

Planetary magnetic fields: where do they all come from?

Ankit Barik
Planetary Interiors

2 April 2021

Why do we care?

What information can we get?

What information can we get?

- Interior structure

What information can we get?

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- Interior dynamics

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- Interior structure
- Interior dynamics
- Plate tectonics

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What information can we get?

- Interior structure
- Interior dynamics
- Plate tectonics
- Solar wind dynamics
- Habitability

'Actively generated' magnetic field?

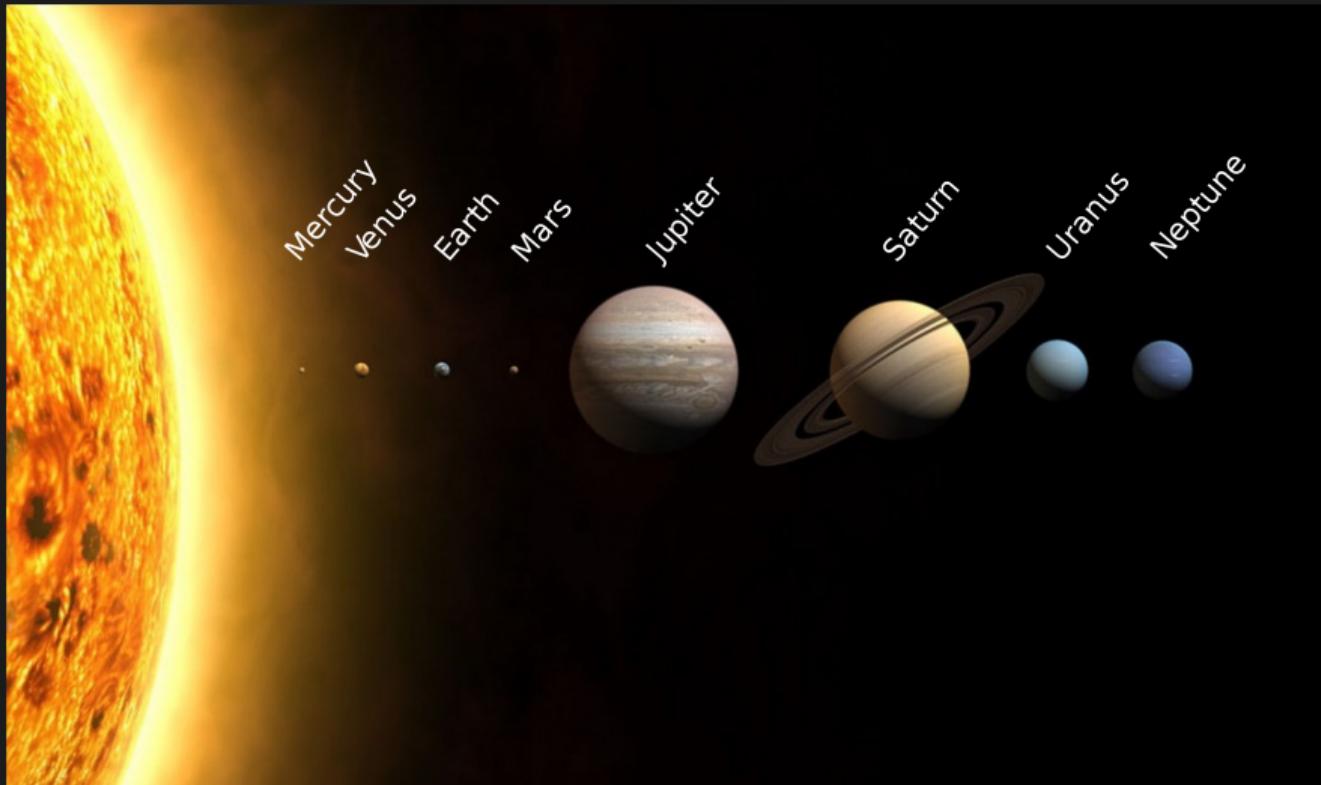
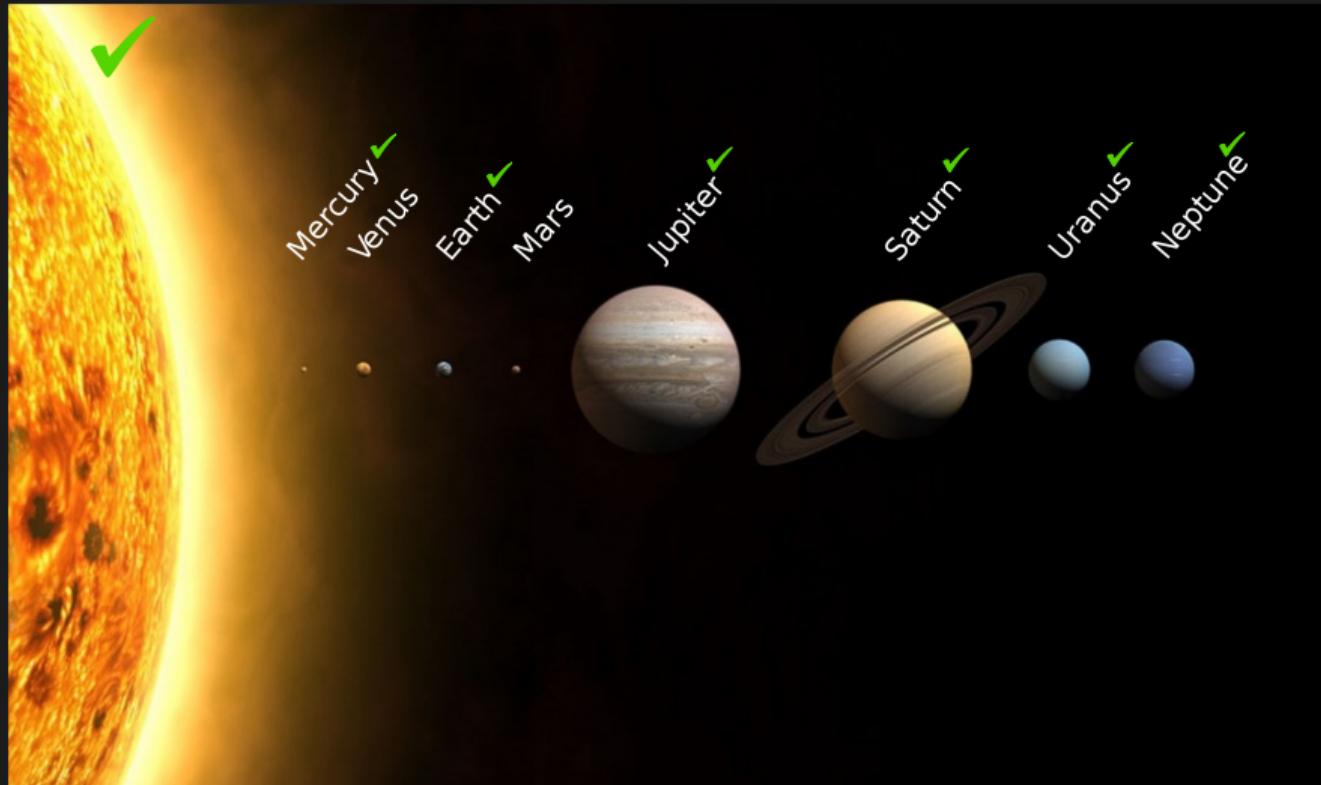
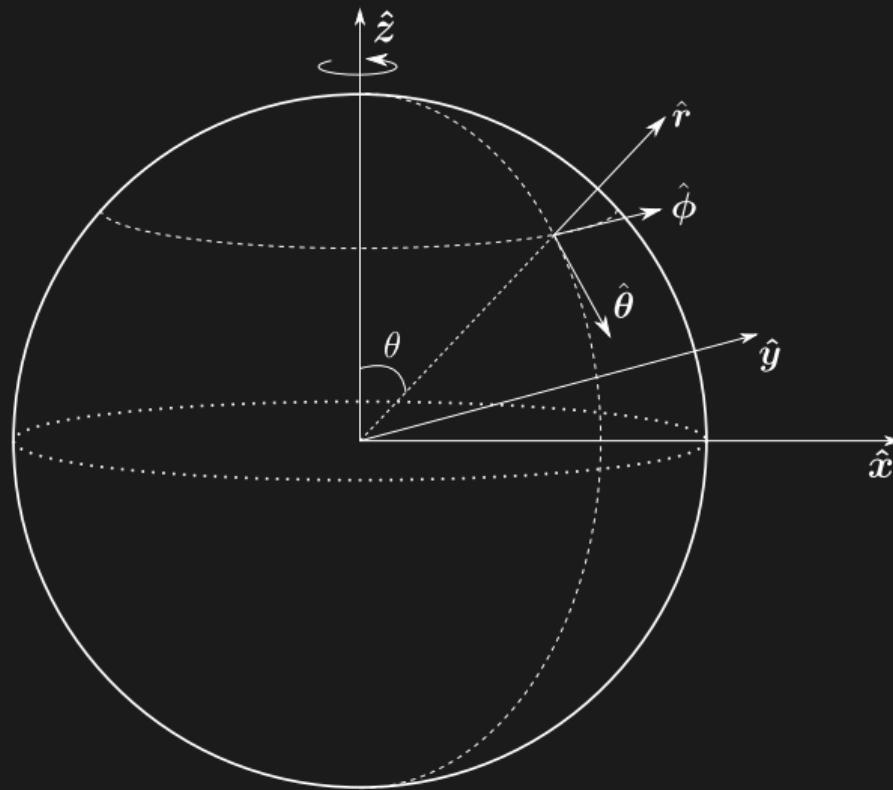


Figure by WP - Planets2008.jpg, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=45708230>

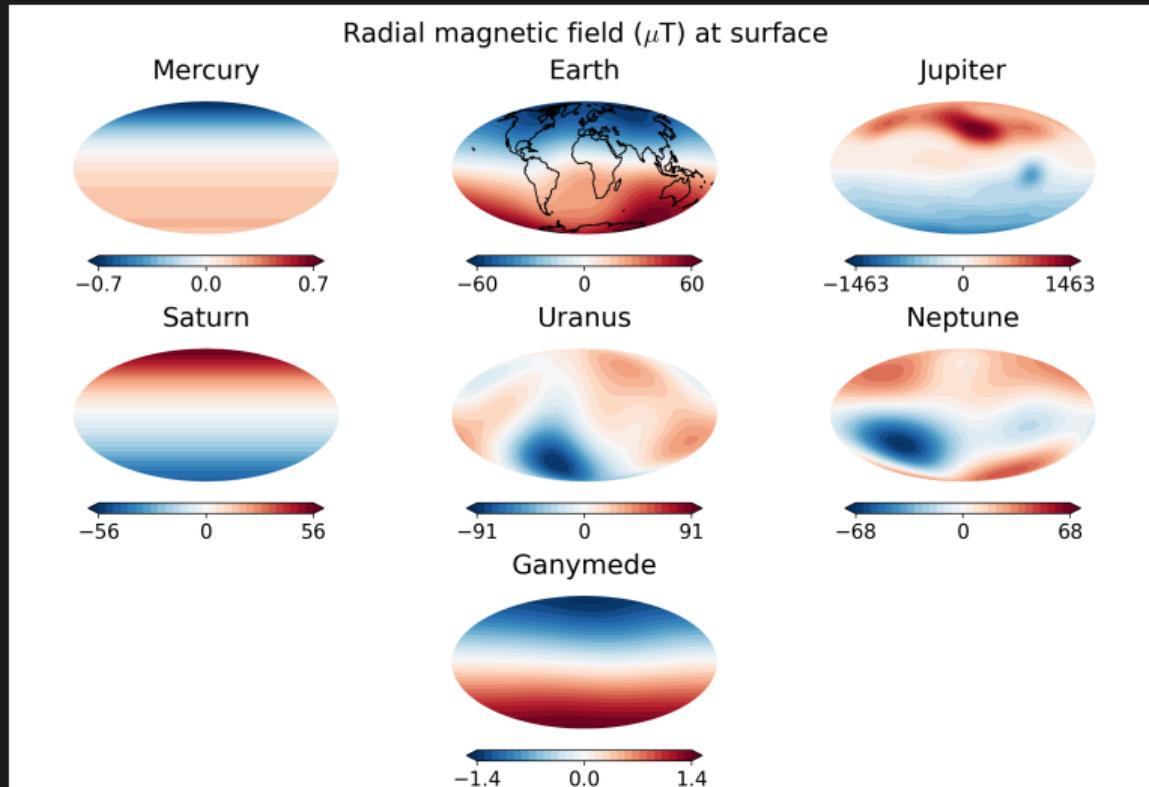
'Actively generated' magnetic field?



Magnetic field components



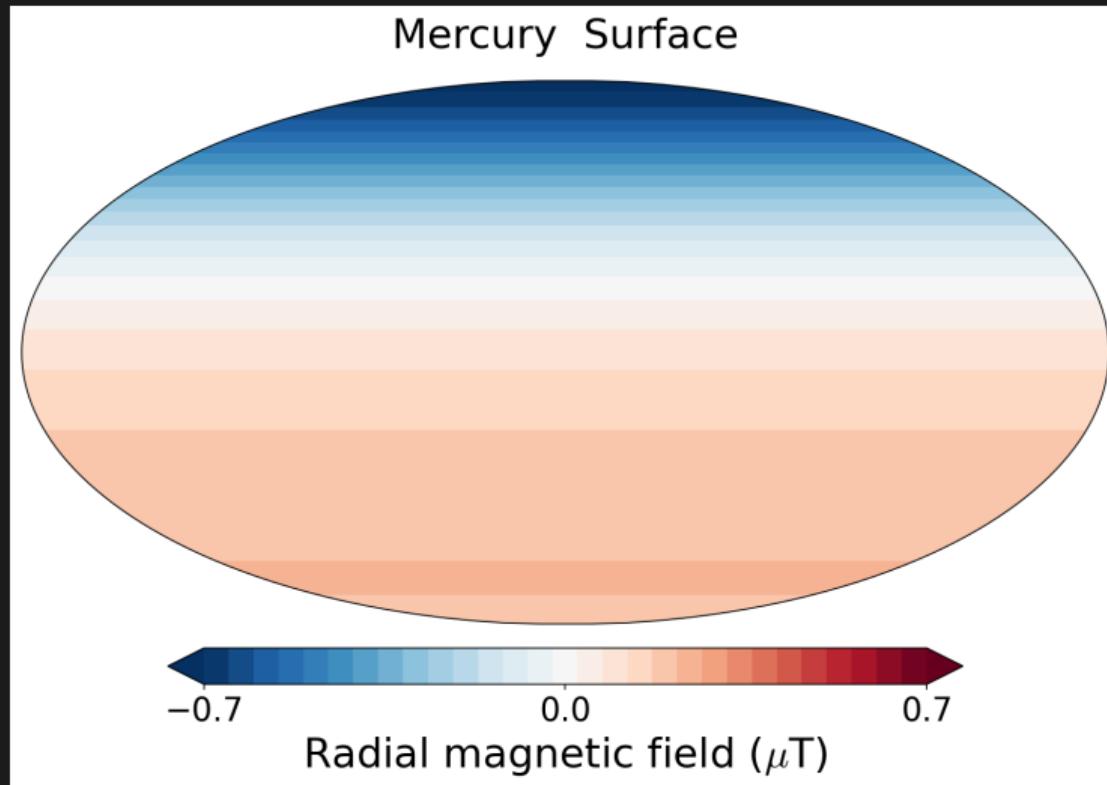
Magnetic fields of different bodies



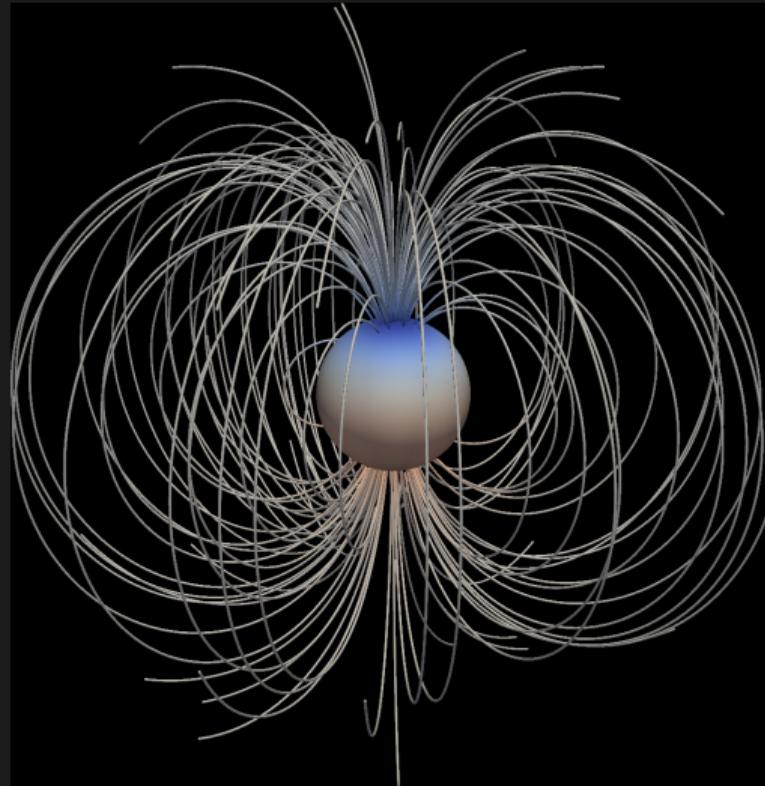
Section 1

Terrestrial planets

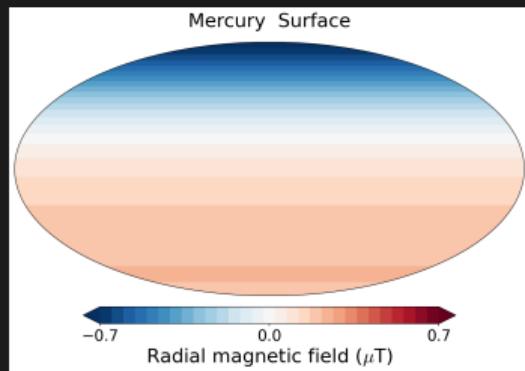
Mercury



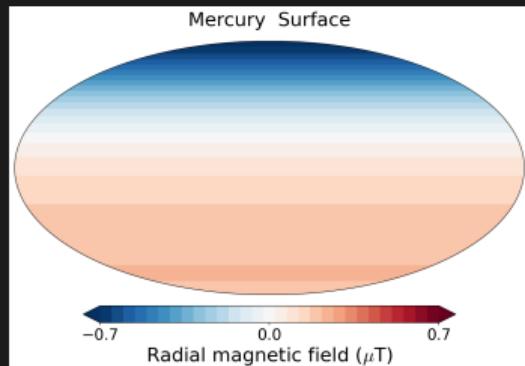
Mercury



Mercury

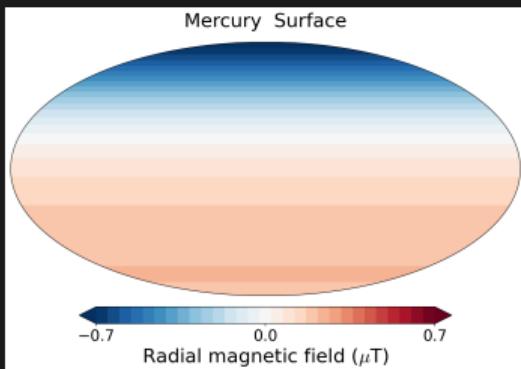


Mercury



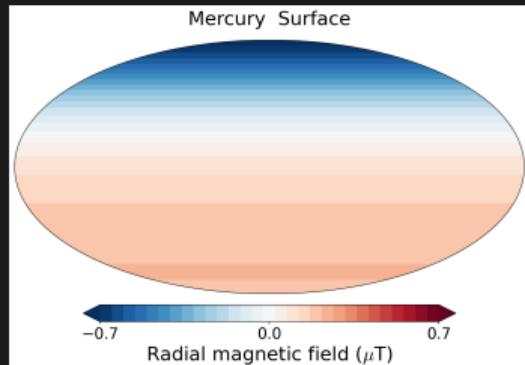
- Very weak

Mercury



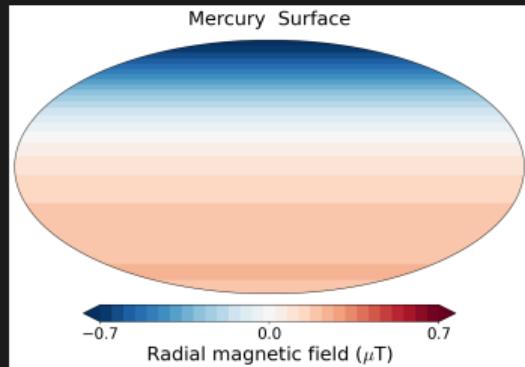
- Very weak
- *Very dipolar*

Mercury



- Very weak
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- Magnetic equator offset to the north by about 500 km w.r.t planetary equator

Mercury



- Very weak
- *Very* dipolar
- Magnetic equator offset to the north by about 500 km w.r.t planetary equator
- Magnetic axis is almost aligned with rotation axis (tilt $< 0.8^\circ$)

The Earth

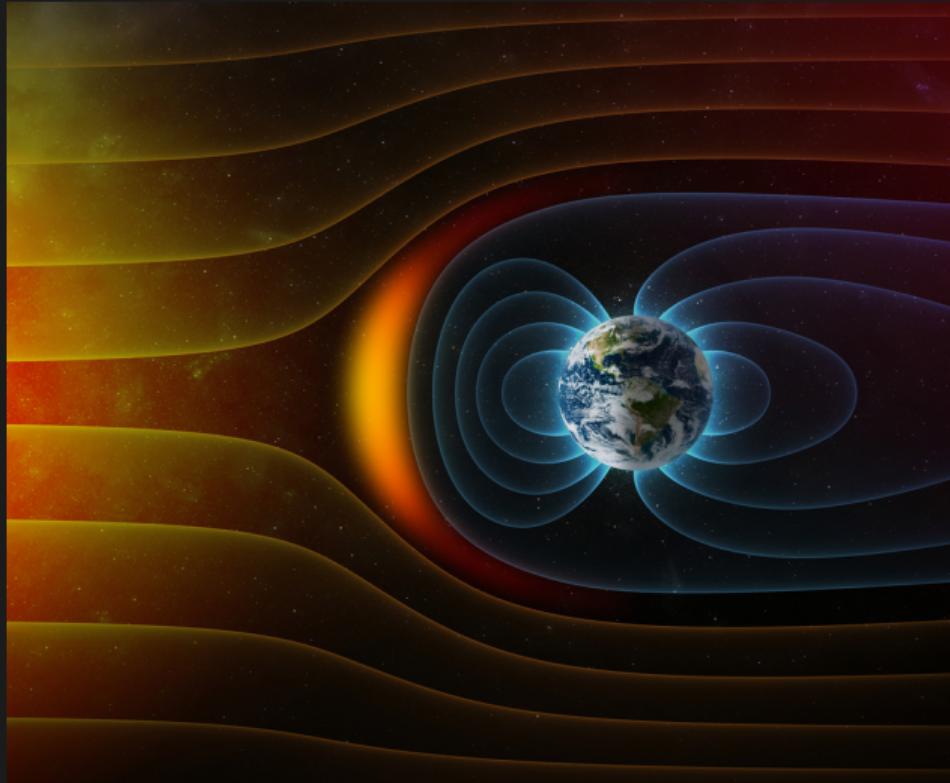
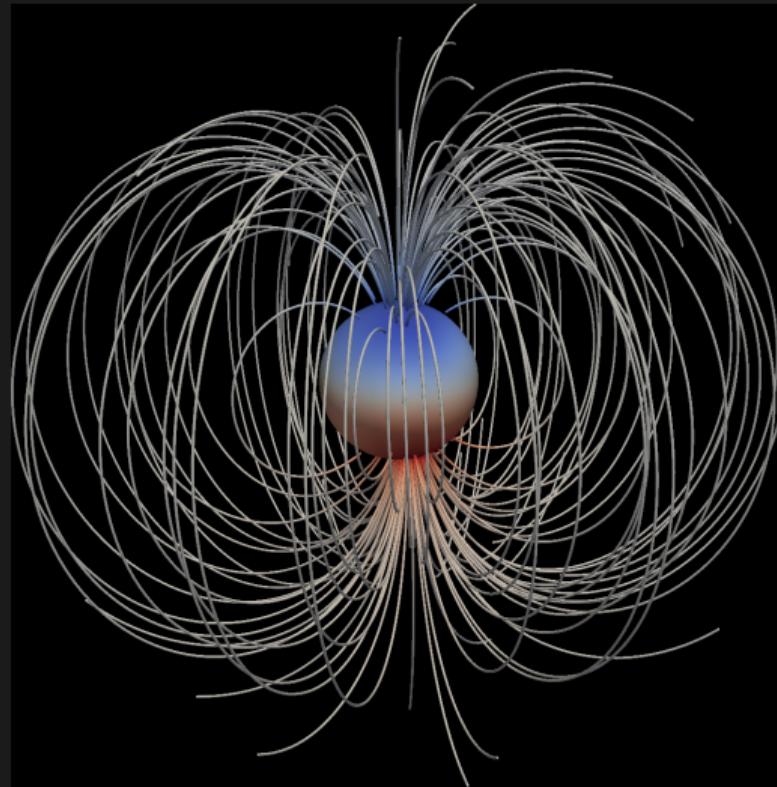
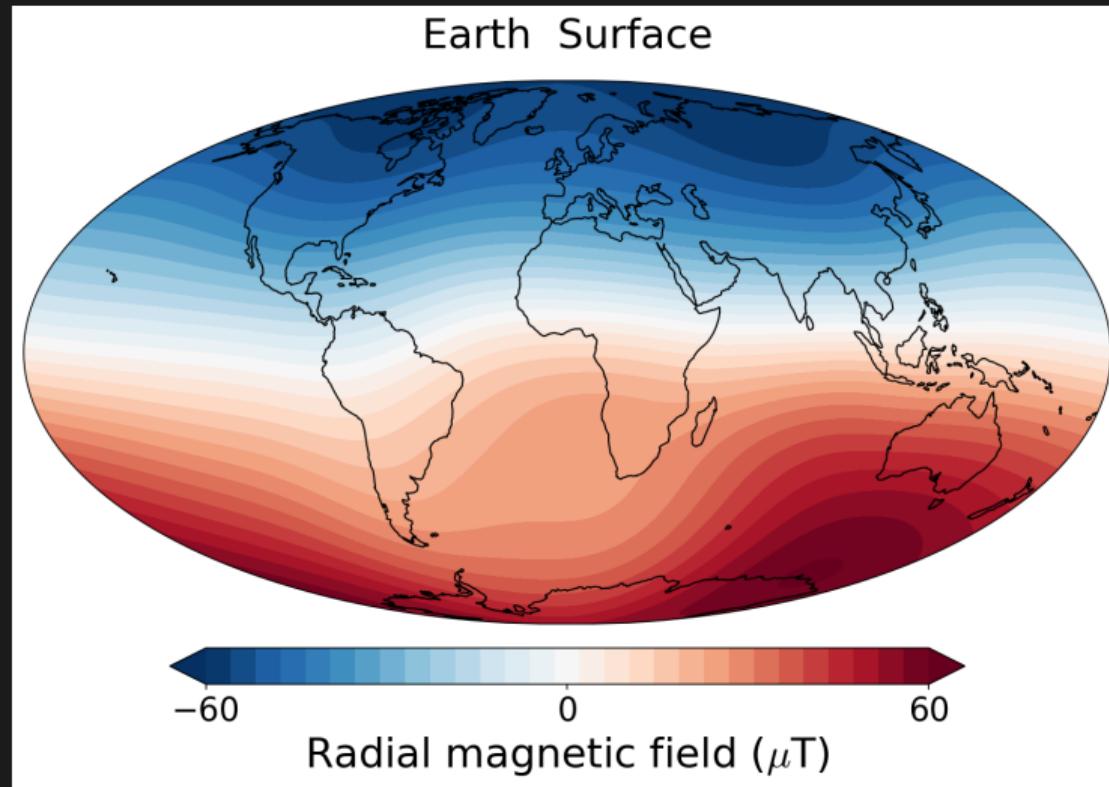


Image credit: TodayIFoundOut.com

The Earth



The Earth



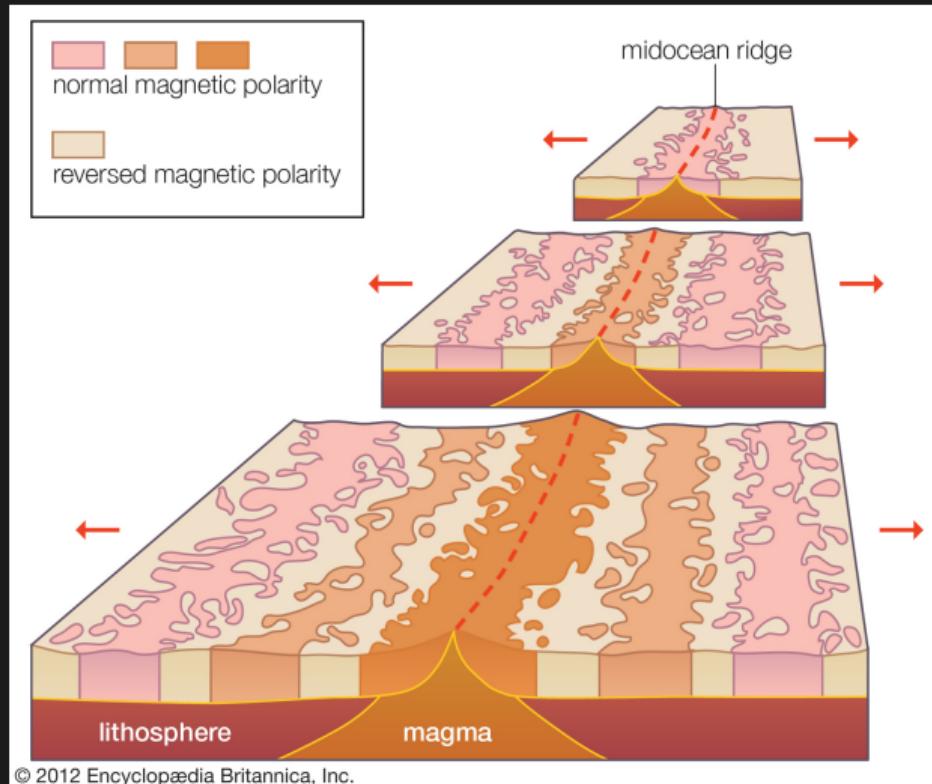
Secular variation

Courtesy: Sabrina Sanchez, MPI for Solar System Research, Germany

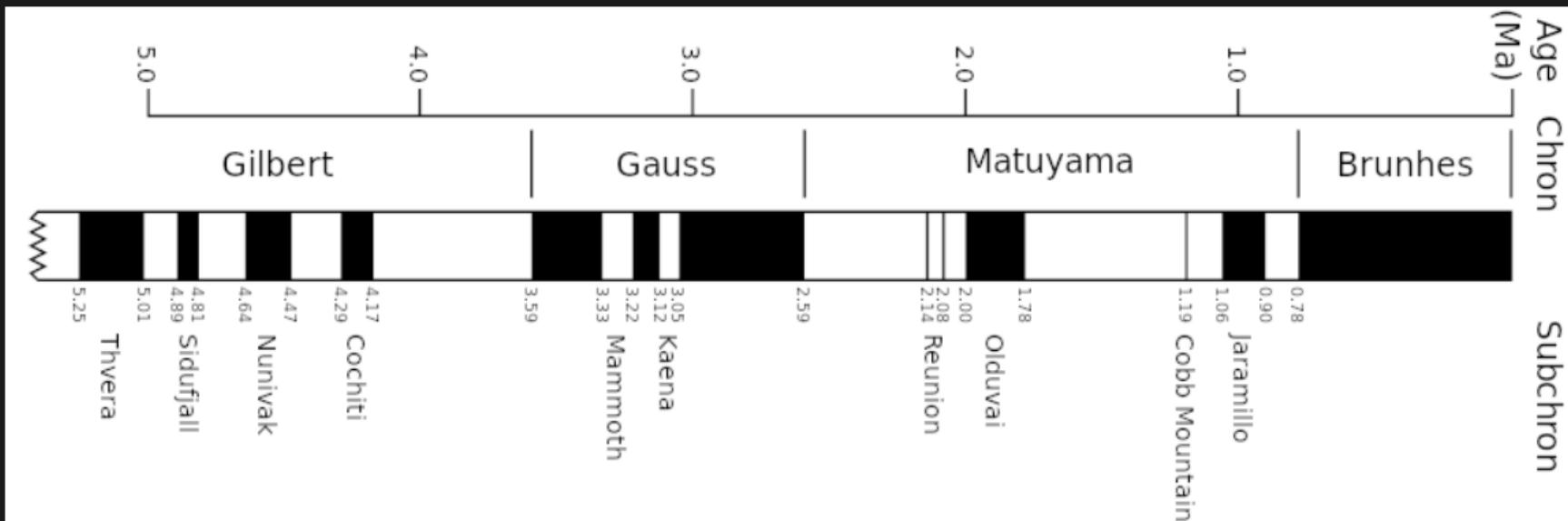
Secular variation

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Reversals

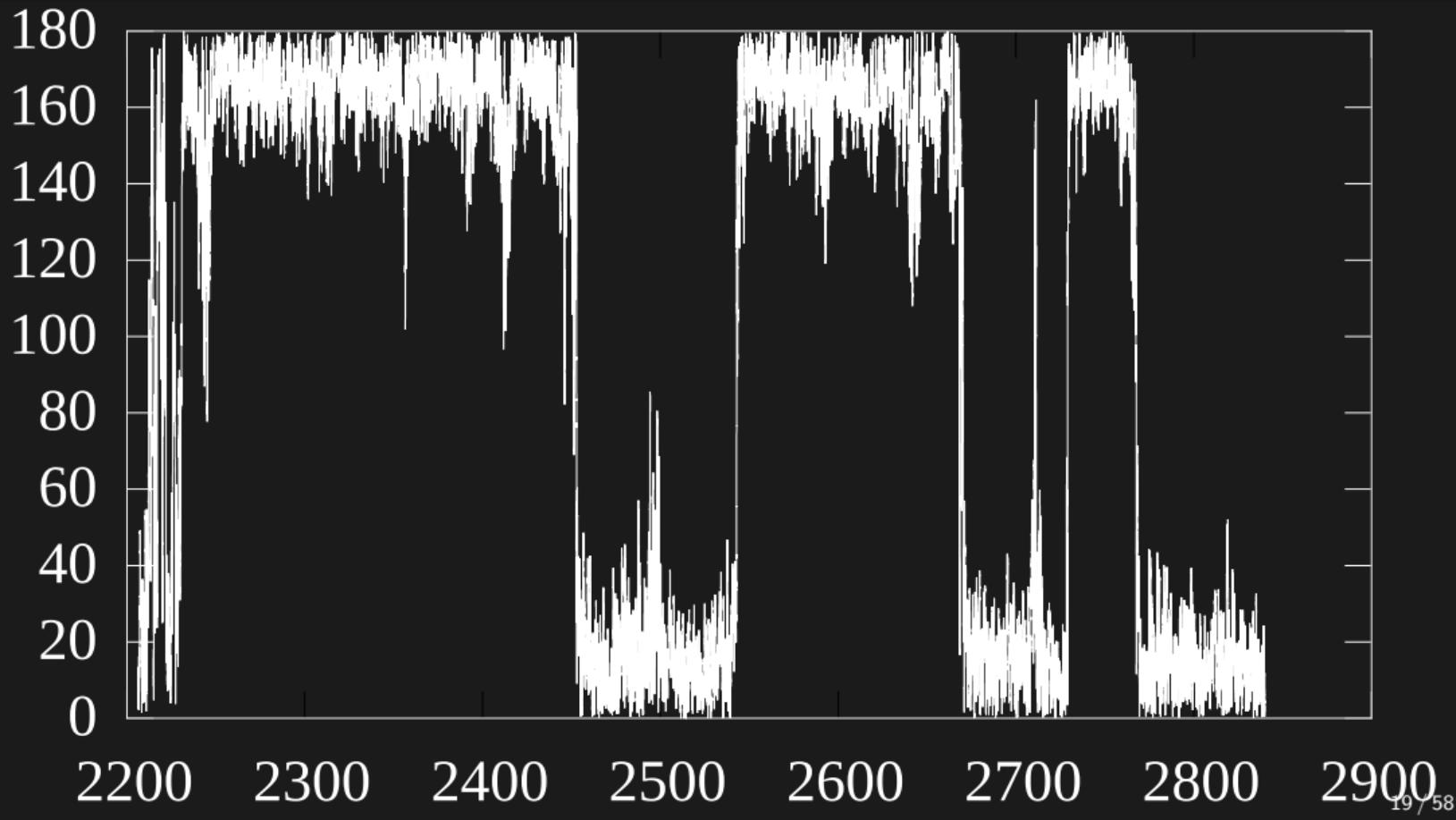


Reversals

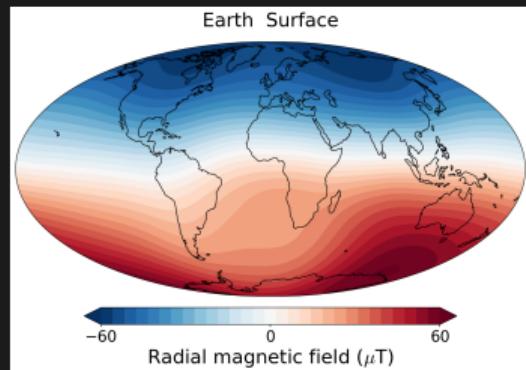


Reversals

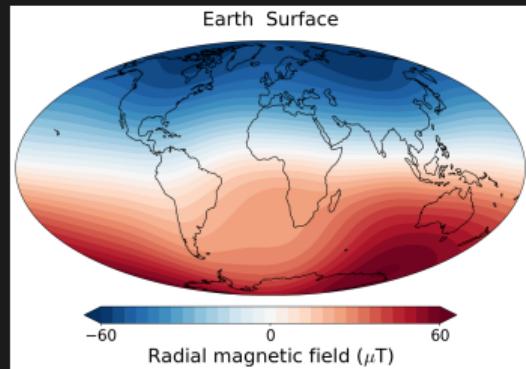
Dipole Tilt



Major features of Earth's field

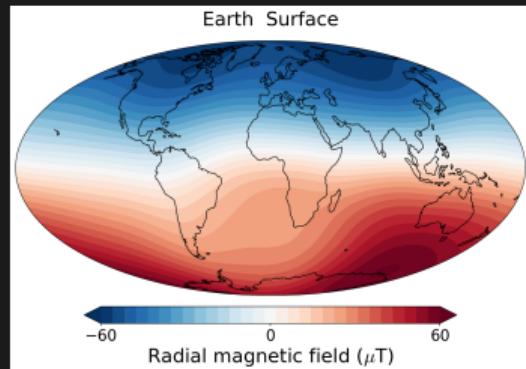


Major features of Earth's field



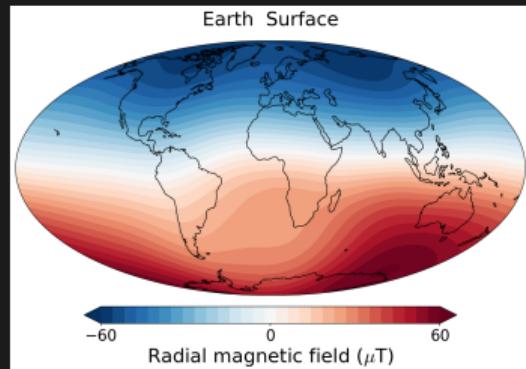
- Largely dipolar

Major features of Earth's field



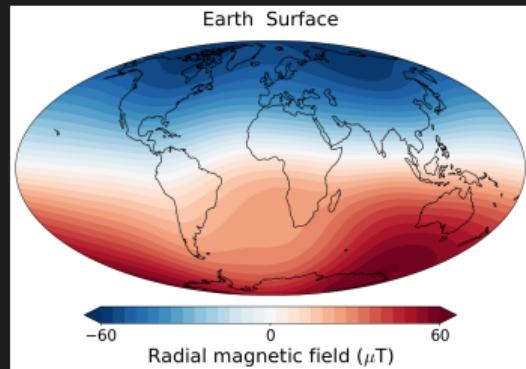
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- Magnetic axis tilted by about 10° with respect to rotation axis

Major features of Earth's field



- Largely dipolar
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- “Westward drift”

Major features of Earth's field



- Largely dipolar
- Magnetic axis tilted by about 10° with respect to rotation axis
- “Westward drift”
- Geomagnetic reversals

Section 2

Gas giants

Aurorae : Jupiter

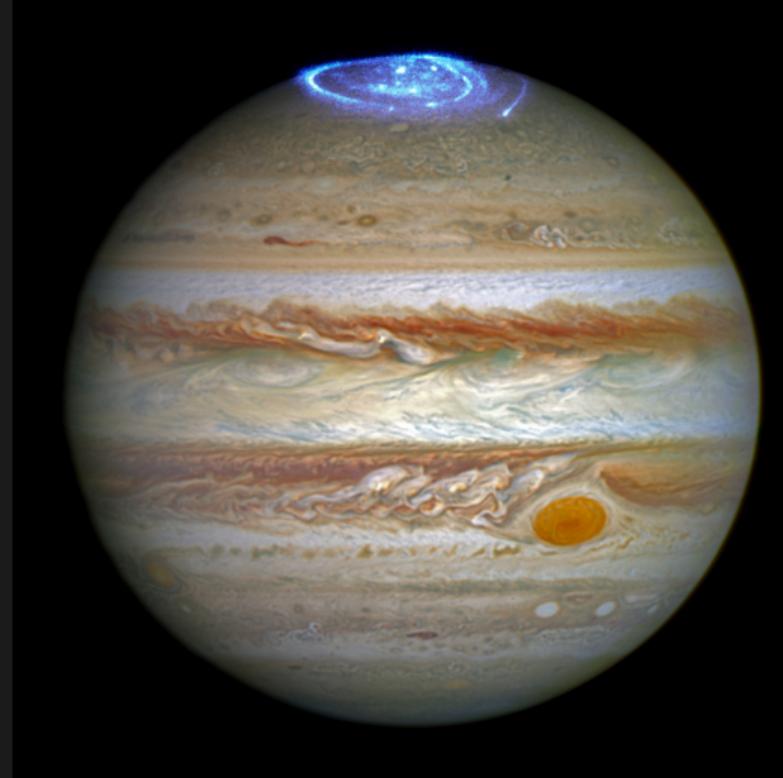


Figure : NASA/Hubble

Aurorae : Saturn

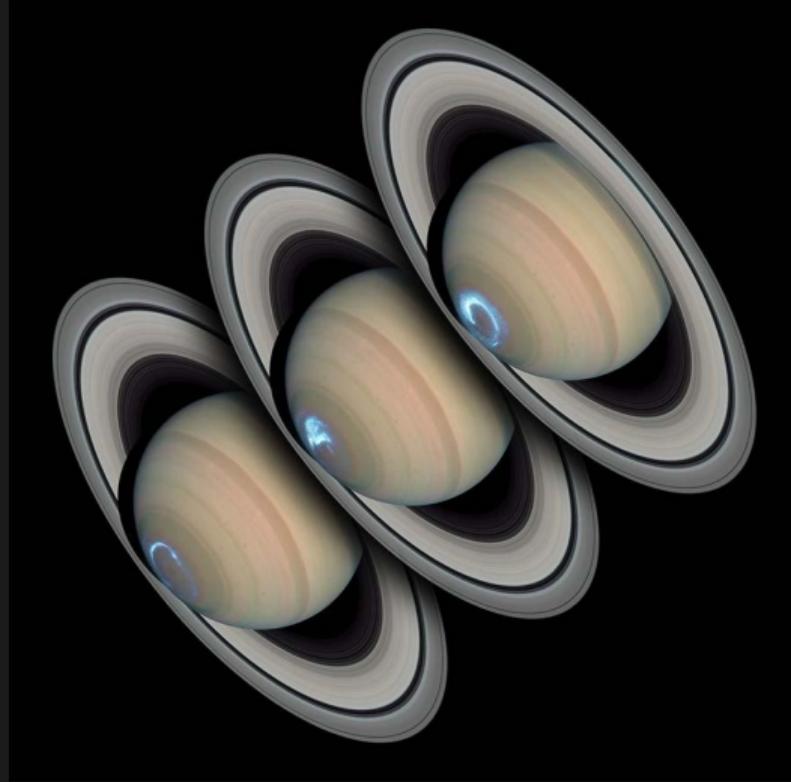
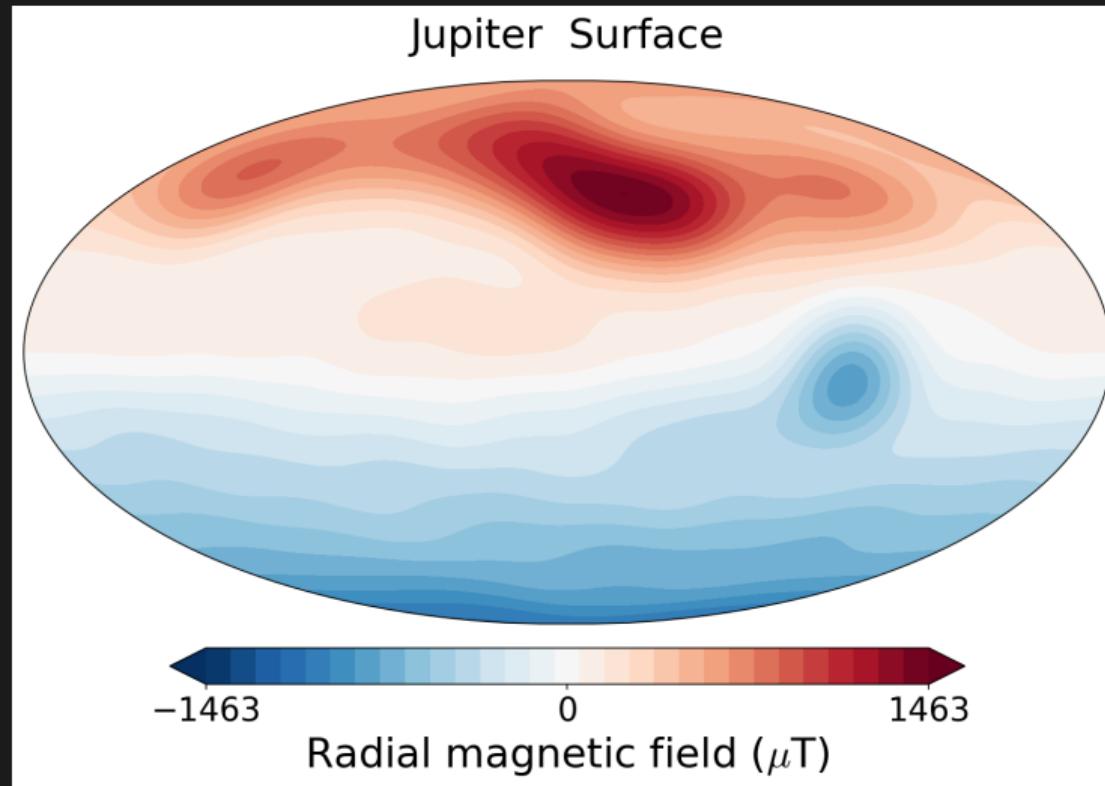


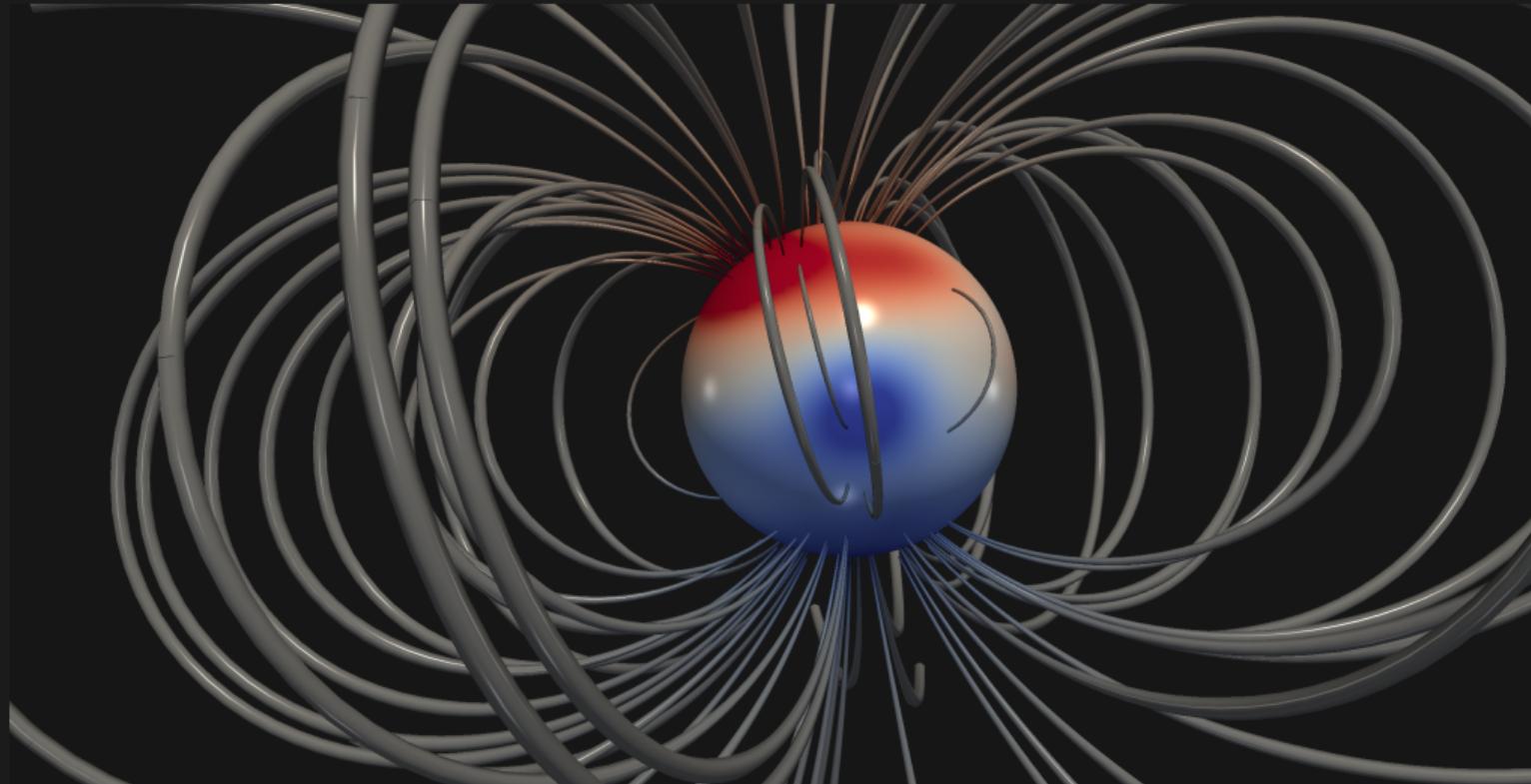
Figure : NASA/Hubble

Jupiter

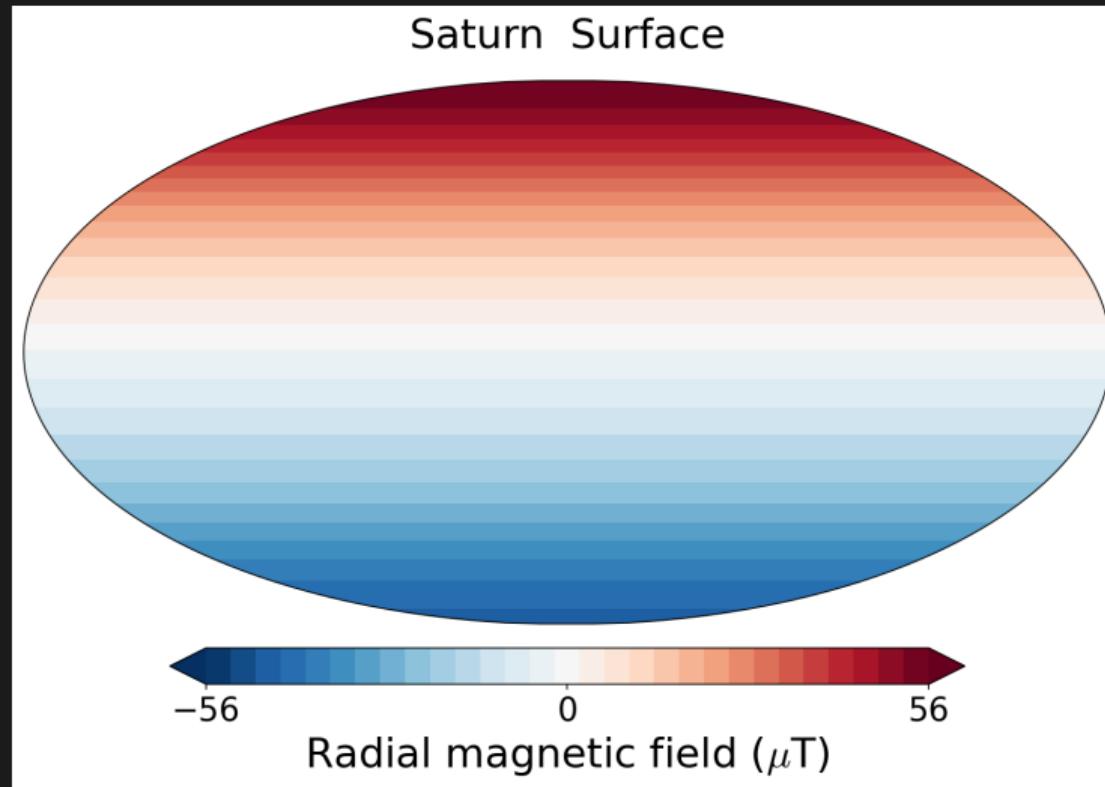


Dipole tilt = 10.3°

Jupiter

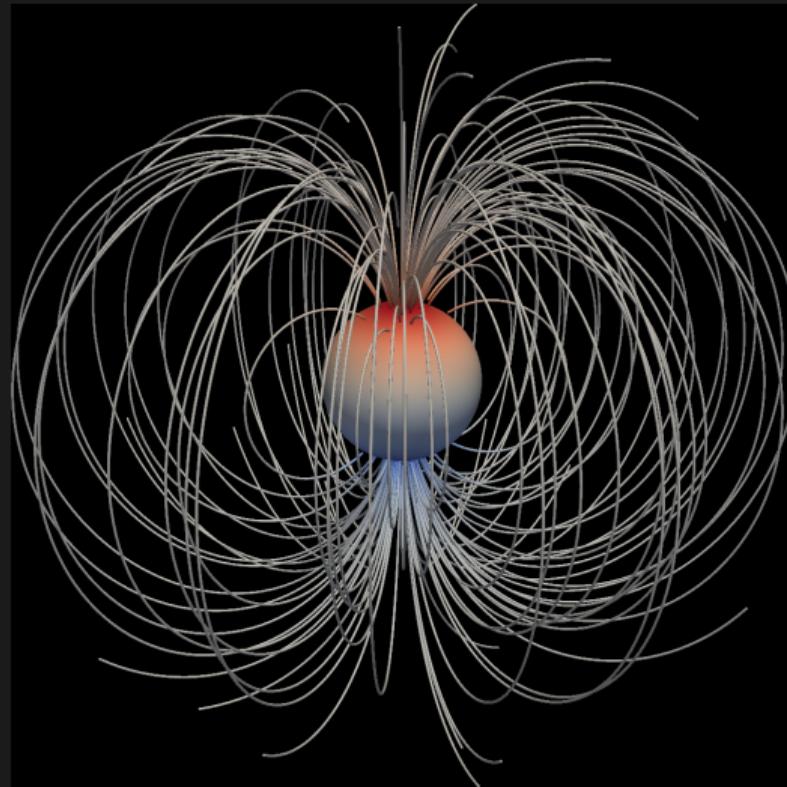


Saturn

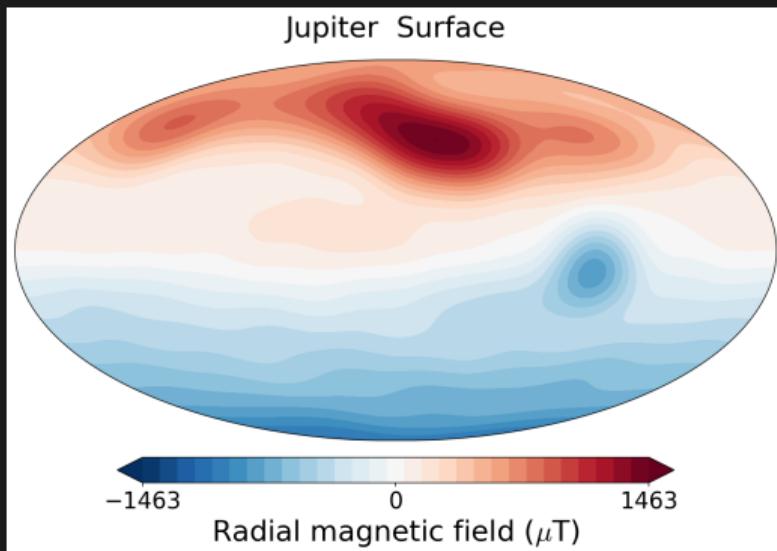


Dipole tilt $\leq 0.0095^\circ$

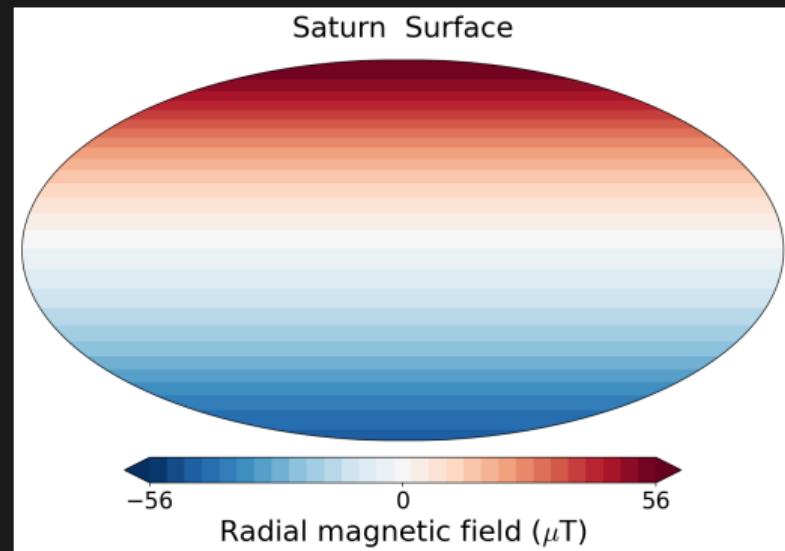
Saturn



Gas giants

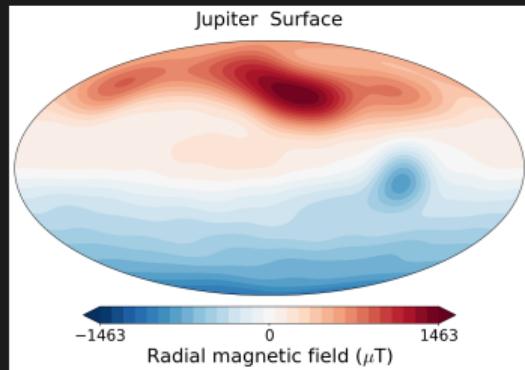


Jupiter
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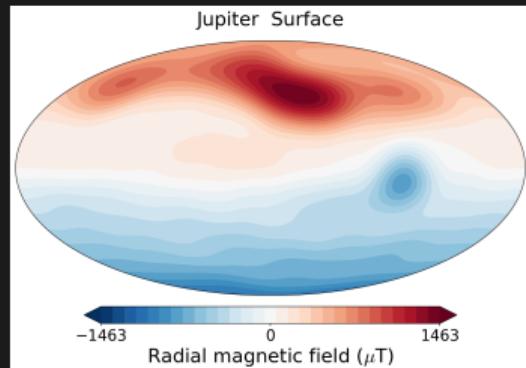


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Dipole tilt $\leq 0.0095^\circ$

Gas giants: Jupiter

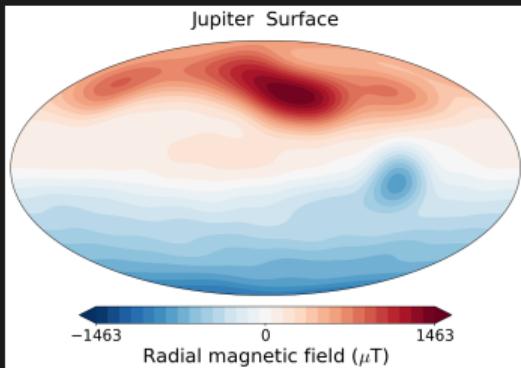


Gas giants: Jupiter



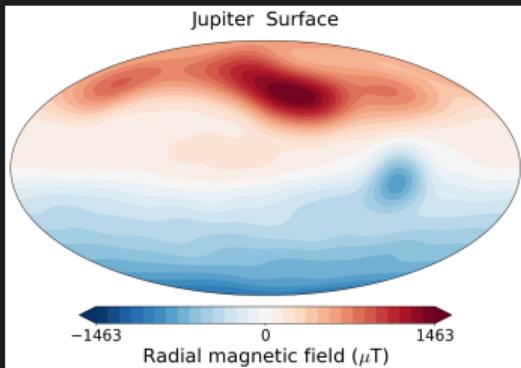
- Strongest field of all

Gas giants: Jupiter



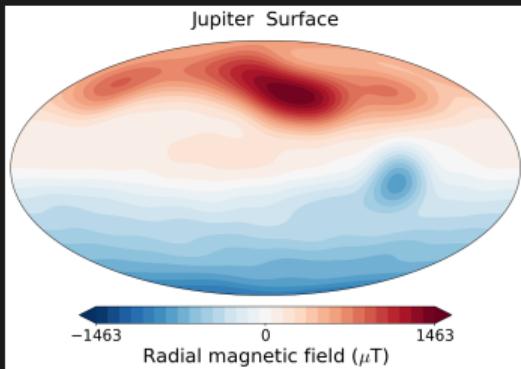
- Strongest field of all
- Broadly dipolar

Gas giants: Jupiter



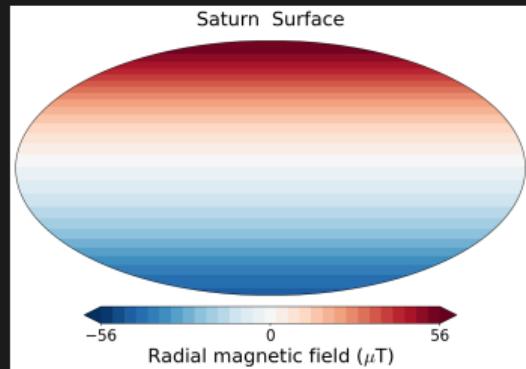
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- The “great blue spot”

Gas giants: Jupiter

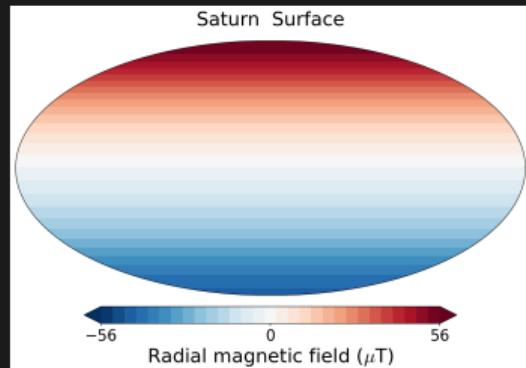


- Strongest field of all
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- Magnetic axis tilted by about 10° w.r.t rotation axis

Gas giants: Saturn

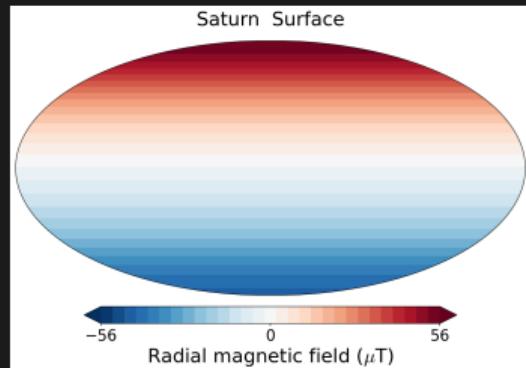


Gas giants: Saturn



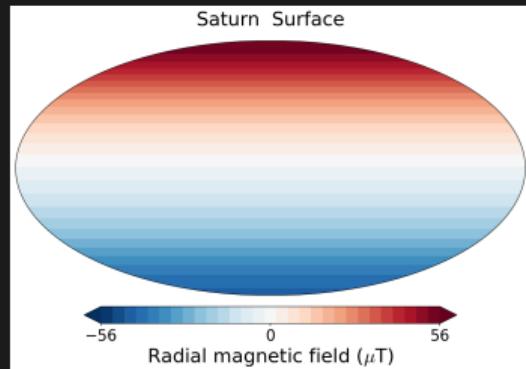
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Gas giants: Saturn



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Gas giants: Saturn

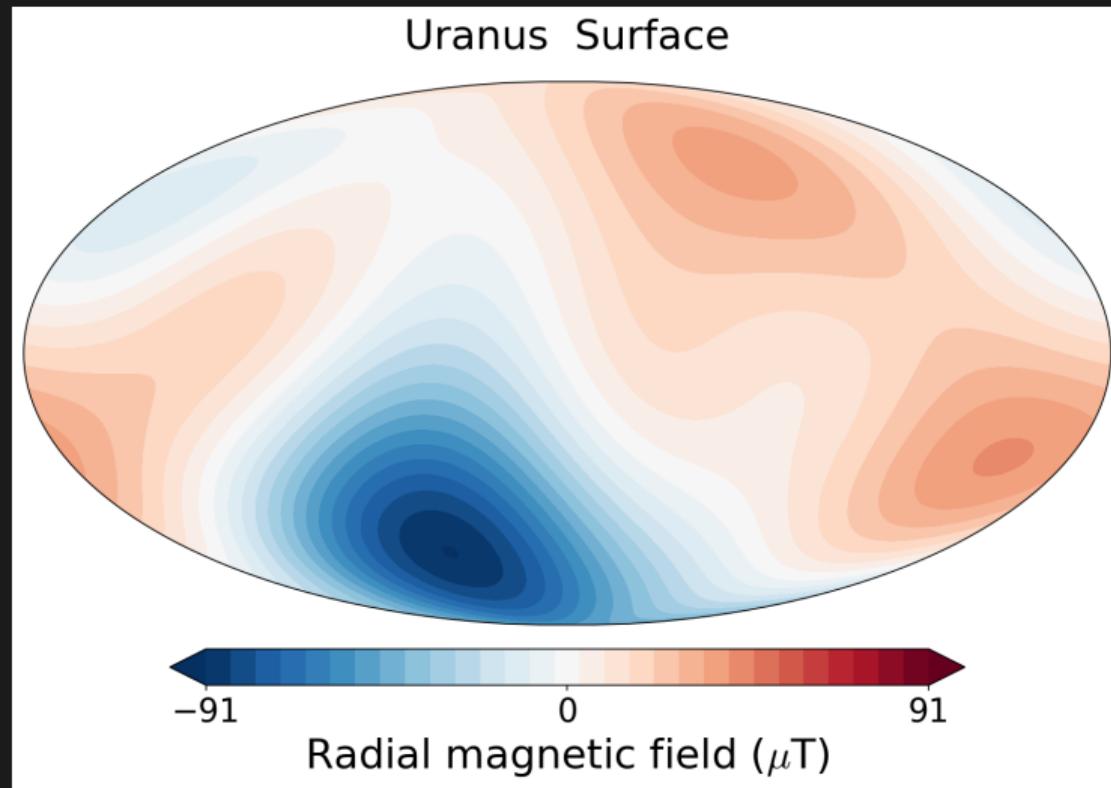


- Field comparable to Earth
- *Very* dipolar
- Magnetic axis almost aligned with rotation axis ($\text{tilt} \leq 0.0095^\circ$)

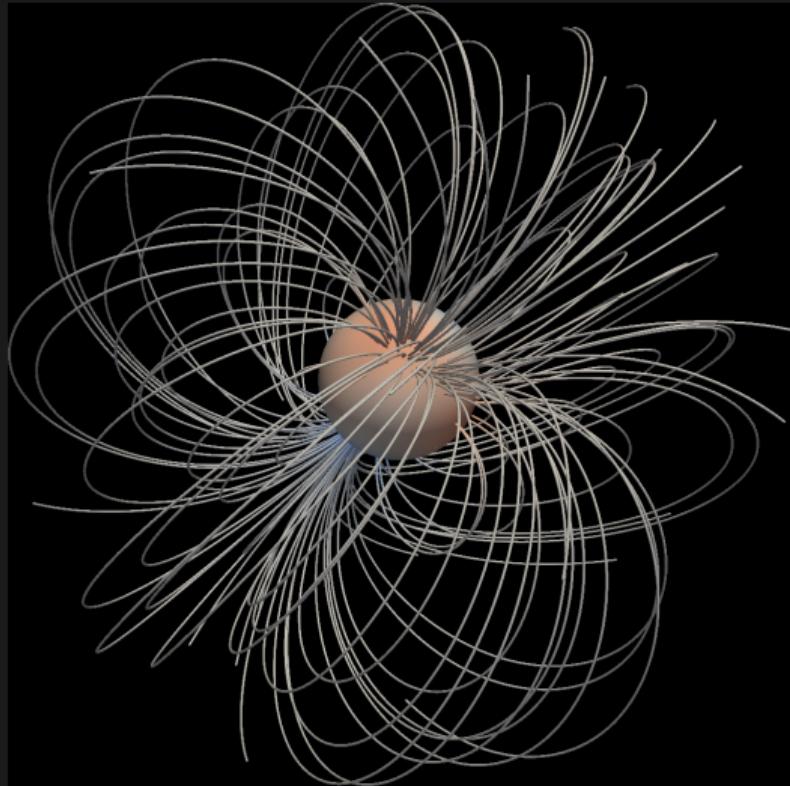
Section 3

Ice giants

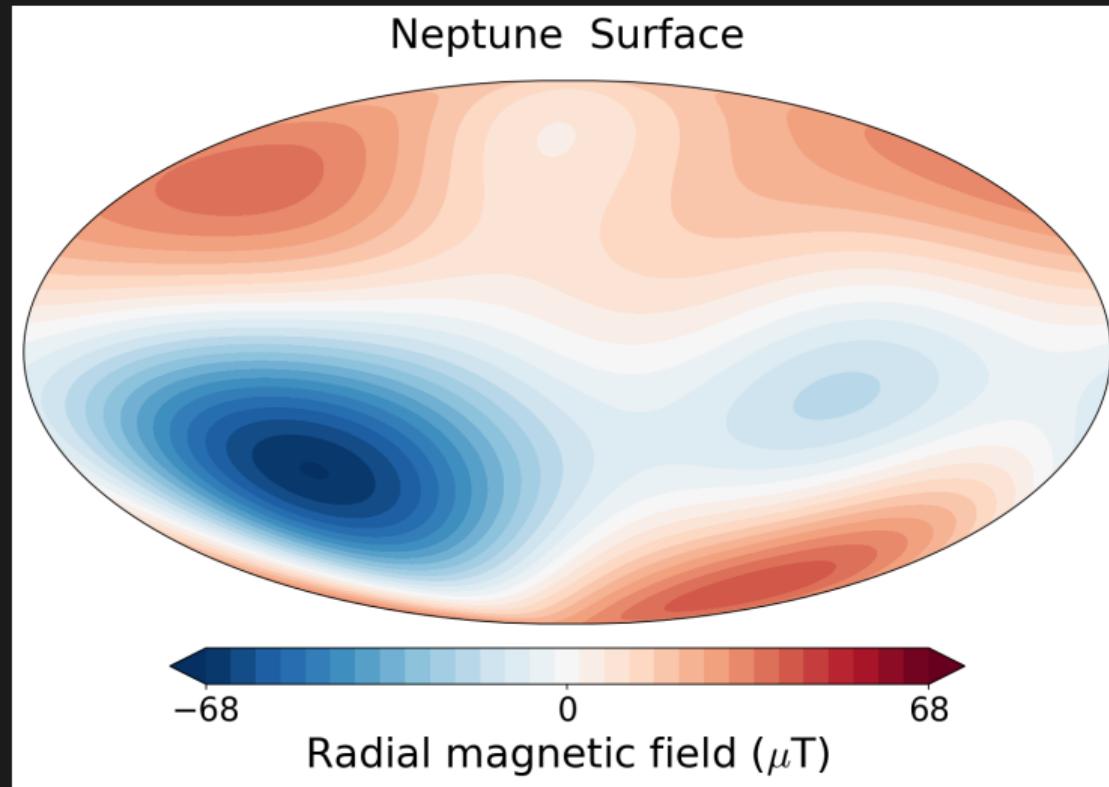
Uranus



Uranus

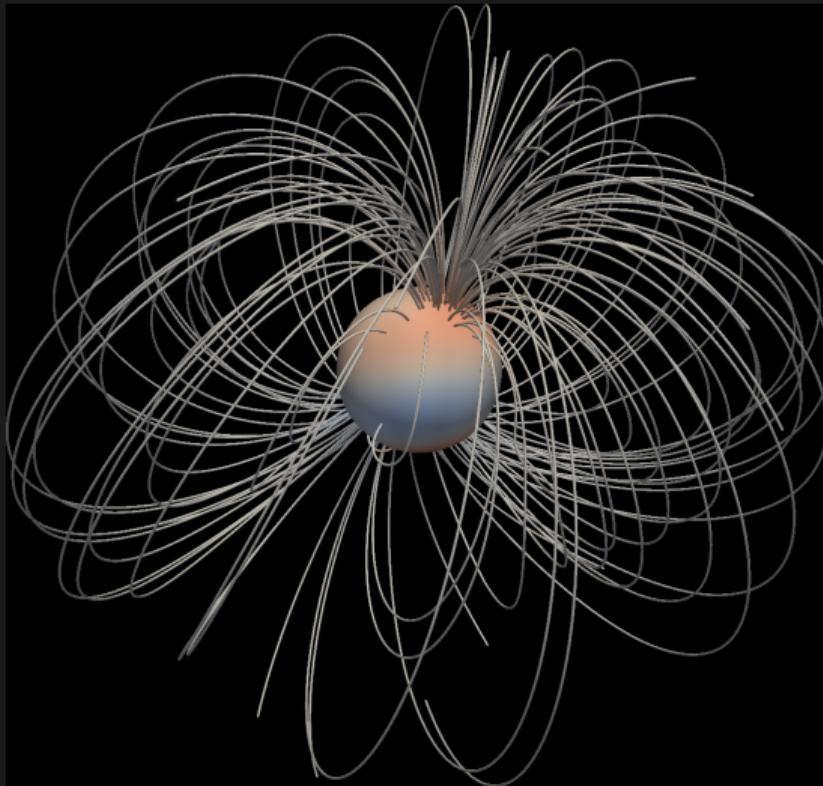


Neptune

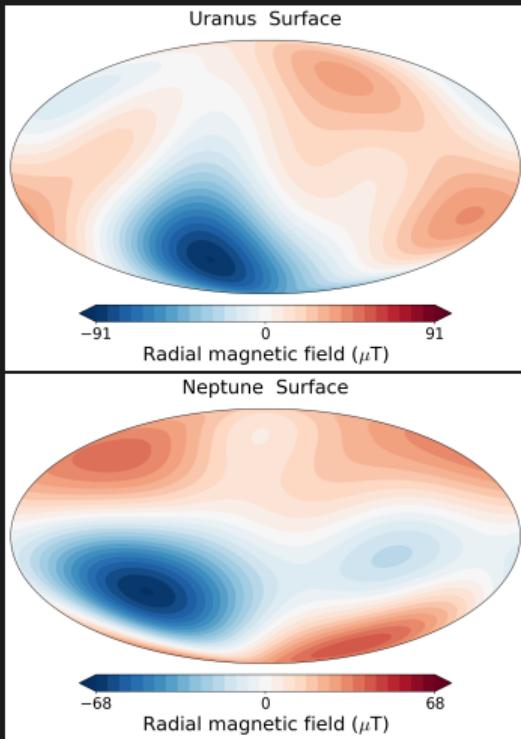


Dipole tilt: 46.9°

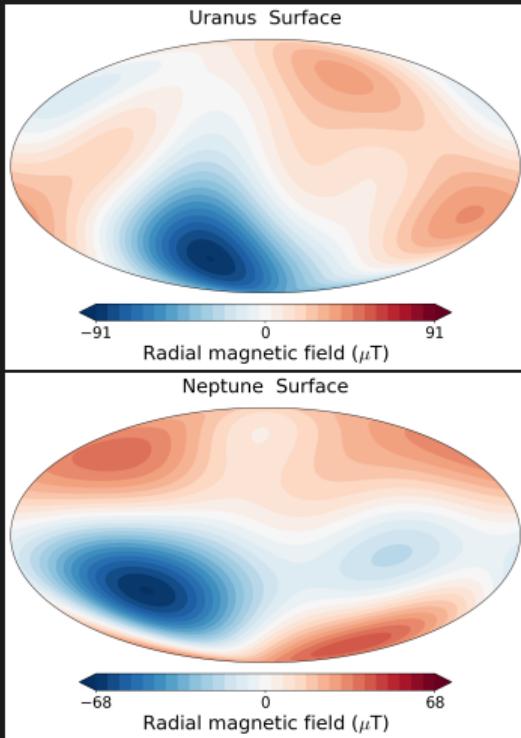
Neptune



Ice giants

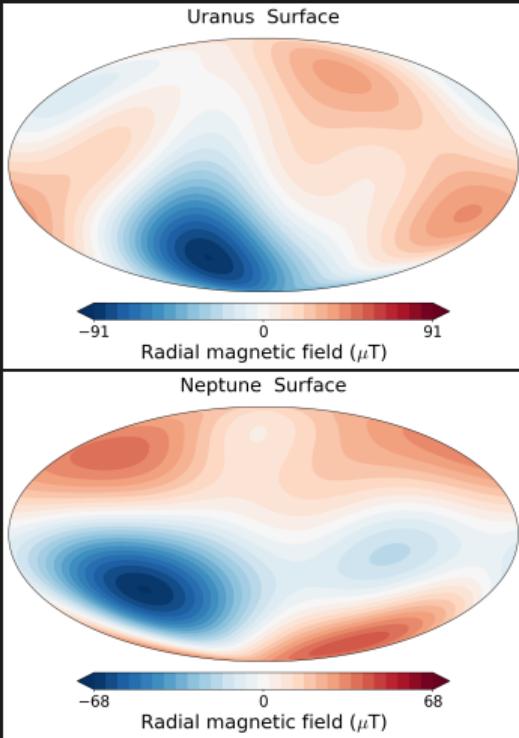


Ice giants



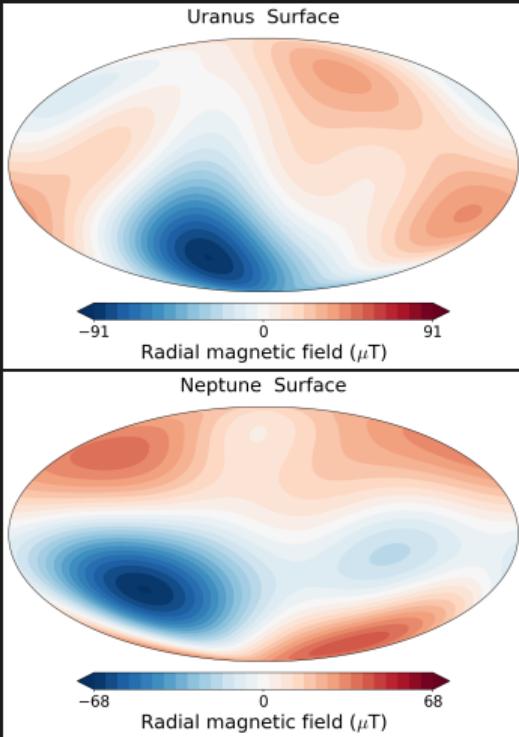
- Very “multipolar” (no clear dipole)

Ice giants



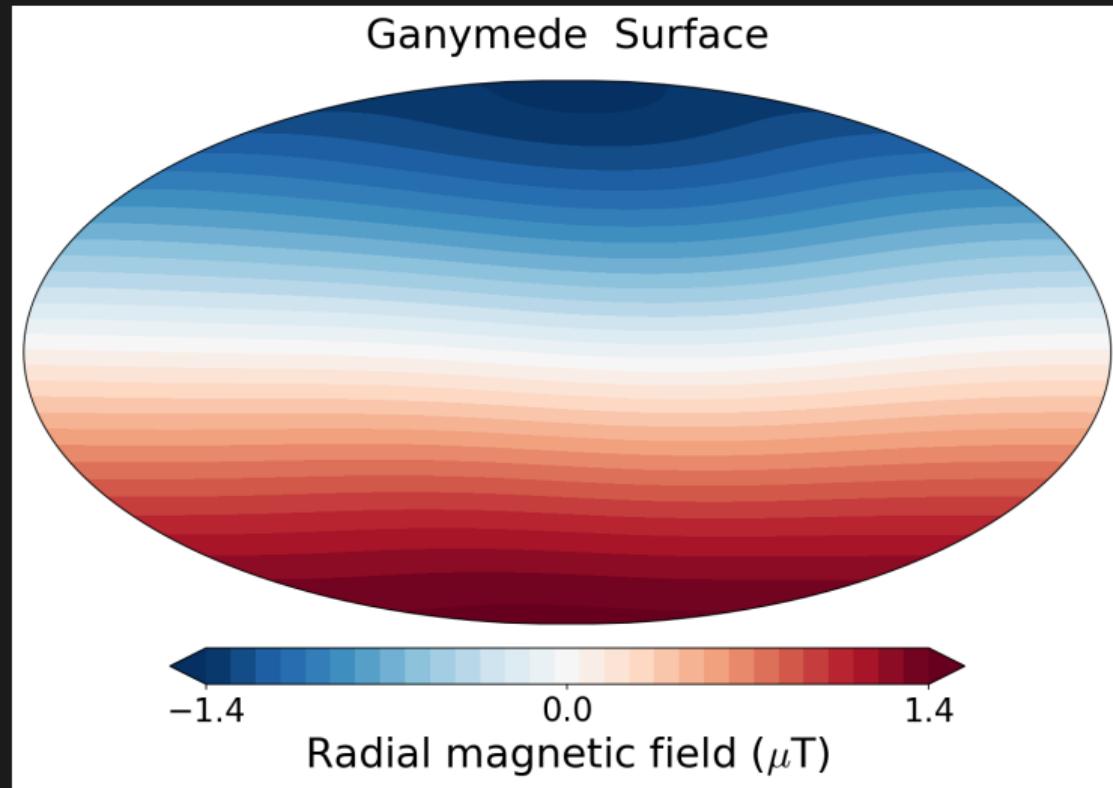
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Ice giants



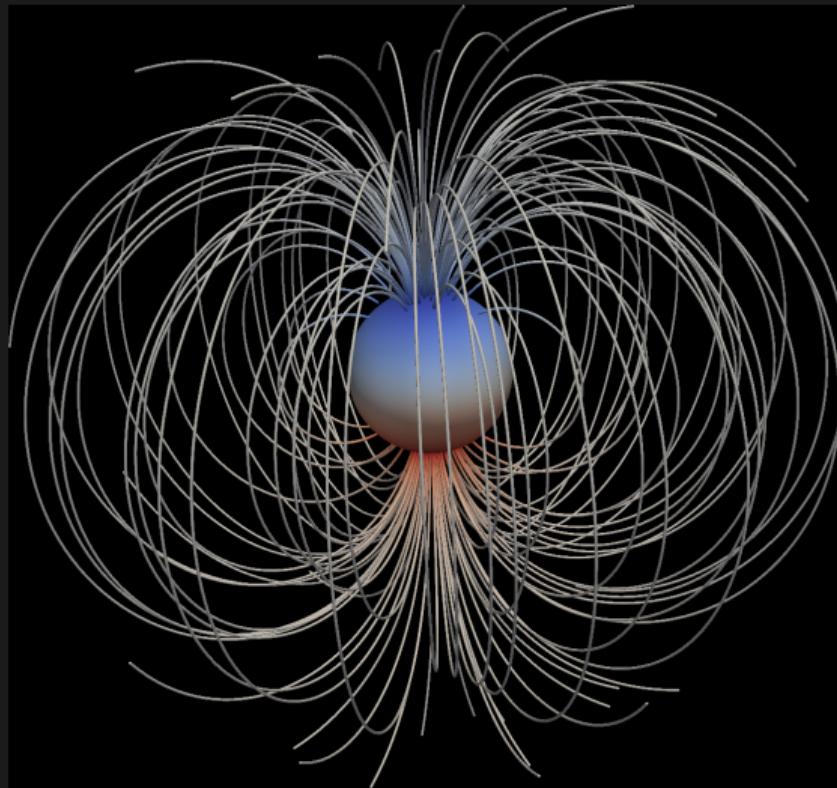
- Very “multipolar” (no clear dipole)
- The dipole is highly tilted w.r.t rotation axis
- Field strengths comparable to Earth/Saturn

Ganymede



Dipole tilt: 4.2°

Ganymede



Honorable mentions

Ancient magnetic fields locked in crust:

- Mars (Mars Global Surveyor, MAVEN, InSight)
- Moon (Rocks from Apollo missions, Lunar Prospector)

Where does the field come from? :O

Early ideas

- Gilbert (1600) : Permanent magnet
- Halley (1683, 1692) : Secular variation due to fluid
- Wiechert (1897); Oldham (1906); Gutenberg (1912); Jeffreys (1926); Lehmann (1936) : Structure of earth from seismology



Figure: Treatise on Geophysics, Volume 8

Early ideas

- Hale (1908) : Magnetic nature of sunspots
- Larmor (1919) : Theory of hydromagnetic dynamo

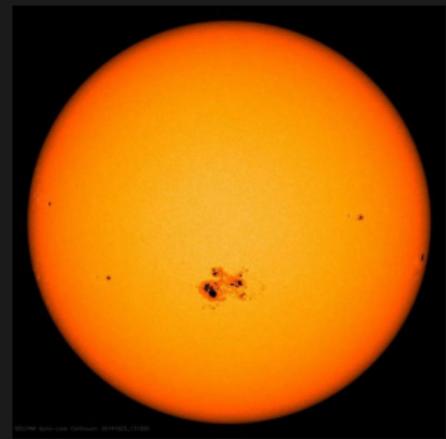


Figure: NASA

Pioneers of Geodynamo theory

REVIEWS OF MODERN PHYSICS

VOLUME 22, NUMBER 1

JANUARY, 1950

The Earth's Interior and Geomagnetism

WALTER M. ELSASSER*

Randal Morgan Laboratory of Physics, University of Pennsylvania, Philadelphia, Pennsylvania

HOMOGENEOUS DYNAMOS AND TERRESTRIAL MAGNETISM

BY SIR EDWARD BULLARD, F.R.S. AND H. GELLMAN

National Physical Laboratory and University of Toronto

(Received 17 November 1953—Revised 1 June 1954)

Einstein refused to believe Walter M. Elsasser because the theory is too messy!

Interior

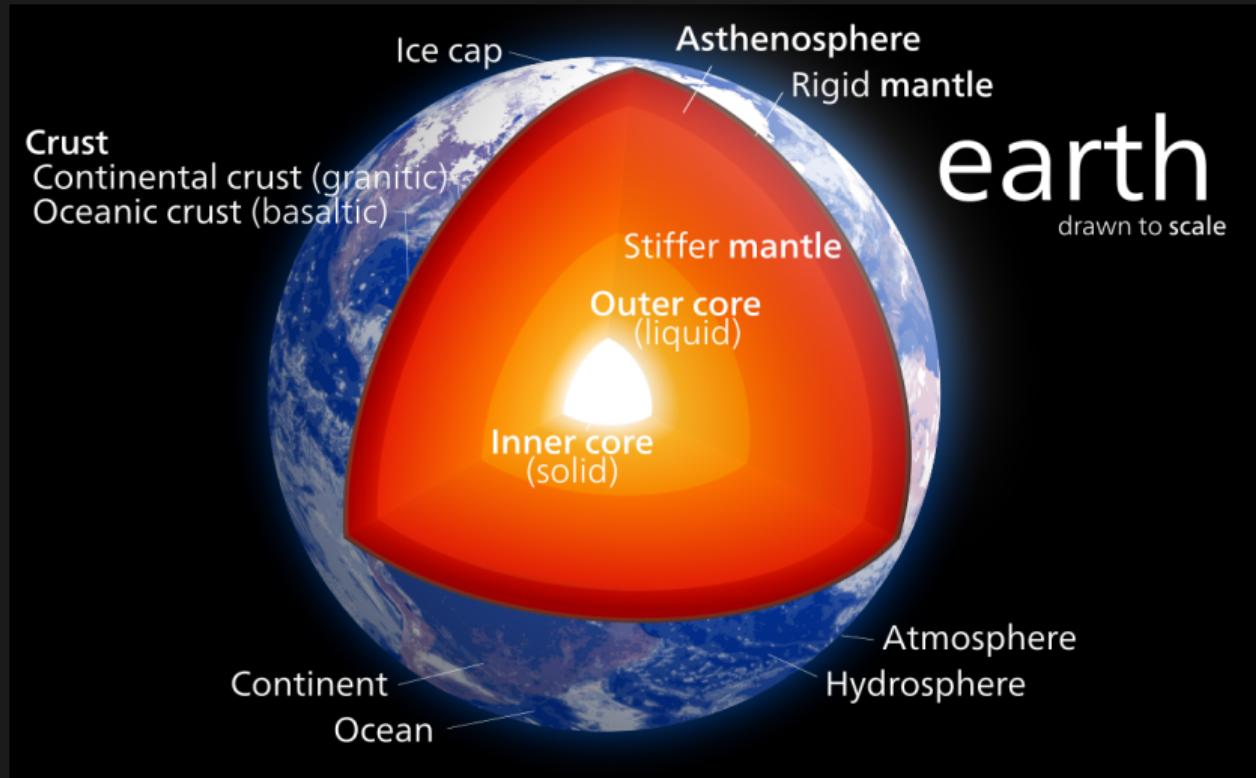


Figure by Kelvinsong - Own work, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=23966175>

Dynamo theory

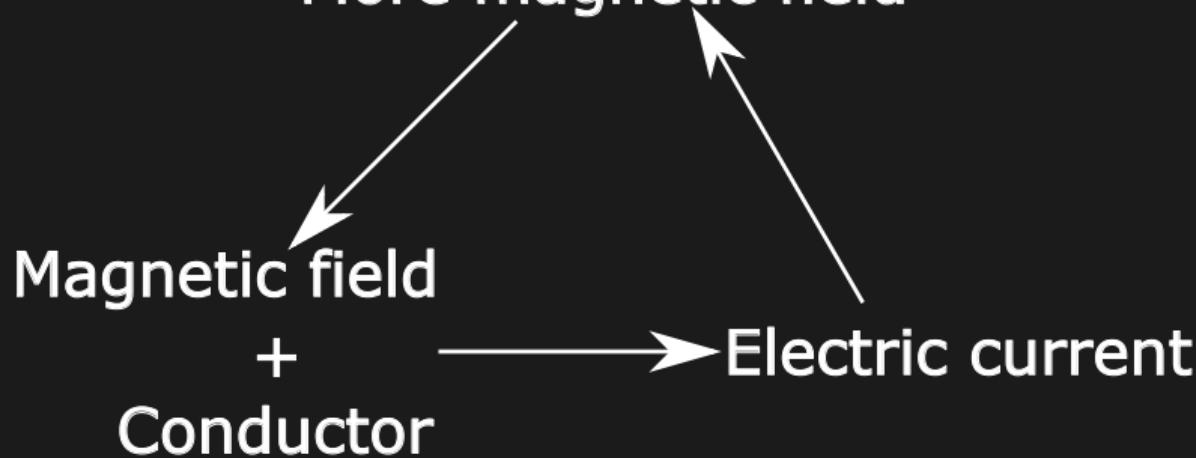


Image from <http://mooniesdynamo.blogspot.com/>

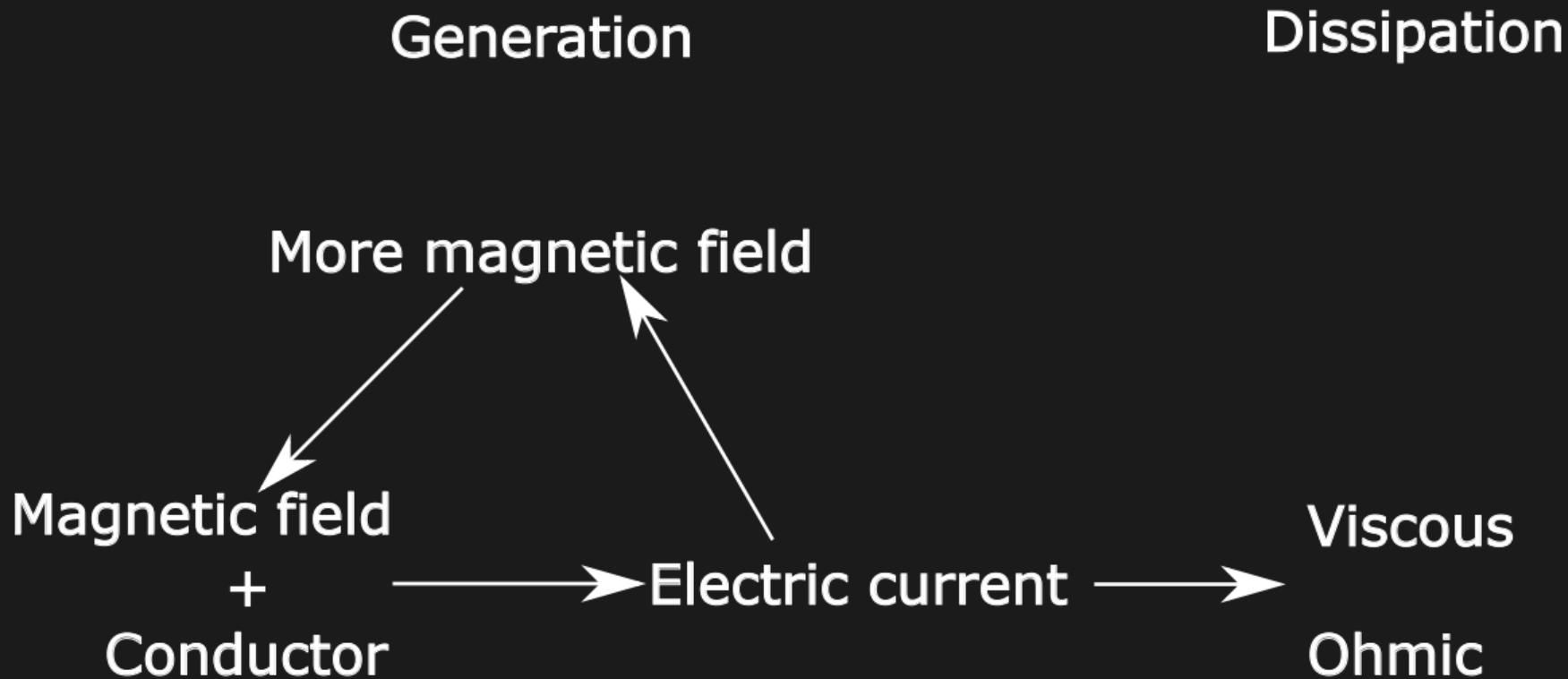
Dynamo theory

Generation

More magnetic field

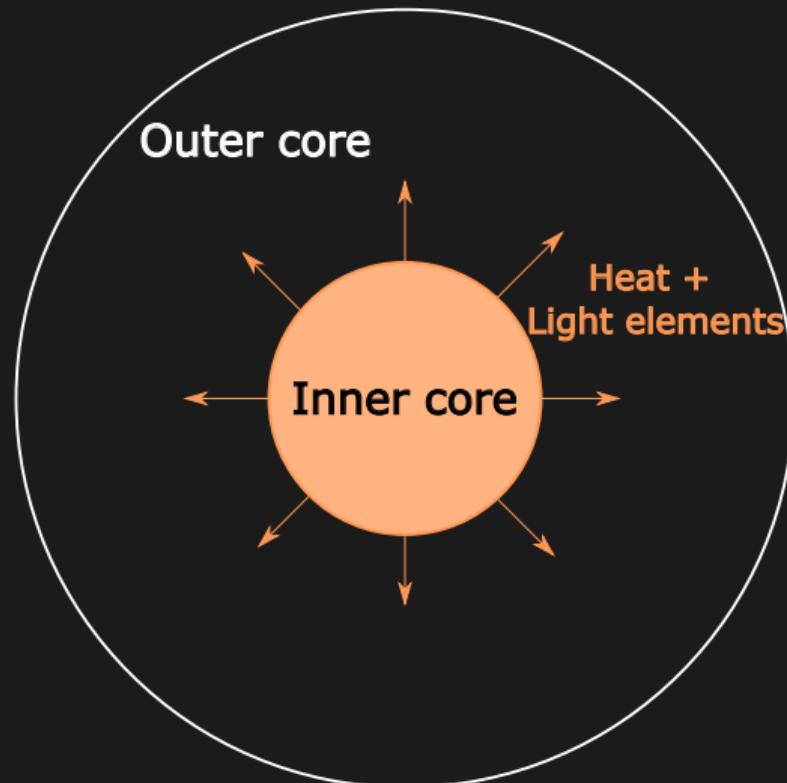


Dynamo theory

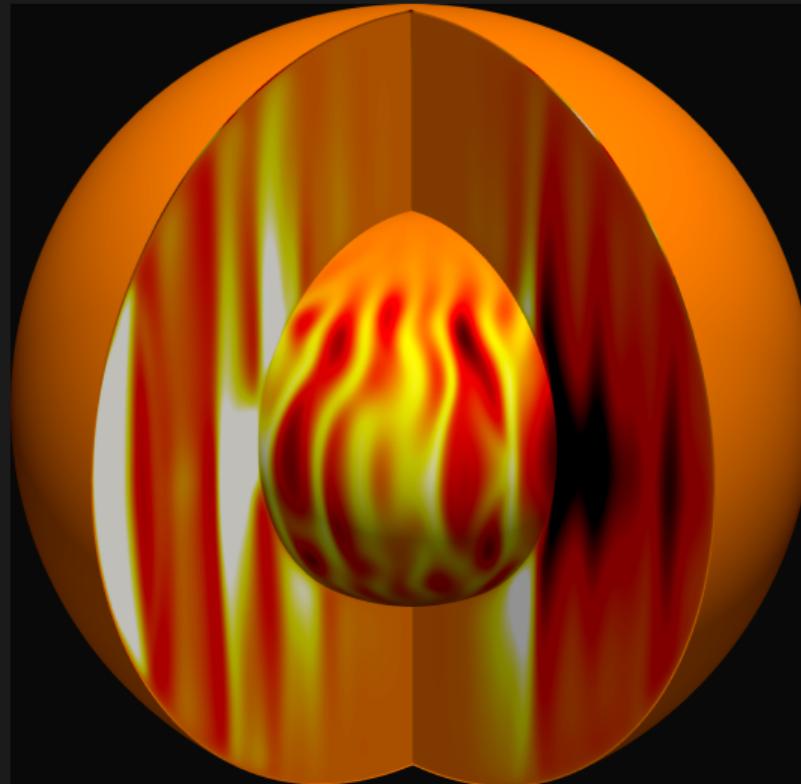


But how?

Convection



Rotating convection



Dynamo action

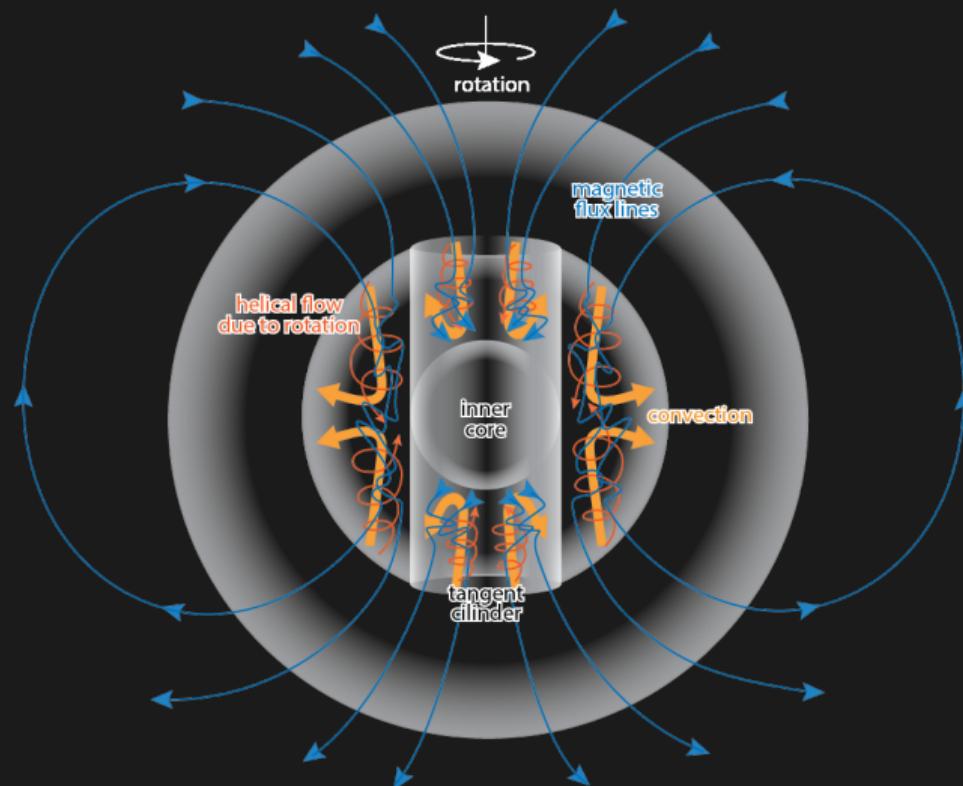


Figure by Sabrina Sanchez, MPI for Solar System Research, Germany

Planetary interiors : Terrestrial planets

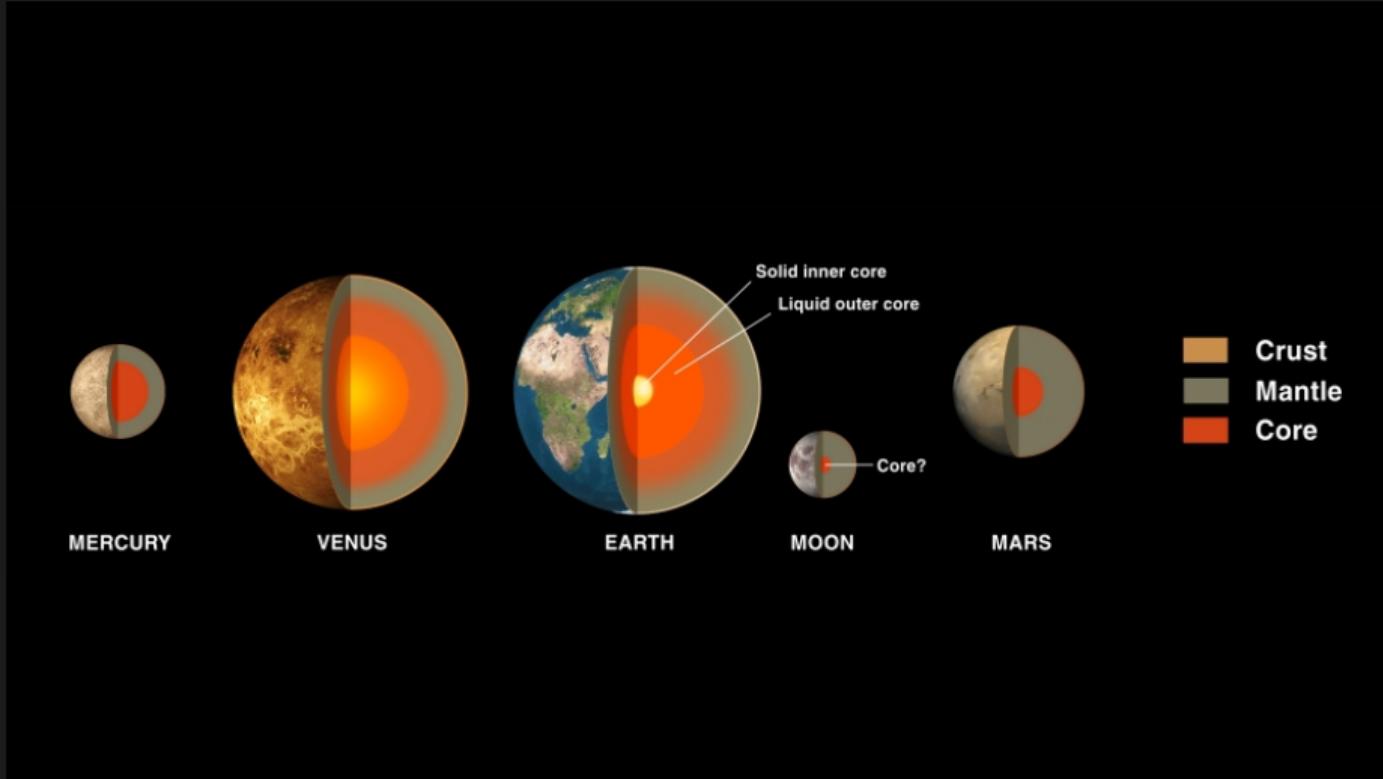


Figure : NASA

Planetary interiors : Gas and Ice giants

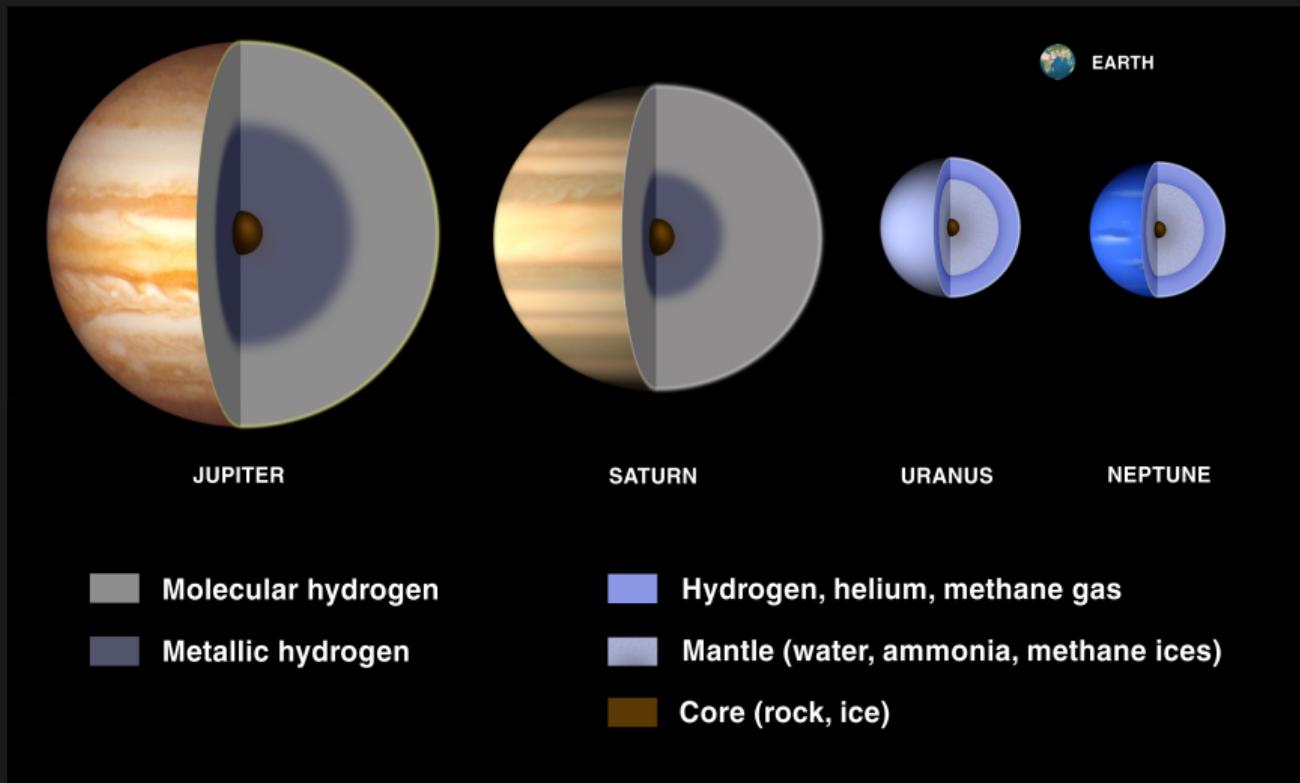


Figure : NASA

What do magnetic fields tell us about planets?

Planetary interiors

Magnetic fields go through the entire planet and thus carry information about different layers making tiny changes to them

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- Presence of magnetic field generation \Rightarrow dynamic interior + possible plate tectonics (e.g: Venus vs Earth)

Planetary interiors

Magnetic fields go through the entire planet and thus carry information about different layers making tiny changes to them

- Presence of magnetic field generation \Rightarrow dynamic interior + possible plate tectonics (e.g: Venus vs Earth)
- Dynamic history \rightarrow seafloor spreading, ancient crustal fields

Planetary interiors

Details of magnetic field:

Planetary interiors

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- Weak and rotation aligned : non-convecting filtering layer (skin effect)?

Planetary interiors

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Planetary interiors

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Planetary interiors

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- Weak and rotation aligned : non-convecting filtering layer (skin effect)?
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- Heat flux pattern on top of the conducting layer

Planetary interiors

Details of magnetic field:

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Planetary interiors

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- Dipole dominated : high effect of rotation
- Not dipolar : thin fluid layer?
- Heat flux pattern on top of the conducting layer
- Electrical conductivity structure
- Interaction with solar wind

Big questions in planetary dynamos

- Why are most planetary fields dominated by a dipole?
- Why is Mercury's field so weak?
- Why is there no field on Venus?
- What causes reversals of the geodynamo?
- What powered the geodynamo before inner core formation?
- What powered the Ancient lunar dynamo?
- What killed off the Martian dynamo?
- How does Jupiter maintain its strong jets despite a strong magnetic field?
- Why is Saturn's field aligned with the rotation axis?
- Why are the fields of Uranus and Neptune not dominated by a dipole?

Let's watch a video!