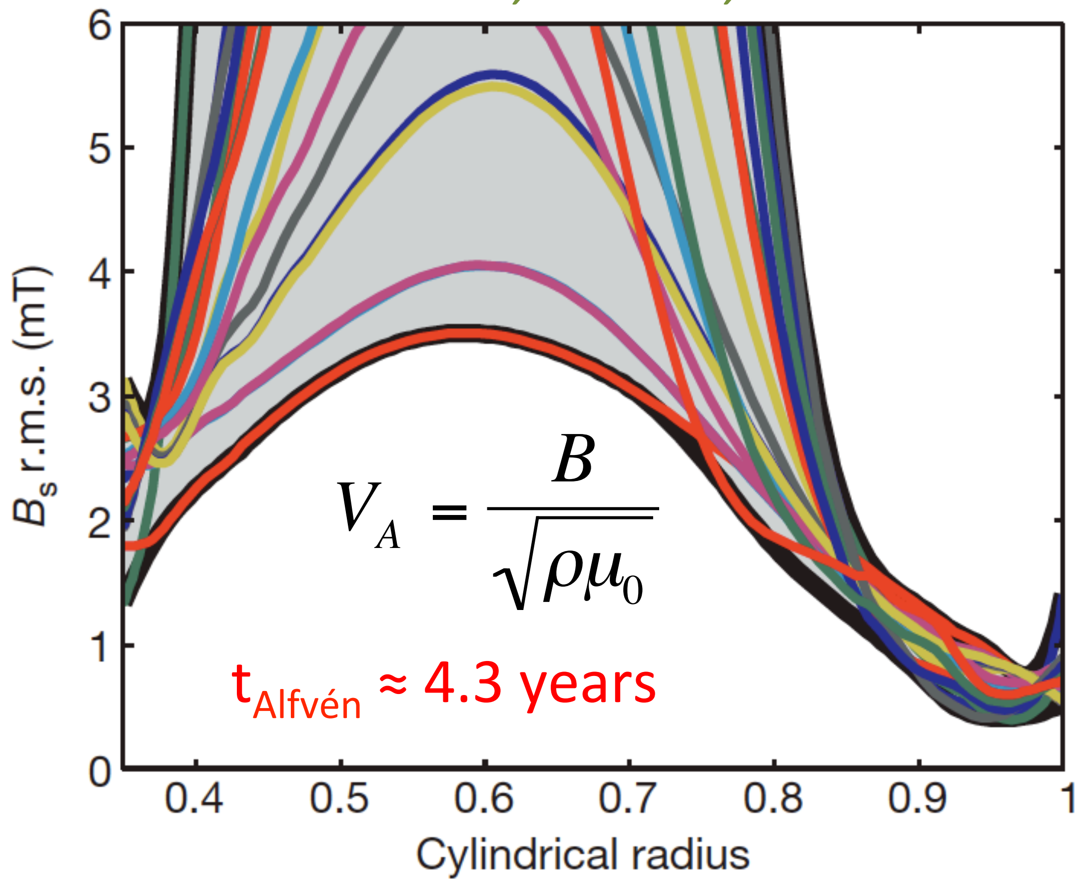
$t_{Alfvén} \approx 4.3$ years

Gillet et al, Nature, 2010

Magnetic field *inside* the core

Gillet et al, Nature, 2010

- Deducing the first profile of magnetic field inside the core.
- In agreement with Lorentz forces needed to sustain the non-axial anticyclone



"from kinetic energy to magnetic energy"

- In the Earth's core:

$$\frac{E_M}{E_K} \sim 10^4$$

Exploring a geodynamo simulation

- A journey inside one of the most recent highest-resolution numerical simulations, performed by Nathanaël Schaeffer.

  (Schaeffer et al, 2017)

$E = 10^{-7}$, $Pm = 0.1$, $Rm = 570$

It achieves a magnetic/kinetic energy ratio of **10** (in most dynamo simulations magnetic energy is *smaller* than kinetic energy).

A strong contrast between *inside* and *outside* the 'tangent cylinder'

- The tangent cylinder (tangent to the inner core, aligned with the rotation axis) retains a strong and wide temperature anomaly.
- Outside, thin thermal plumes form on the inner core and spread into large-scale features.

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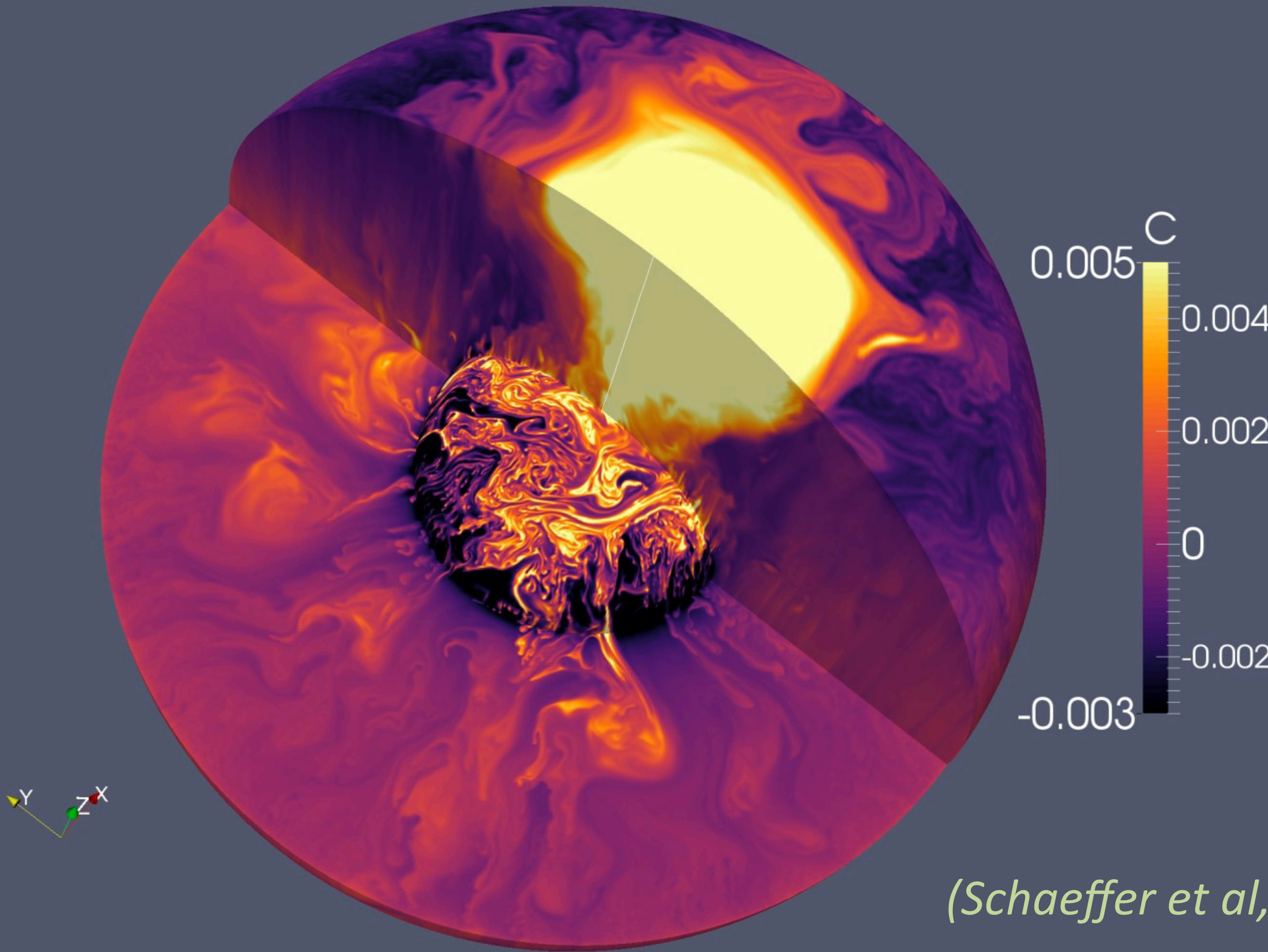

(Schaeffer et al, 2017)

A strong contrast between *inside* and *outside* the 'tangent cylinder'

- A huge twisted vortex inside the tangent cylinder.
- Thin columnar vortices outside.

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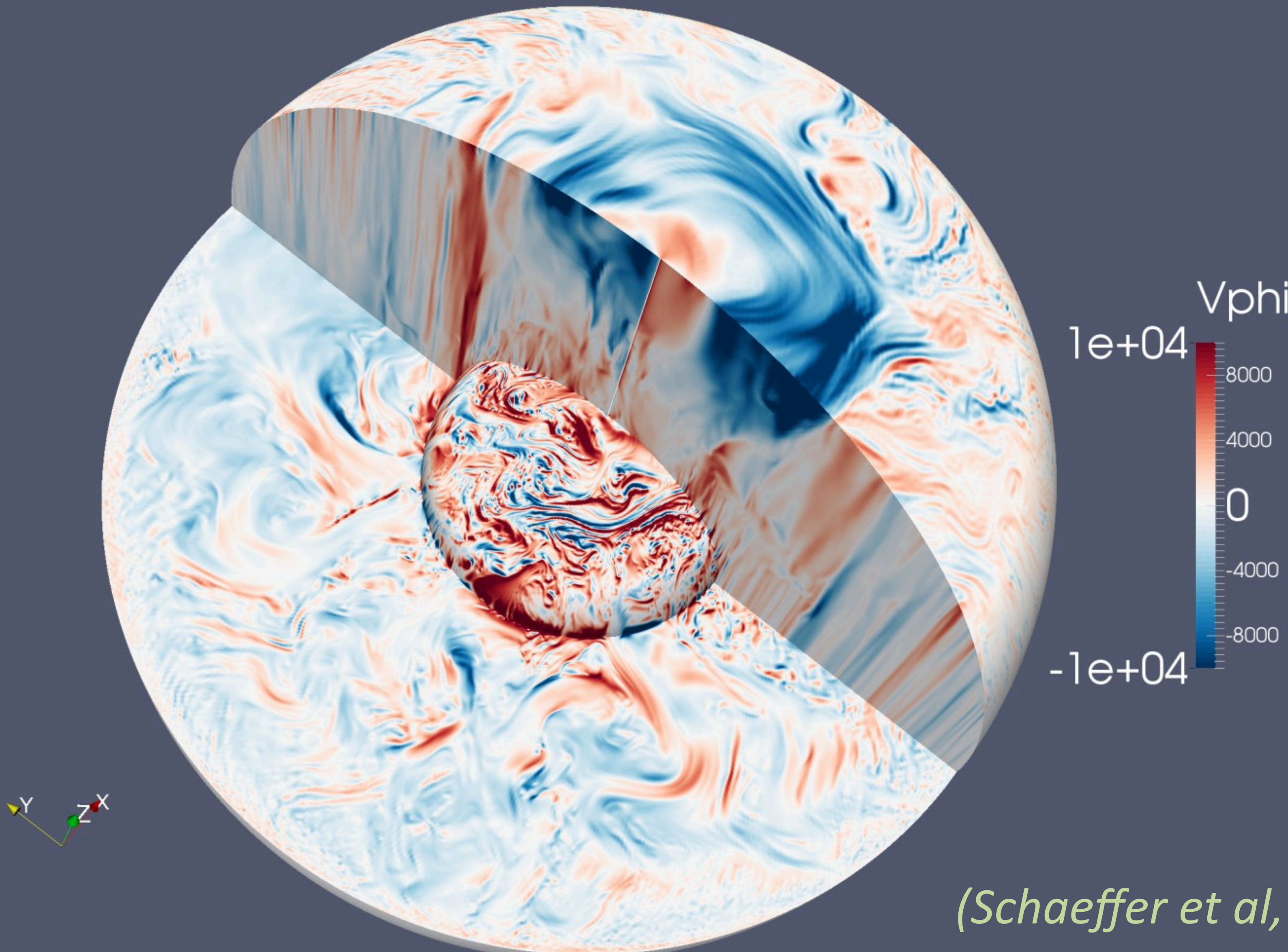
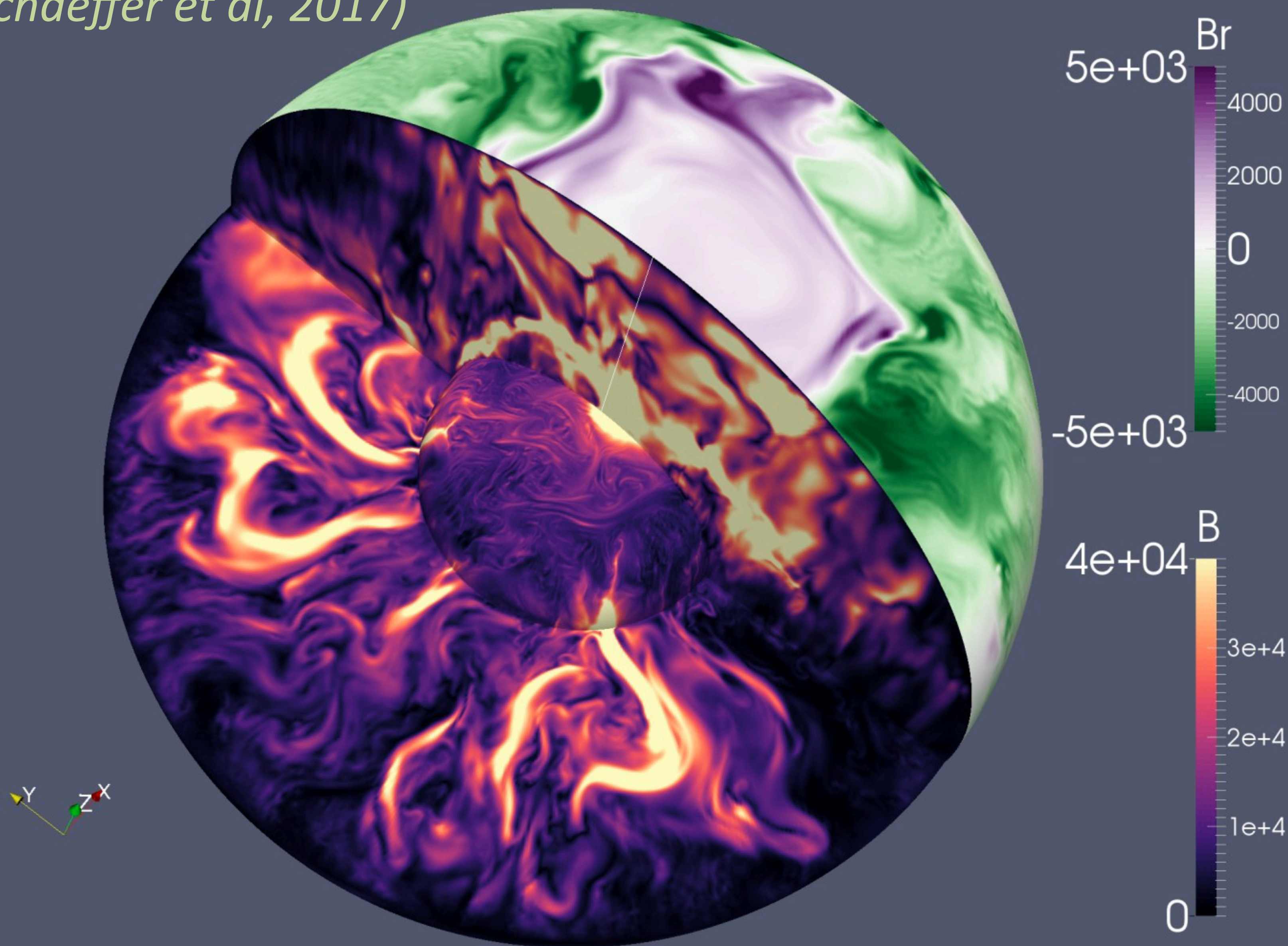


(Schaeffer et al, 2017)

A strong contrast between *inside* and *outside* the 'tangent cylinder'

- Strong magnetic field generation inside the tangent cylinder.
- Meandering tongues of intense magnetic field in a weak background.

(Schaeffer et al, 2017)



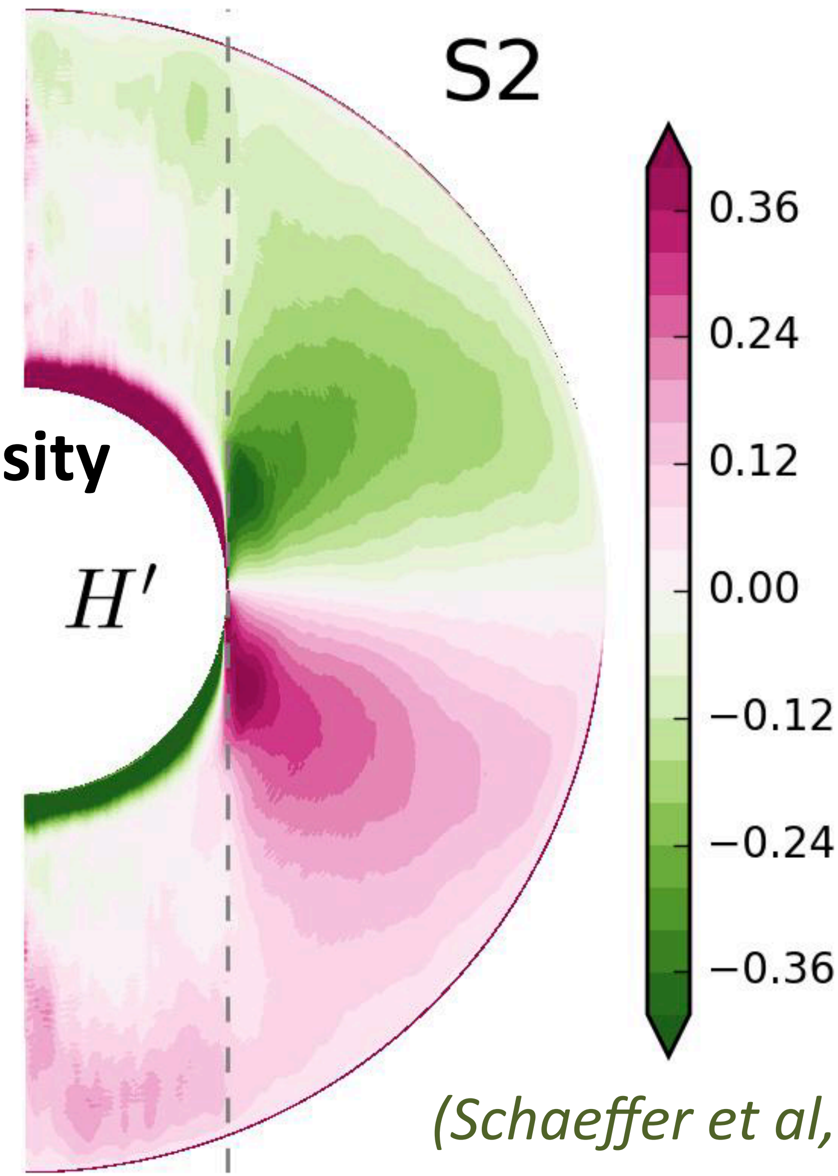
A strong contrast between *inside* and *outside* the 'tangent cylinder'

- A thin region of intense helicity density on the inner sphere inside the tangent cylinder.
- A very organized distribution of mean helicity density outside, which is *not* due to Ekman pumping.

Flow helicity density

$$h = \mathbf{U} \cdot (\nabla \times \mathbf{U})$$

Moffatt, 1969

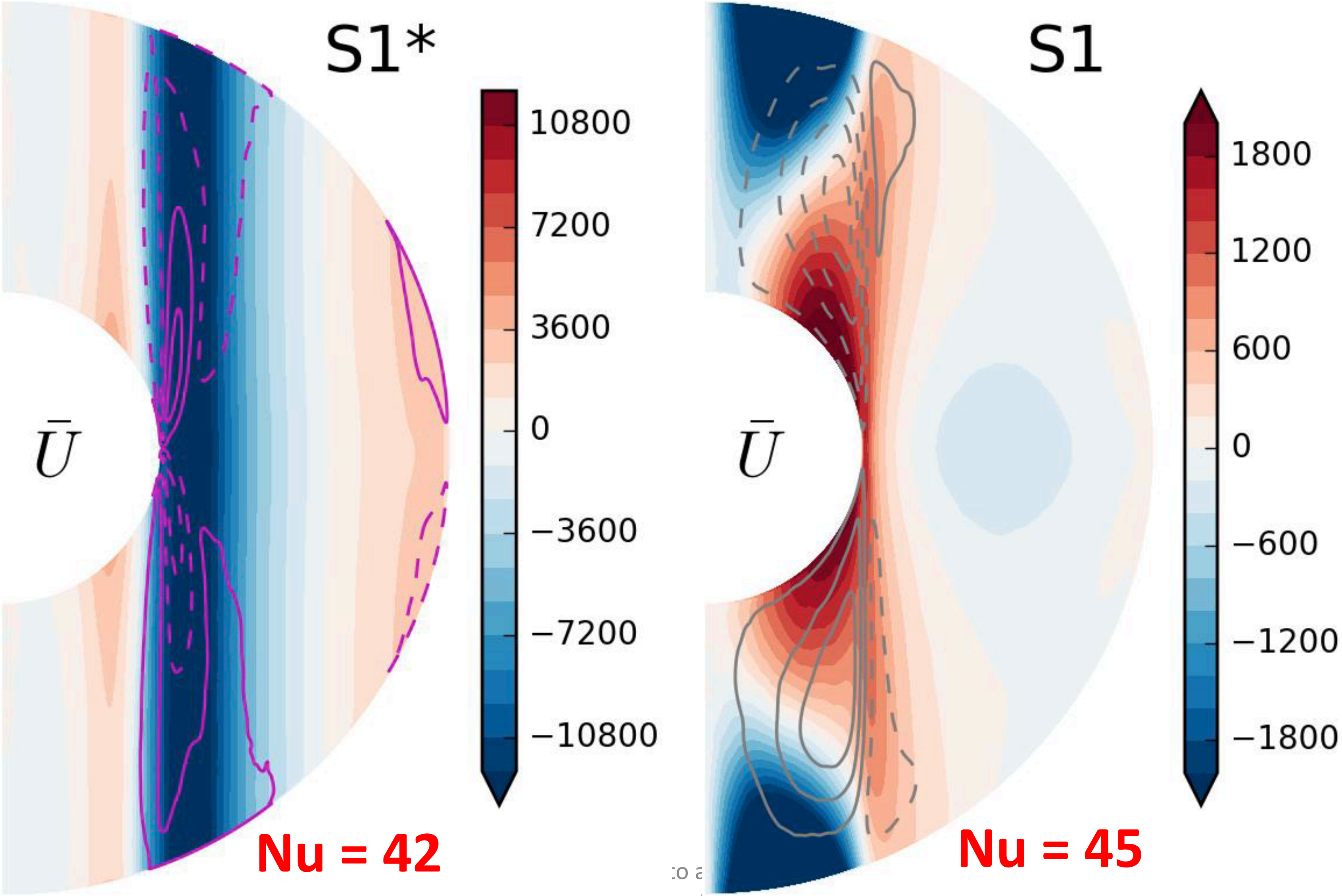


(Schaeffer et al, 2017)

The magnetic field kills zonal jets

- Comparing one of the dynamo simulations (S1) with the same simulation deprived of a magnetic field (S1*) demonstrates that the presence of Lorentz forces inhibits the strong zonal jets typical of rotating convection.
- Despite a much lower kinetic energy, the dynamo simulation transports heat more efficiently.

without B **with B**



(Schaeffer et al, 2017)

- movie

Conclusions

- Dynamos all around! Imaginative Nature.
- Terrestrial planets at the margin…
- Torsional Alfvén waves in the Earth's core.
- $E_M/E_K \sim 10^4$
- What turbulence for planetary dynamos?
- What asymptotic regimes?
- Magnetic fields for exoplanets?

ÉCOLE DE PHYSIQUE des HOUCHES

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Further reading

- Baraffe et al, 2014. https://arxiv.org/abs/1401.4738
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