COSMIC MAGNETIC FIELDS

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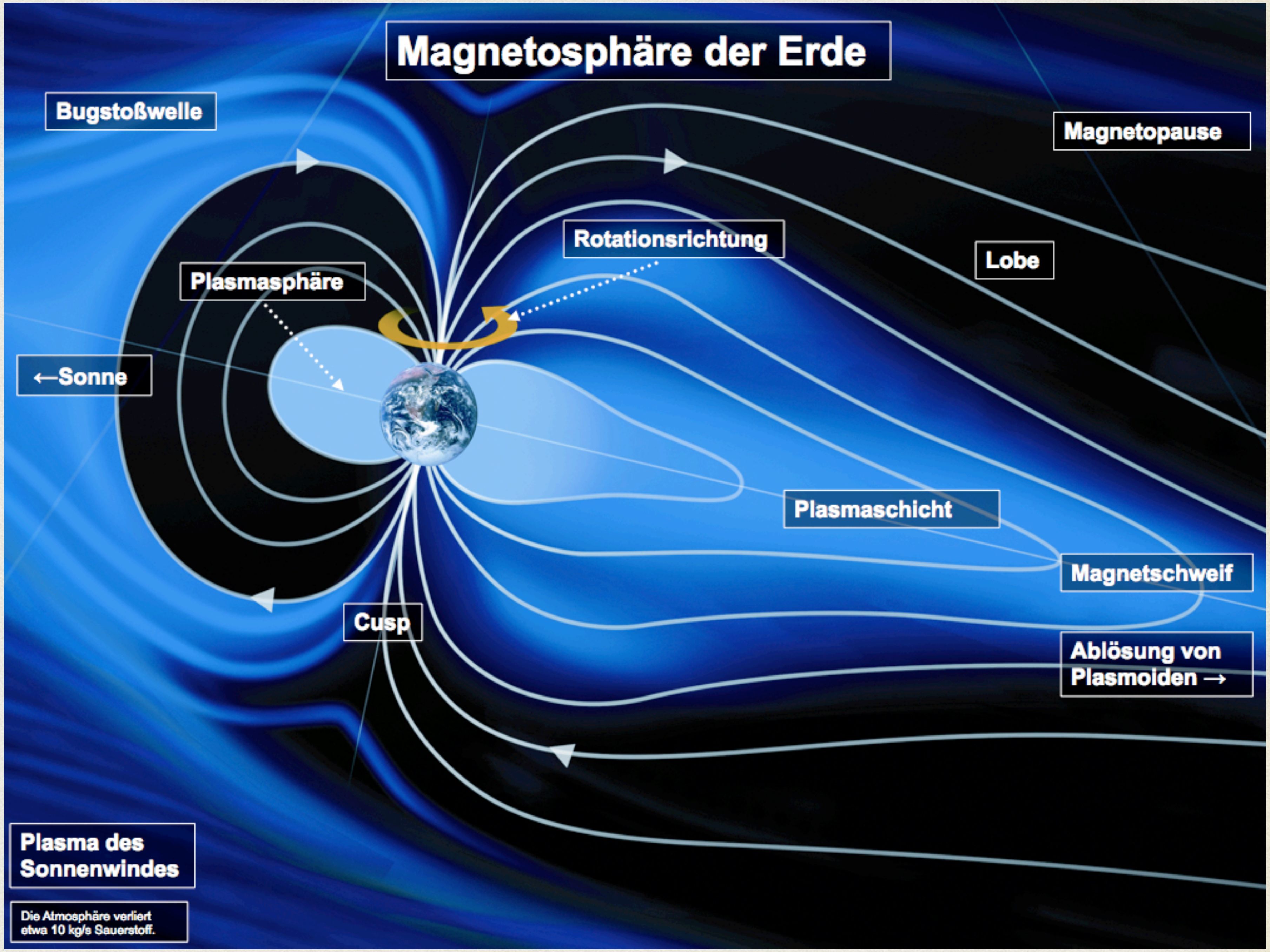
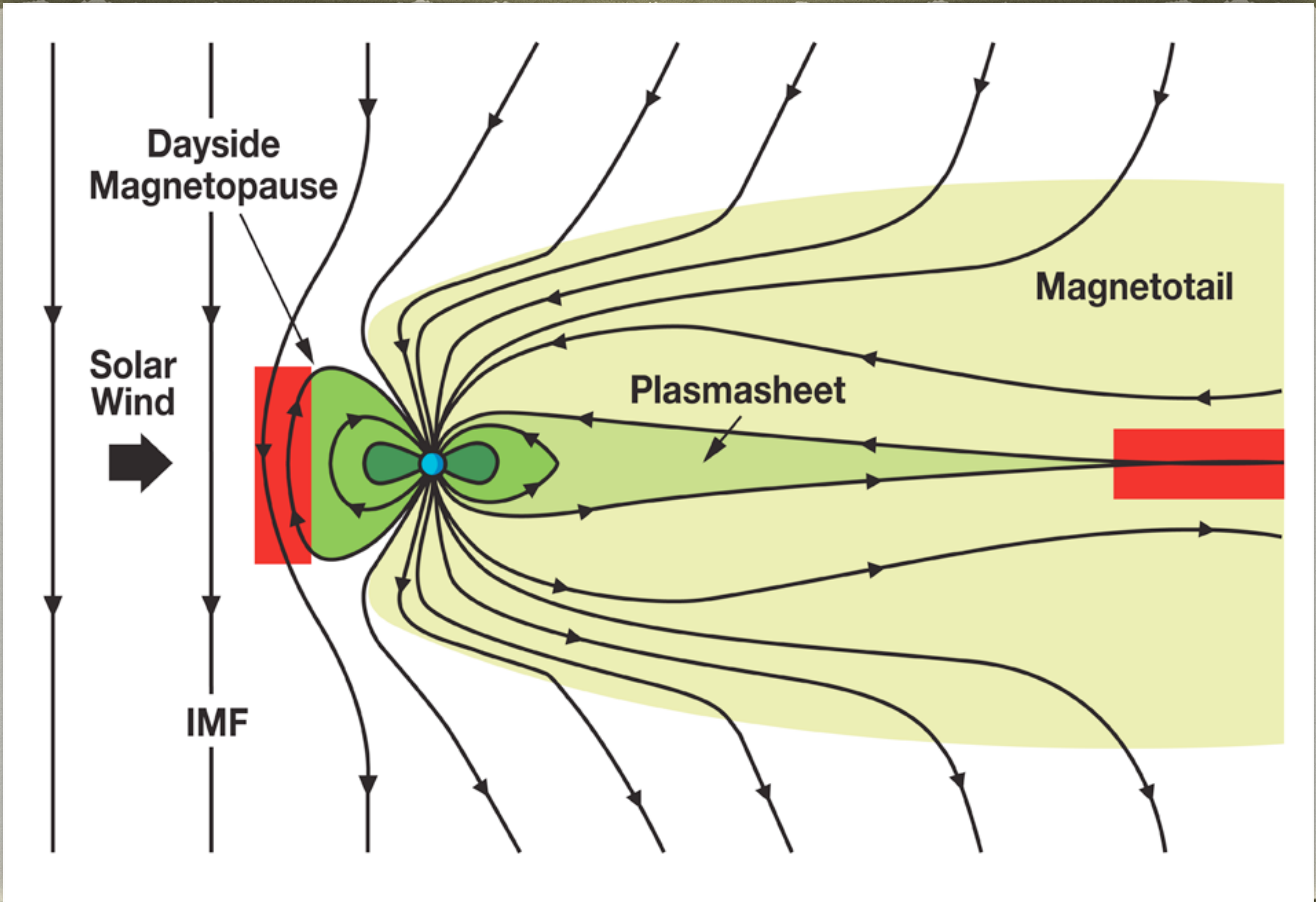
Planets

EARTH

- mean surface strength 0.3 G
- dipole moment 7.8×10^{22} A m^2 (2000.0), decreasing 5%/century
- magnetic pole inclination 11°



EARTH

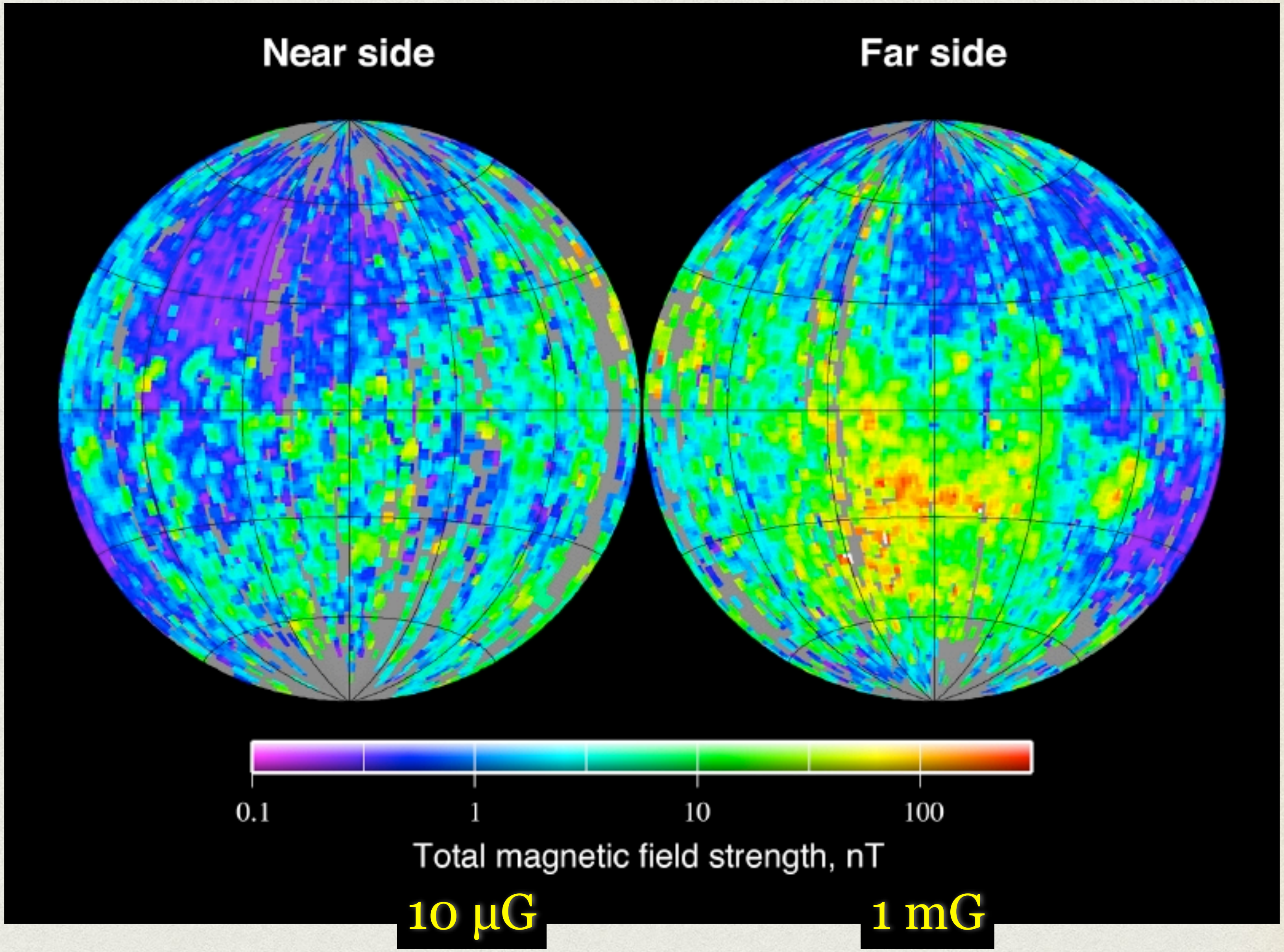


Dayside
Magnetopause
Solar
Wind
IMF
Magnetotail
Plasmasheet

MOON

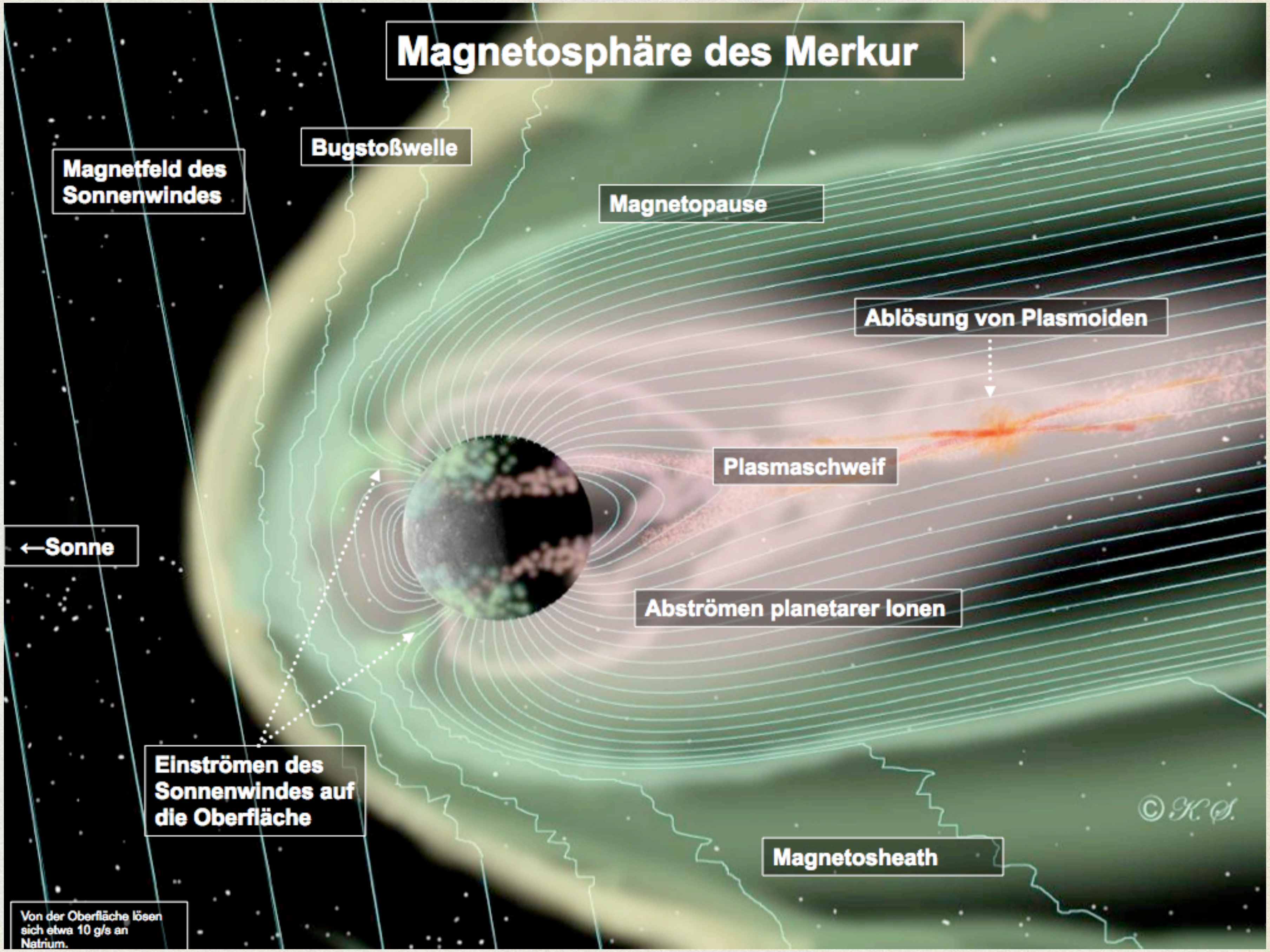
- weak irregular surface field: 3-1000 μG
- could be related to large meteor impacts
- no dynamo today, unclear if ever
- complex interactions with Earth's magnetotail

Lunar Prospector (NASA)

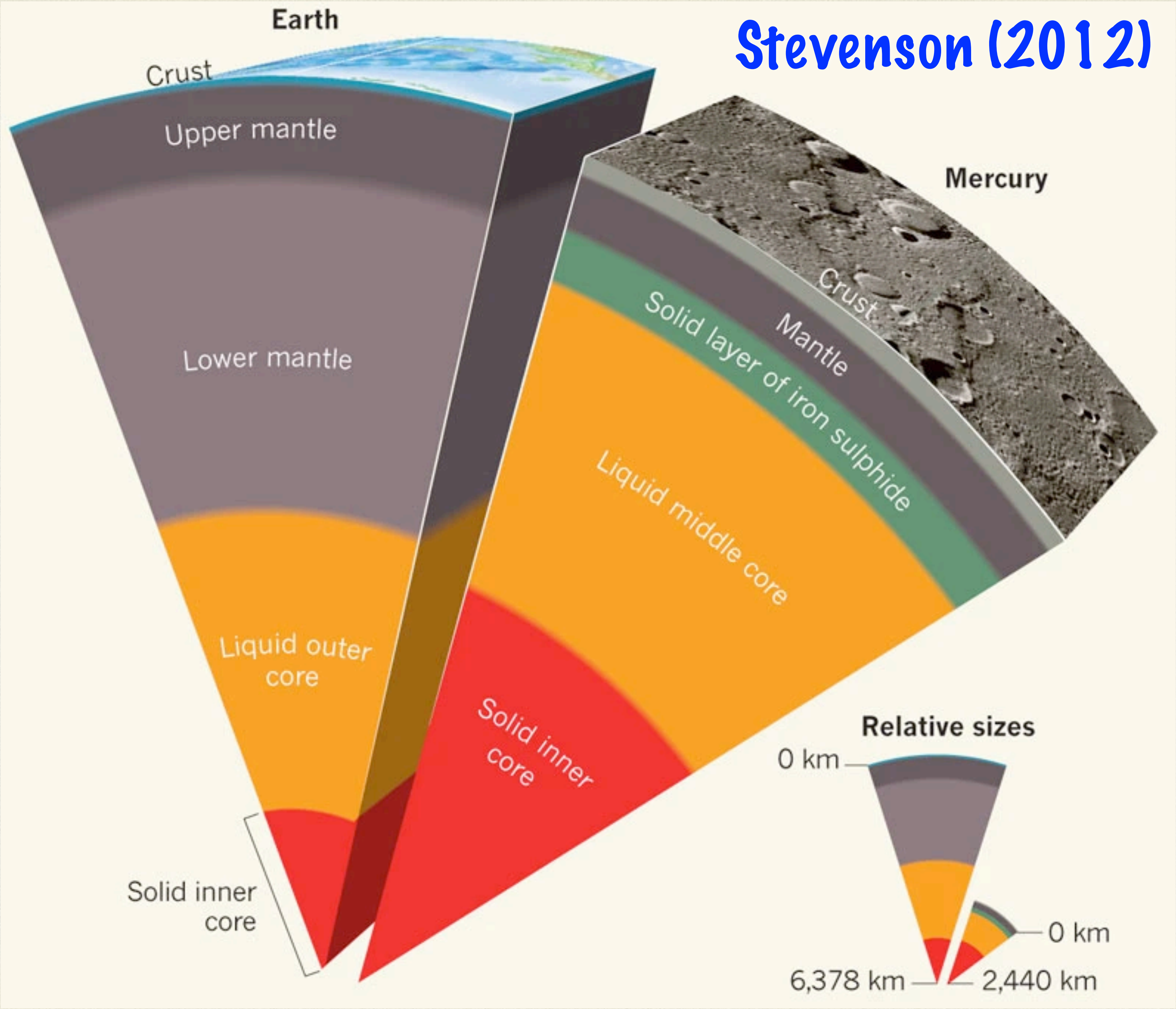


MERCURY

- first measured by Mariner 10 (1974)
- dipole moment $2\,\mathrm{mG} \times R_\mathrm{M}^3$ from MESSENGER (Anderson et al. 2011)
- inclination $< 3^\circ$ offset N by $0.2\,\mathrm{R_M}$
- radius $R_\mathrm{M} = 2436\,\mathrm{km}$ metallic core $0.85\,\mathrm{R_M}$ (partially liquid)
- rotation period $P_\mathrm{M} = 58.6\,\mathrm{d}$



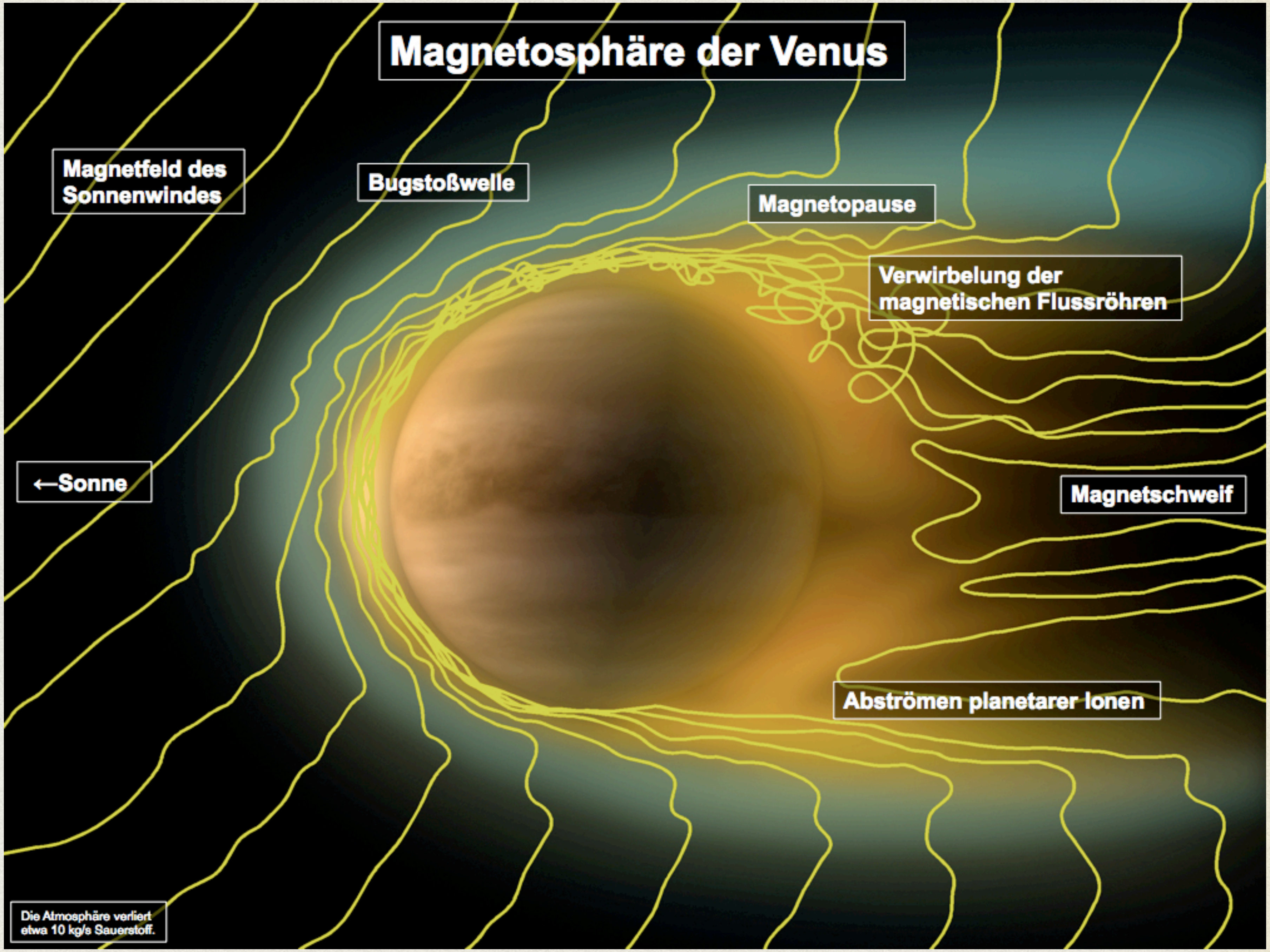
MERCURY



Earth
Stevenson (2012)
Crust
Upper mantle
Lower mantle
Liquid outer core
Solid inner core
Mercury
Crust
Mantle
Solid layer of iron sulphide
Liquid middle core
Solid inner core
Relative sizes
0 km
6,378 km
0 km
2,440 km

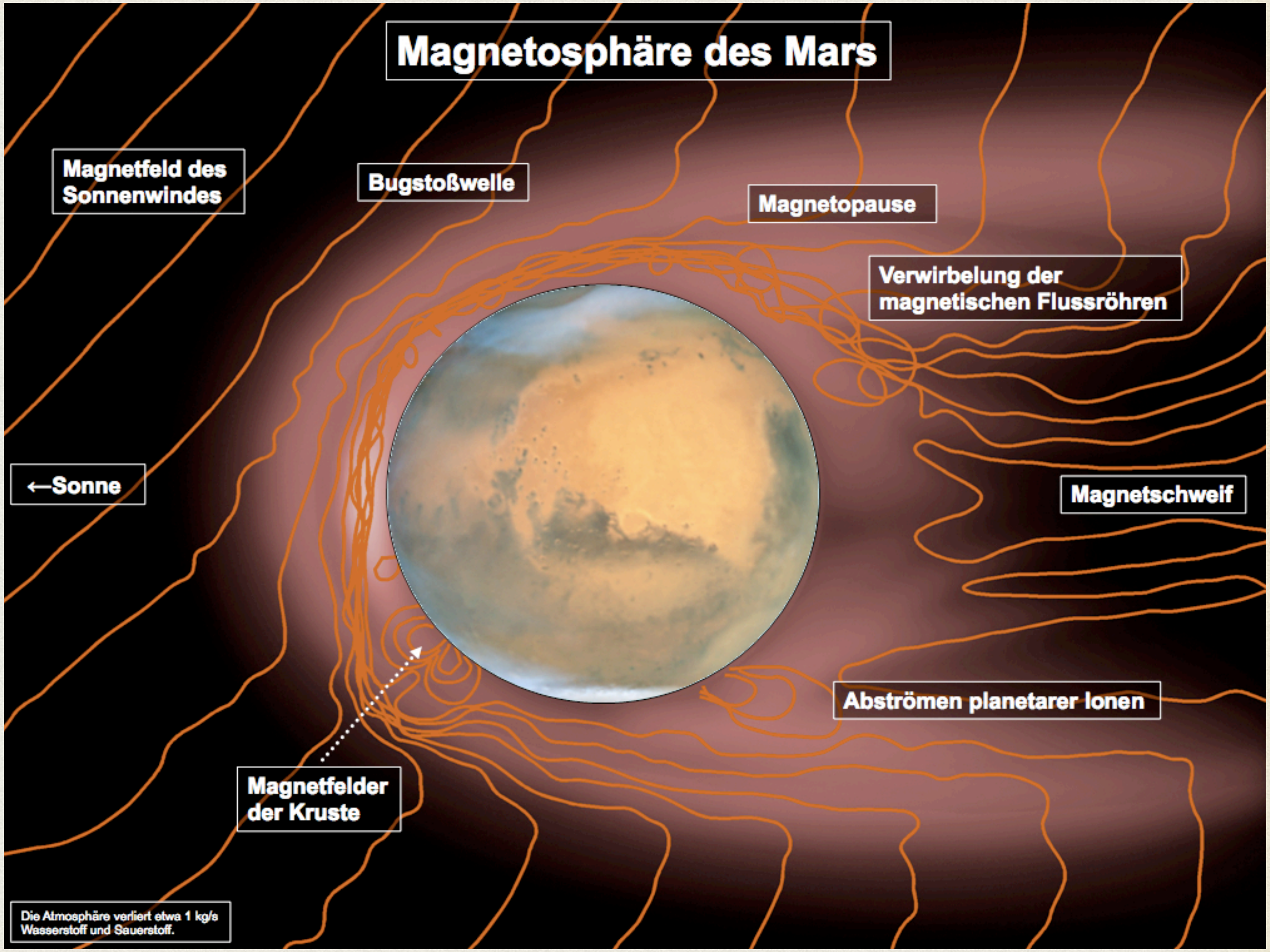
VENUS

- dipole moment $< 20\,\mu\mathrm{G} \times R_\mathrm{V}^3$ (Pioneer Venus, Stevenson 1983)
- inactive plate tectonics reduced heat flux, increased mantle temperature, insufficient convection
- any paleo-fields erased in the hot crust
- radius $R_\mathrm{V} = 6050\,\mathrm{km}$ core $0.58\,R_\mathrm{V}$ (unknown state) (Margot et al. 2021)
- rotation period 243 d



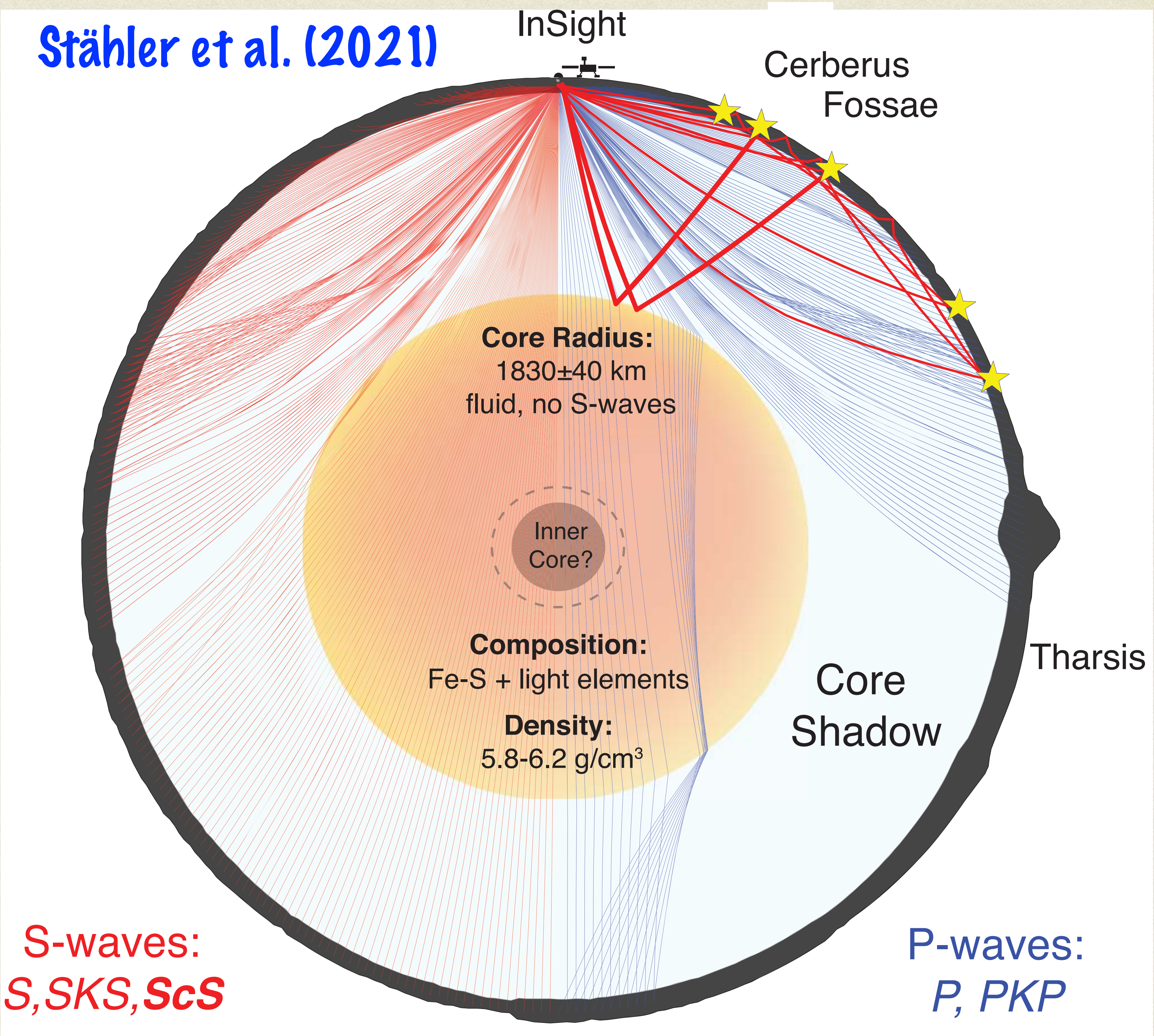
MARS

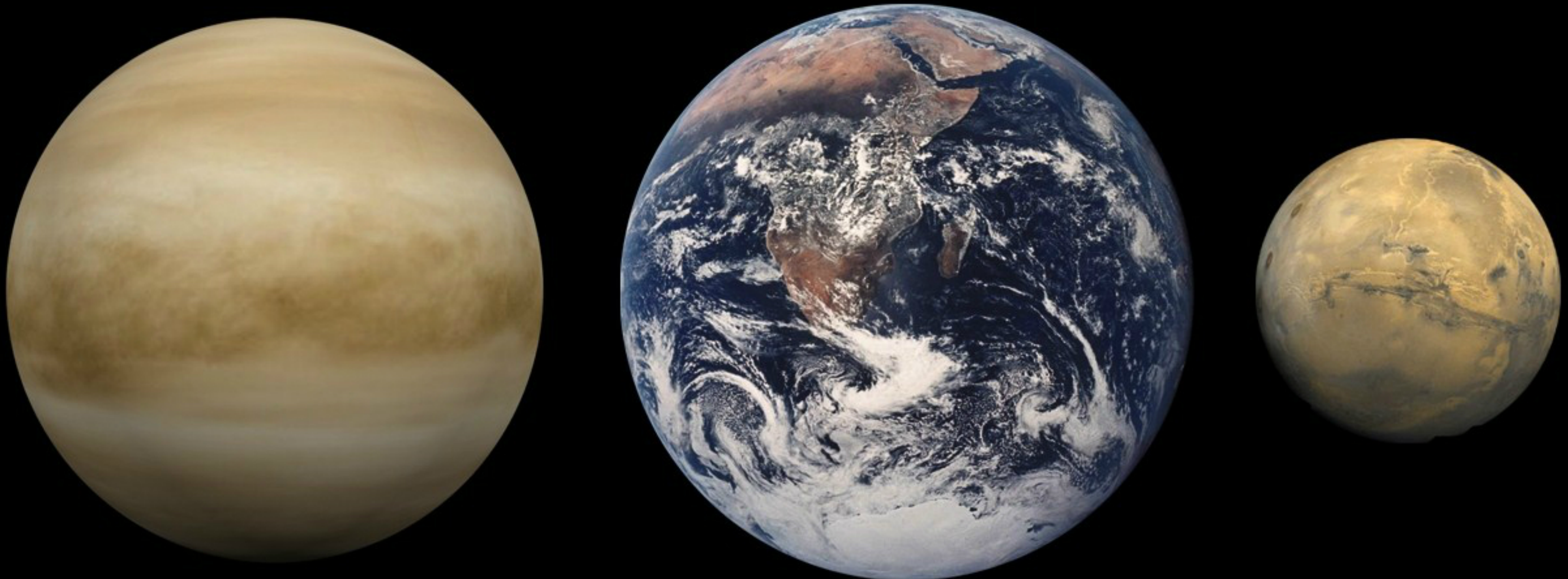
- dipole moment $< 0.1\,\mathrm{mG} \times R_\mathrm{M}^3$ (Stevenson 1983)
- weak localized crustal fields
- radius $R_\mathrm{M} = 3390\,\mathrm{km}$ core $0.54\,R_\mathrm{M}$
- rotation period 1.026 d



MARS

- The core of Mars was detected seismically and determined to be fluid by the InSight lander.
- The lack of current dynamo is probably due to lack of inner core (chemical composition, rather low temperature).
- There have likely been a dynamo in the first billion years.

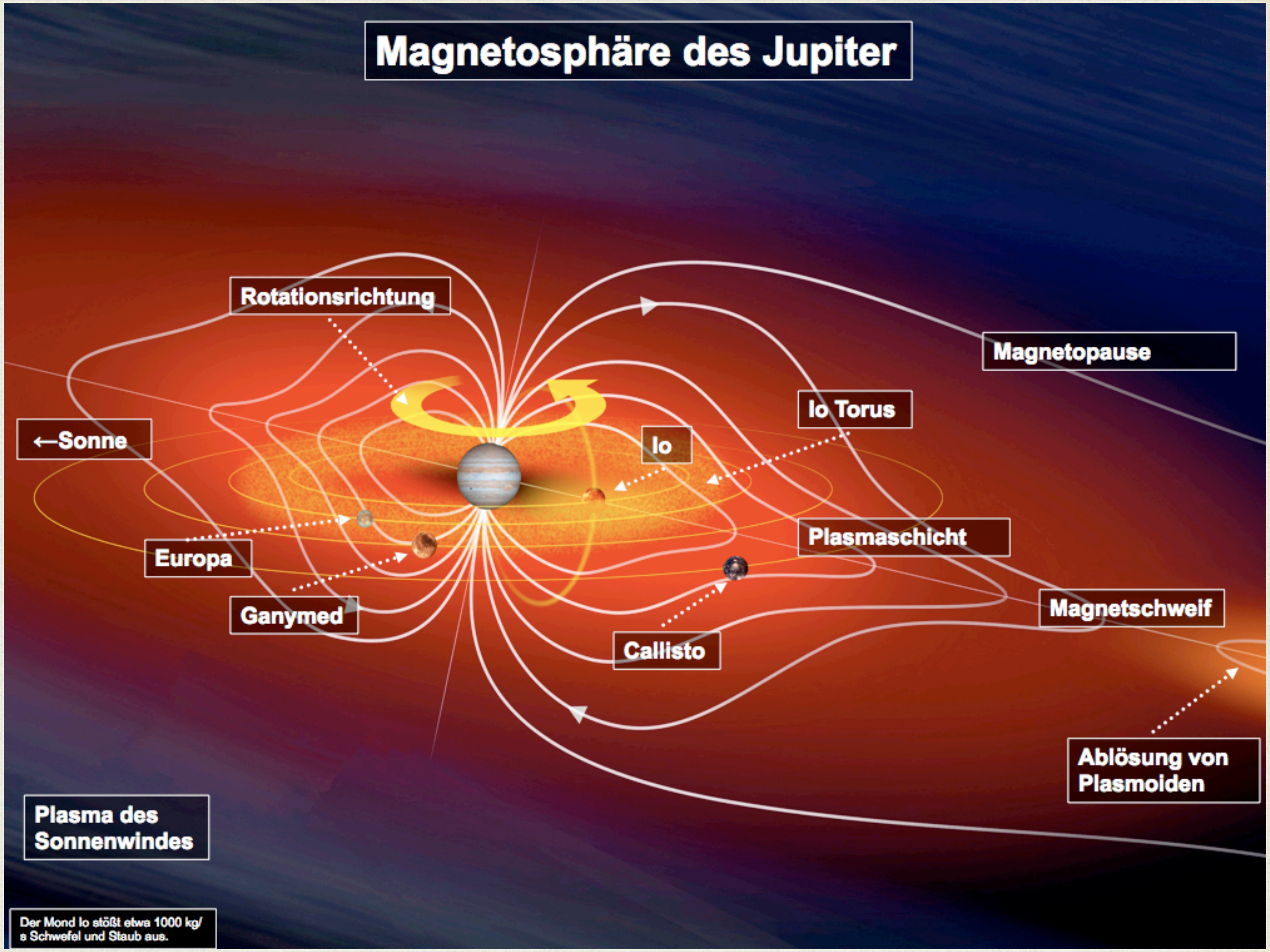




magnetosphere is a factor for habitability
protects the atmosphere from the impact of the solar wind
greatly reduces the rate of hydrogen escape
oceans support plate tectonics that cools the mantle
which allows convection in the core

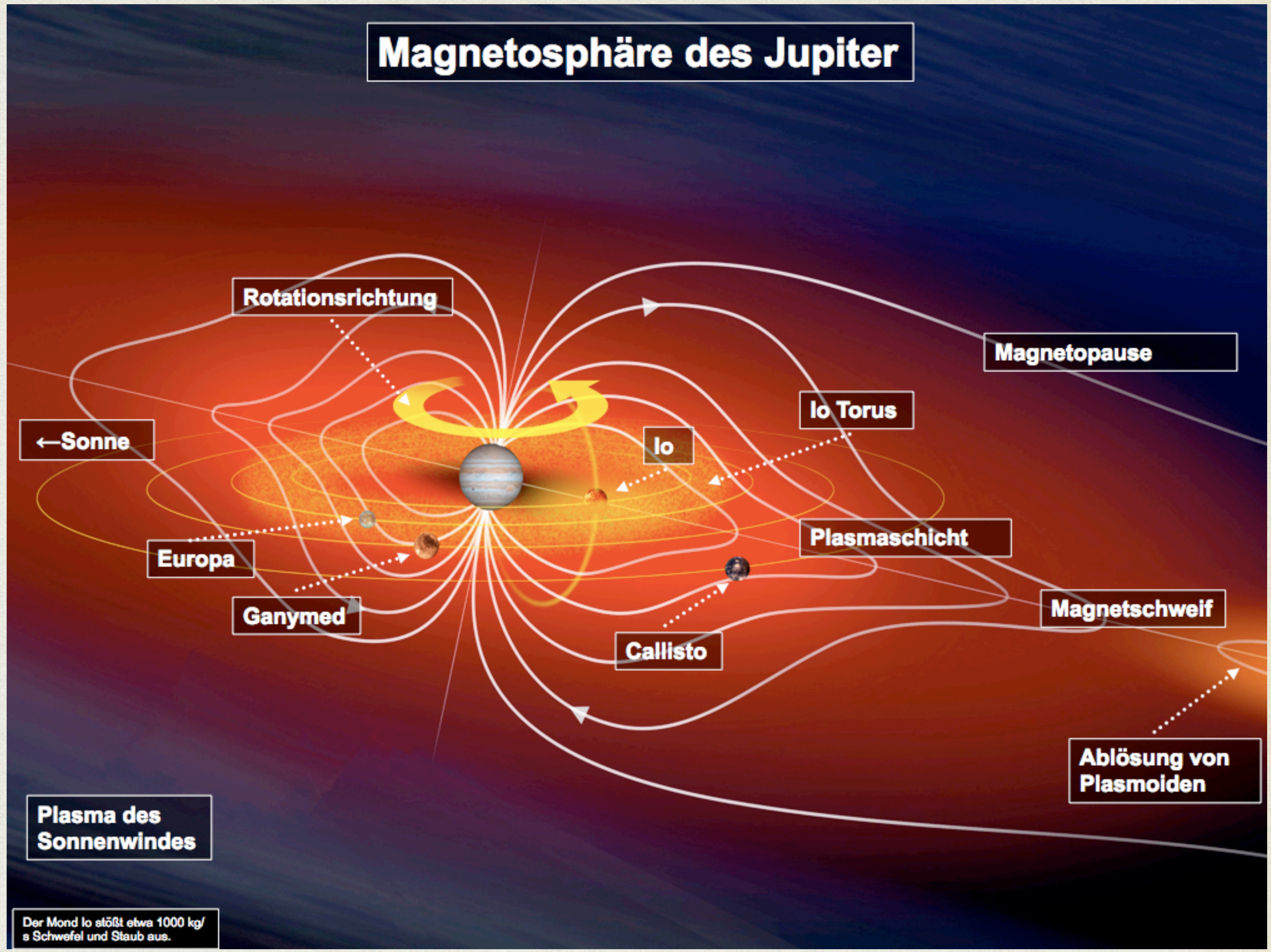
JUPITER

- discovered due to decametric radio emission (Burke & Franklin 1955)
- dipole moment $4.2\,\mathrm{G} \times R_\mathrm{J}^3$ (Juno; Connerney et al. 2018)
- radius $R_\mathrm{J} = 69900\,\mathrm{km}$ metallic hydrogen with $\eta \sim 10^5\,\mathrm{cm}^2/\mathrm{s}$ $\sim 0.8\,R_\mathrm{J}$
- rotation period 0.41 d

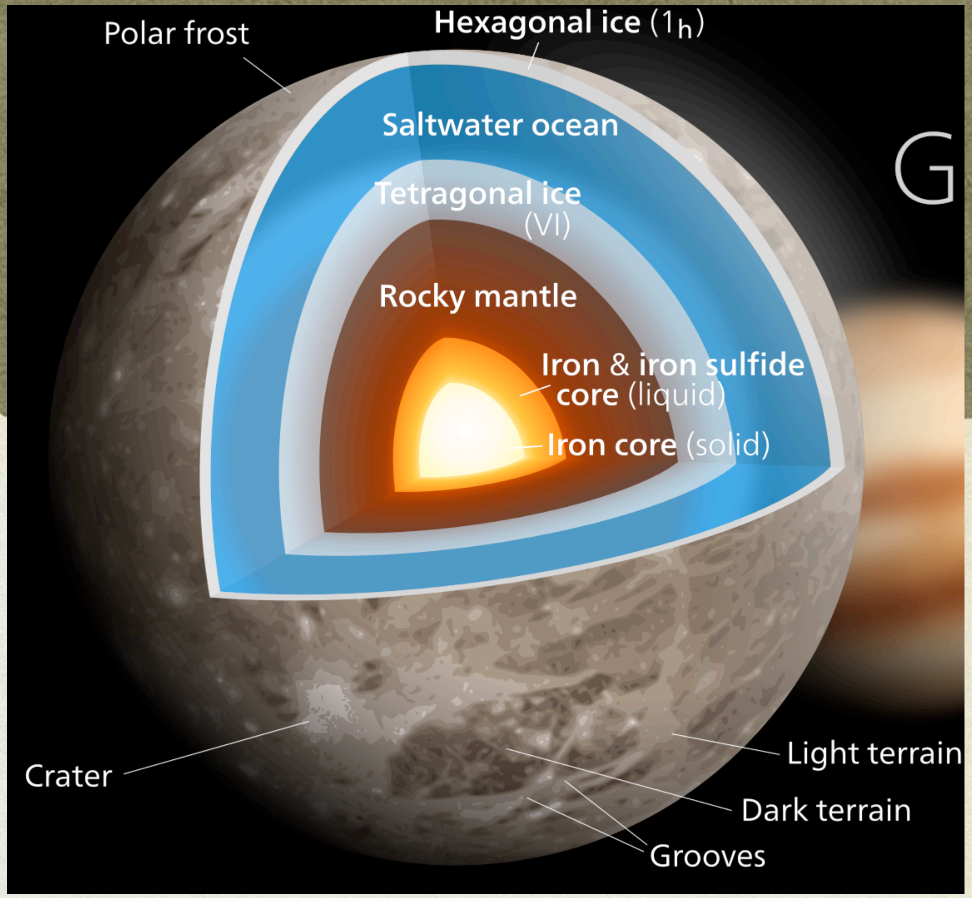


JUPITER MOONS

- strong interaction with the Galilean moons
- inducing large electric potentials and dipole magnetic fields
- volcanic gases from Io form a torus of ionized plasma orbiting Jupiter
- evidence for electrically conducting layer within Europa and Callisto



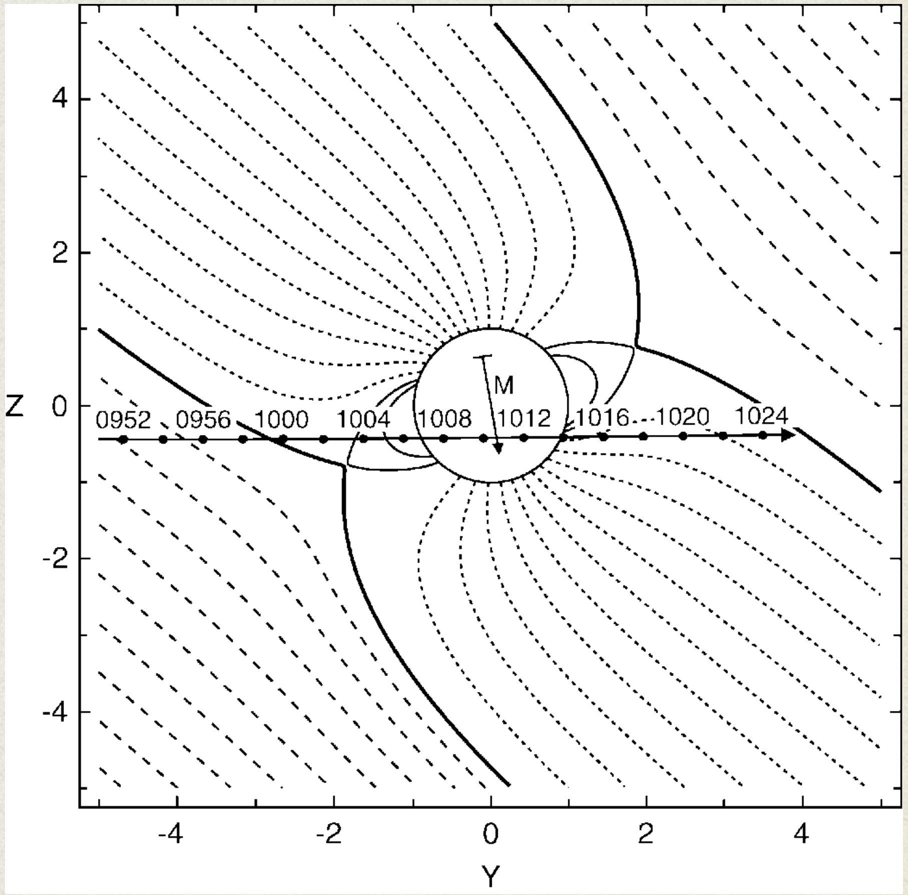
GANYMEDE



- dipole moment
  $7.2\,\mathrm{mG} \times R_{\mathrm{G}}^{3}$
  (Galileo,
  Kivelson et al. 2002)

- radius $R_{\mathrm{G}} = 2634\,\mathrm{km}$
  core $\sim 0.2\,R_{\mathrm{G}}$

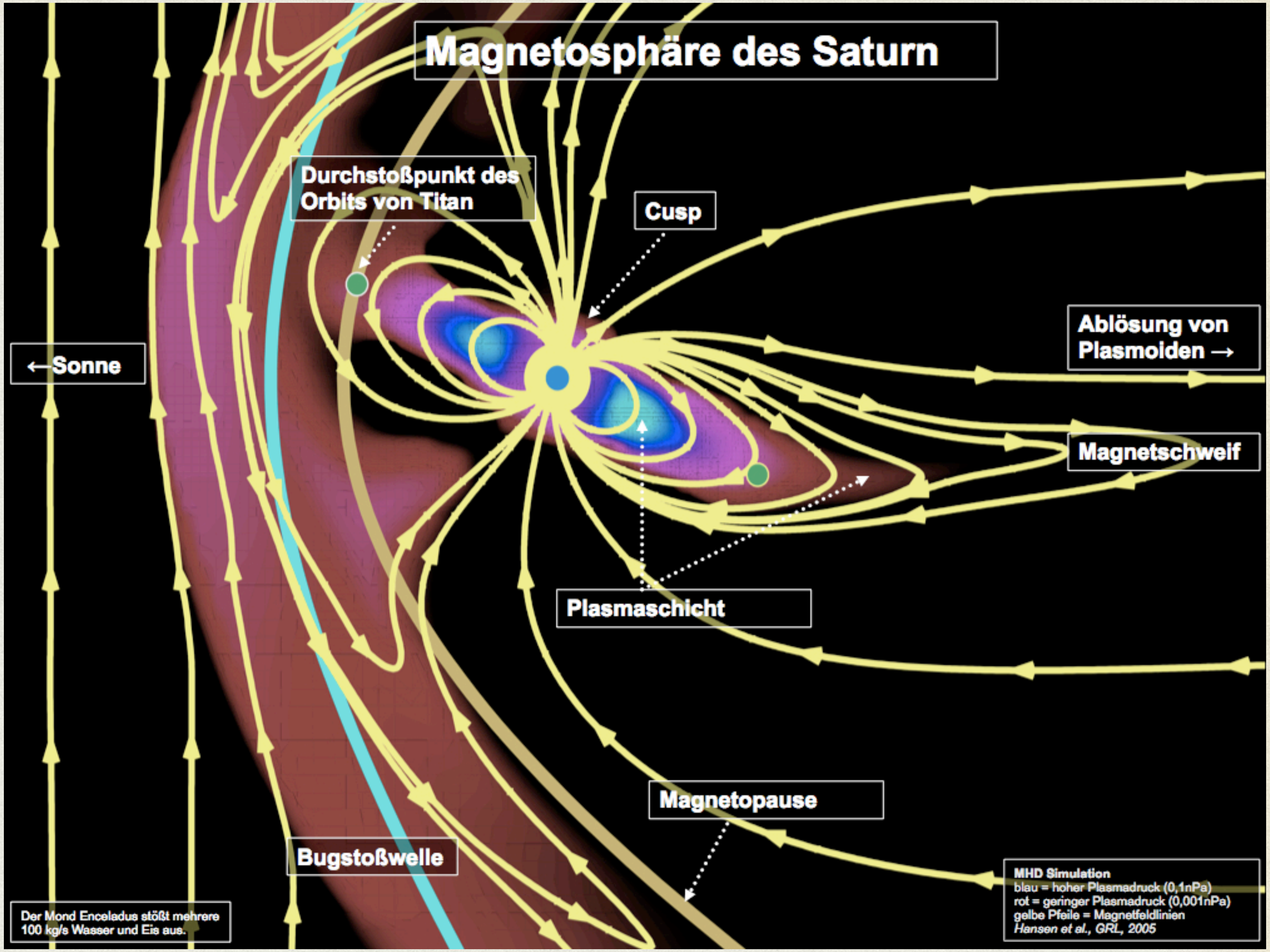
- rotation period 7.2 d



Kivelson et al. (2002)

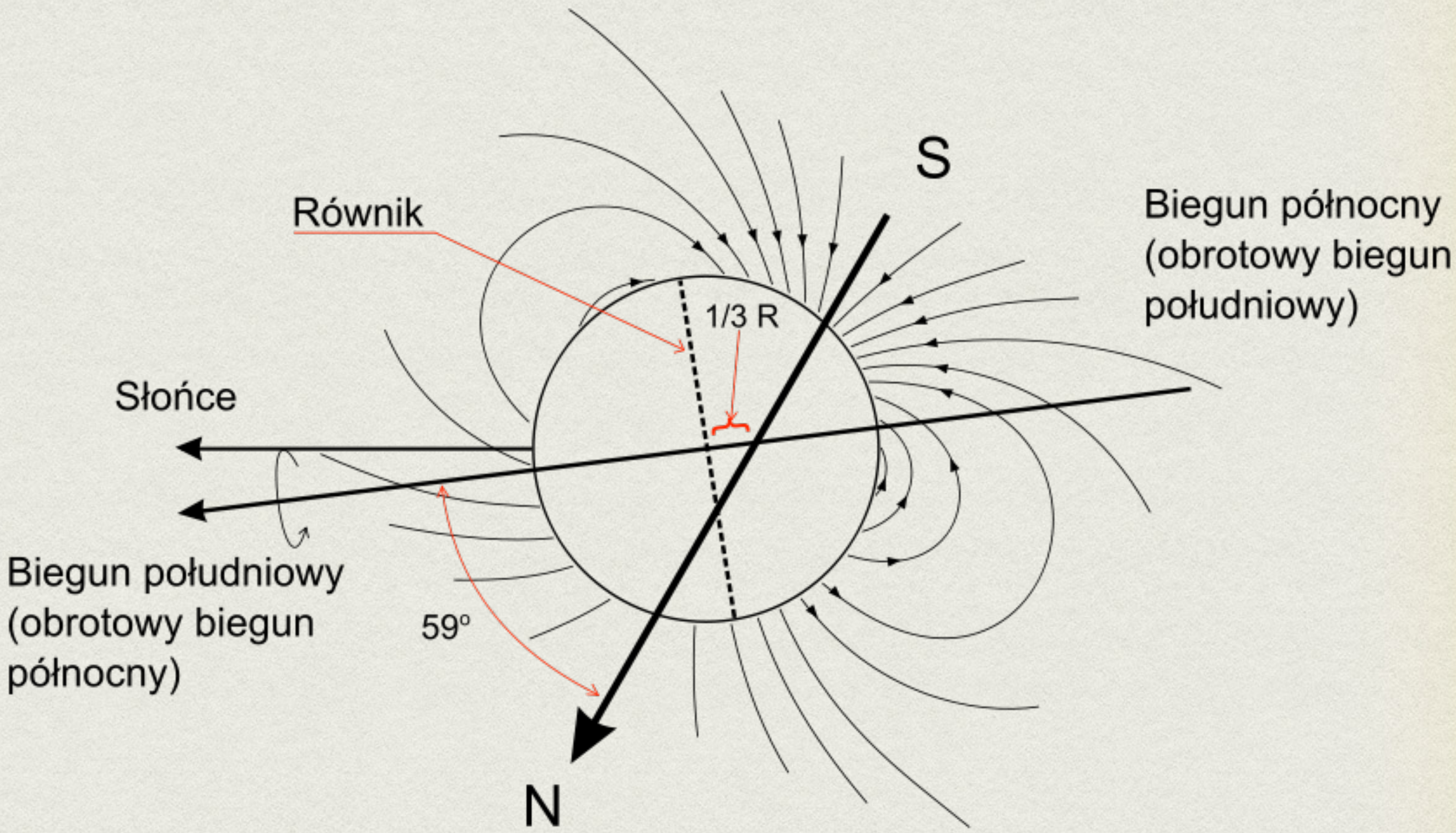
SATURN

- dipole moment
  $0.21\,\mathrm{G} \times R_S^3$
  (Stevenson 1983)
- radius
  $R_S = 58232\,\mathrm{km}$
- metallic hydrogen
- rotation period
  0.44 d



URANUS

- dipole moment $0.23\,\mathrm{G} \times R_\mathrm{U}^3$ (Voyager 2, Ness et al. 1986)
- strongly offset and tilted
- radius $R_\mathrm{U} = 25360\,\mathrm{km}$
- rotation period 0.72 d
- no metallic hydrogen, water-ammonia-methane ("CNO") oceans with $\eta \sim 10^6\,\mathrm{cm}^2/\mathrm{s}$



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NEPTUNE

- dipole moment $0.13\,\mathrm{G} \times R_\mathrm{N}^3$ (Voyager 2, Ness et al. 1989)
- strongly offset and tilted (not a coincidence)
- radius $R_\mathrm{N} = 24620\,\mathrm{km}$
- rotation period 0.67 d
- water-ammonia-methane with $\eta \sim 10^6\,\mathrm{cm}^2/\mathrm{s}$

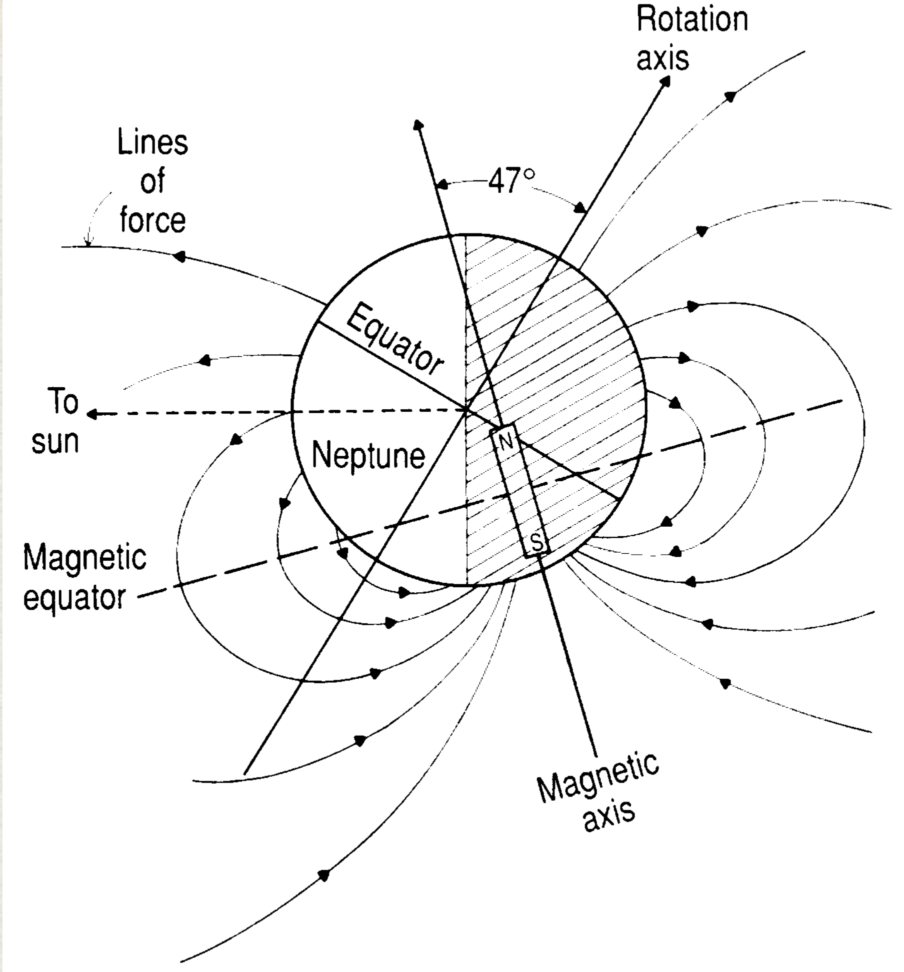
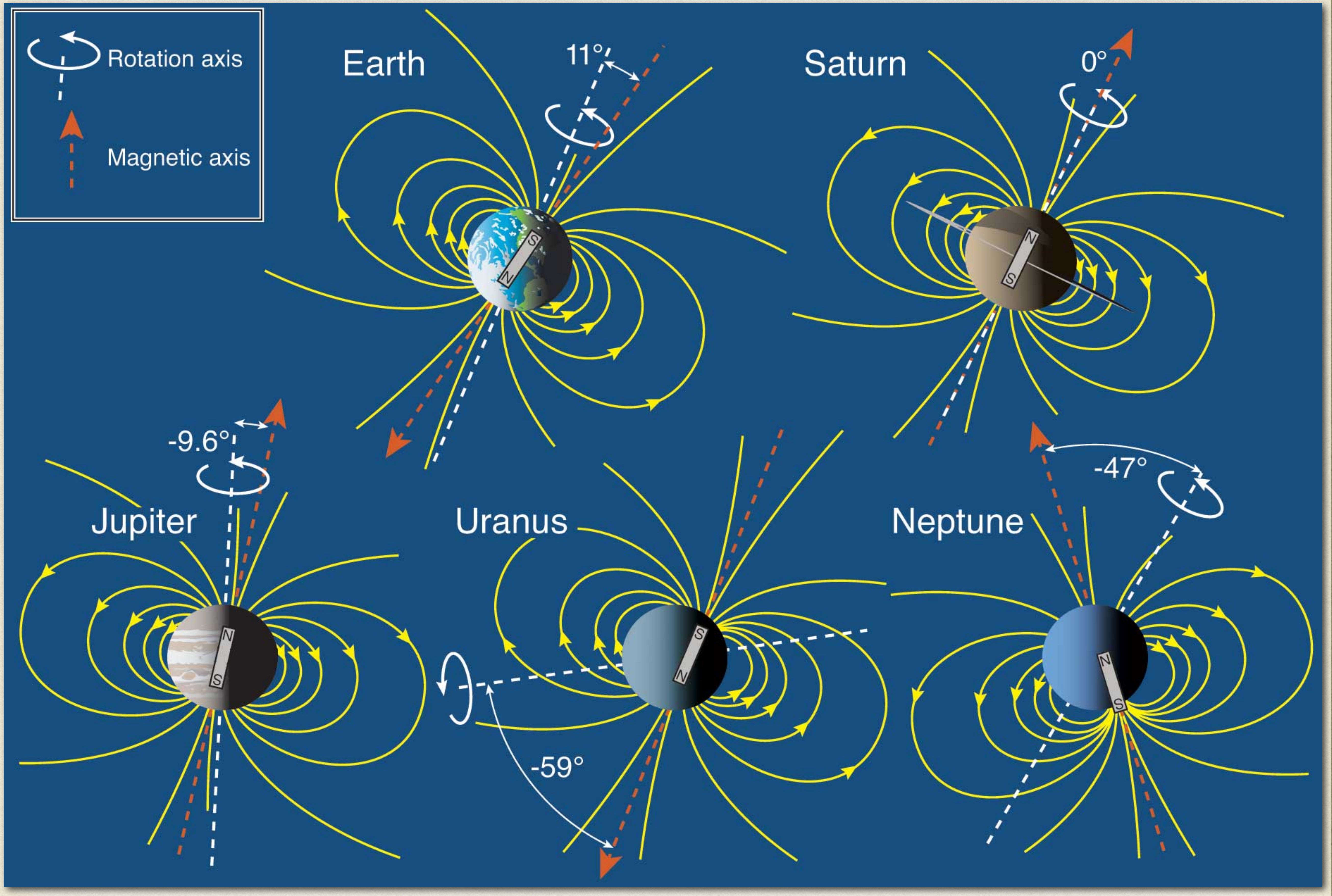


Fig. 4. Diagram of the OTD field lines of Neptune in the meridian plane containing the OTD center and the rotation axis, illustrating the effects of the large dipole tilt and offset on the location of the magnetic equator and pole regions. This figure is an approximation (the OTD axis is actually inclined by 22° with respect to this plane).

Ness et al. (1989)


Rotation axis
Magnetic axis
Earth
11°
Saturn
0°
Jupiter
-9.6°
Uranus
-59°
Neptune
-47°
N
S

PROBLEM 2: ELSASSER NUMBER

- Elsasser number Λ is the strength ratio of the Lorentz force density $\vec{f}_{\rm L} = (\vec{j} \times \overrightarrow{B})/c$ to the Coriolis force density $\vec{f}_{\Omega} = 2\rho\overrightarrow{\Omega} \times \overrightarrow{\rm v}$.

- Create a scatter diagram of equatorial dipole magnetic field strength at the surface $B_{\rm s}$ vs. the rotation period P for planets and moons. Where possible, indicate also the dipole magnetic field strength scaled to the core radius $B_{\rm c}$.

- What values of Λ are inferred? For magnetic diffusivity, assume $\eta \sim 10^4\ {\rm cm^2/s}$ for liquid iron, $\eta \sim 10^5\ {\rm cm^2/s}$ for metallic hydrogen, $\eta \sim 10^6\ {\rm cm^2/s}$ for liquid CNO.

This problem is worth 5 points. Solutions should be sent as 1-page PDF files to knalew@camk.edu.pl before the next lecture.

SUMMARY

- Planets and moons that produce global magnetic fields: Mercury, Earth, Jupiter, Ganymede, Saturn, Uranus, Neptune.
- Rocky planets need convectively unstable liquid metallic core, cooling of outer layers (plate tectonics).
- Gas giants may have layers of metallic hydrogen (Jupiter, Saturn) or "CNO" oceans (Uranus, Neptune).