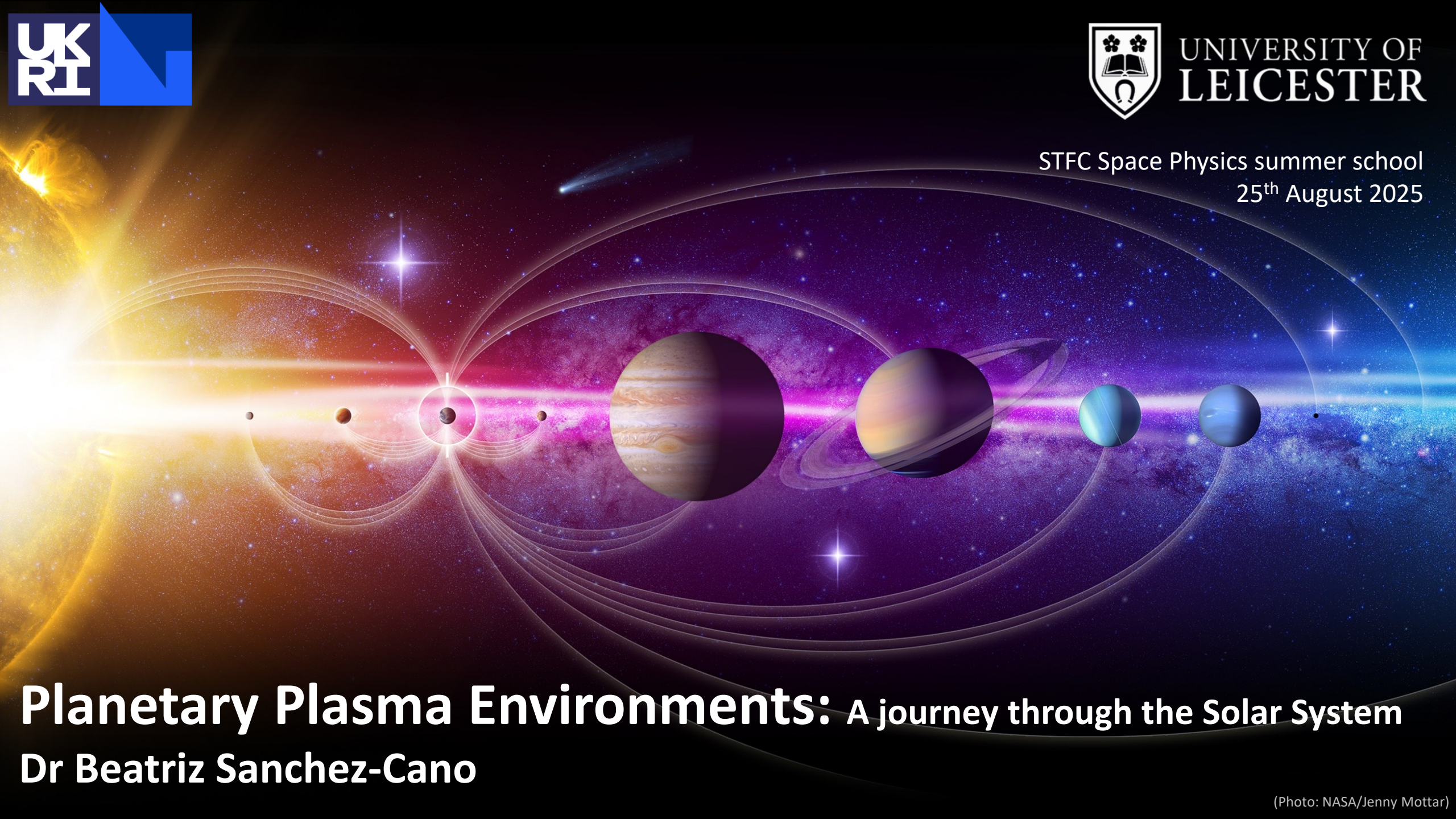

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STFC Space Physics summer school
25th August 2025

Planetary Plasma Environments: A journey through the Solar System

Dr Beatriz Sanchez-Cano

(Photo: NASA/Jenny Mottar)

Key for planetary evolution

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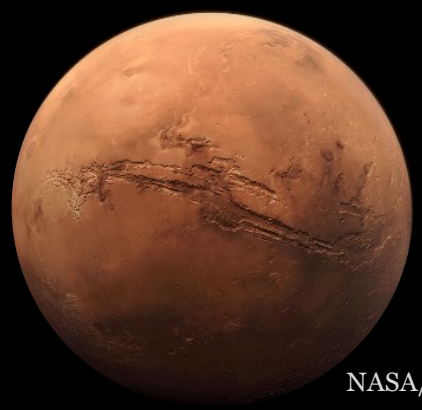


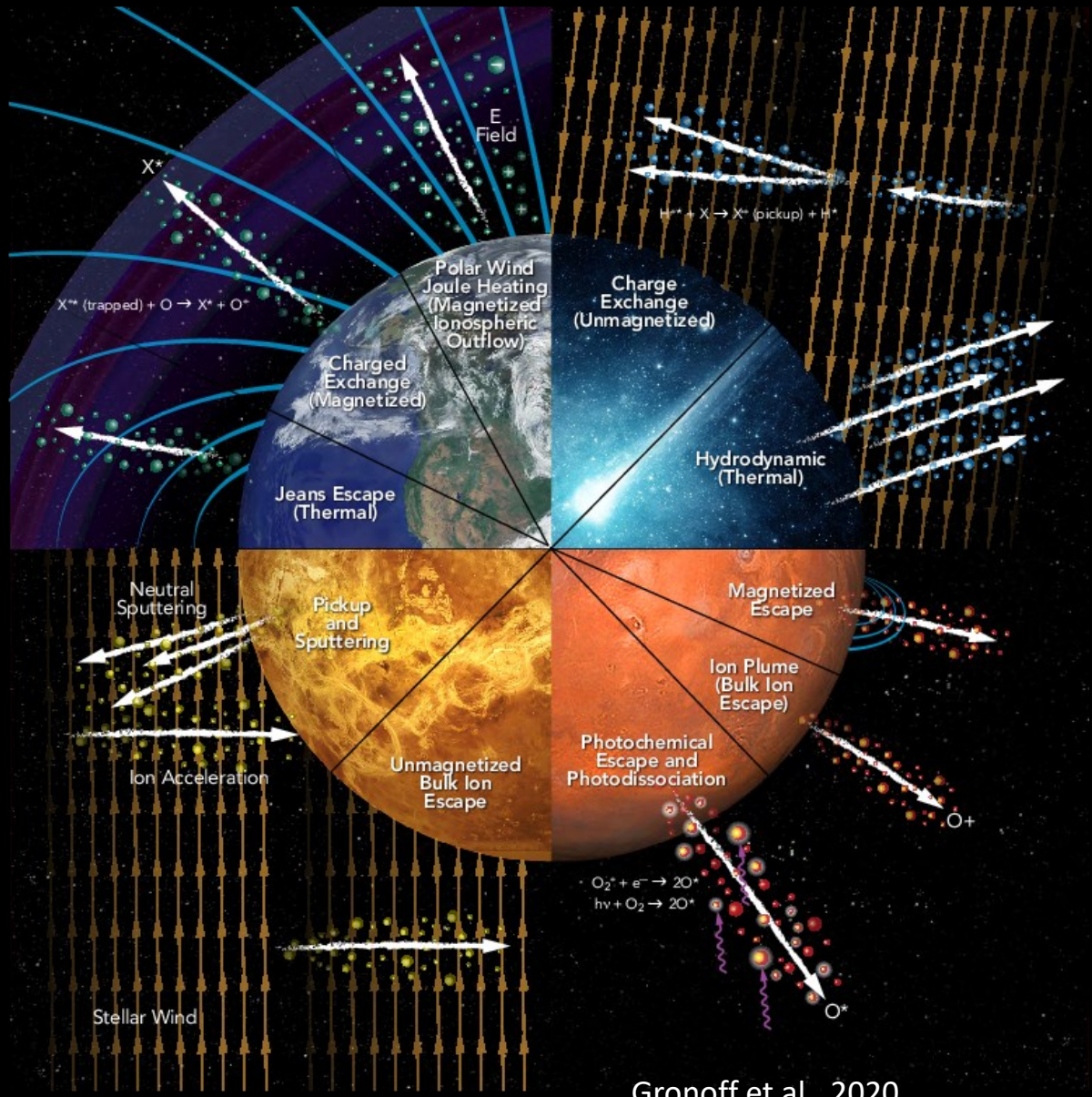
NASA/ESA

Mars today

NASA

Mars in the past

The evolution of planetary atmospheres and their climates is directly related to their interaction with the solar wind



Gronoff et al., 2020

Key for planetary habitability

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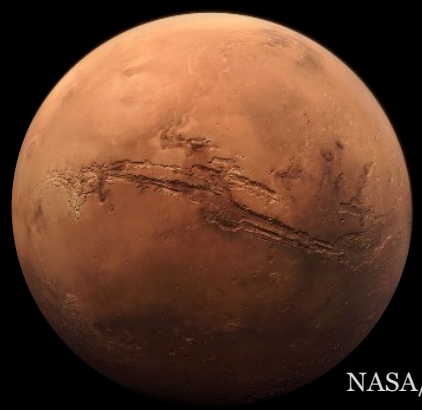


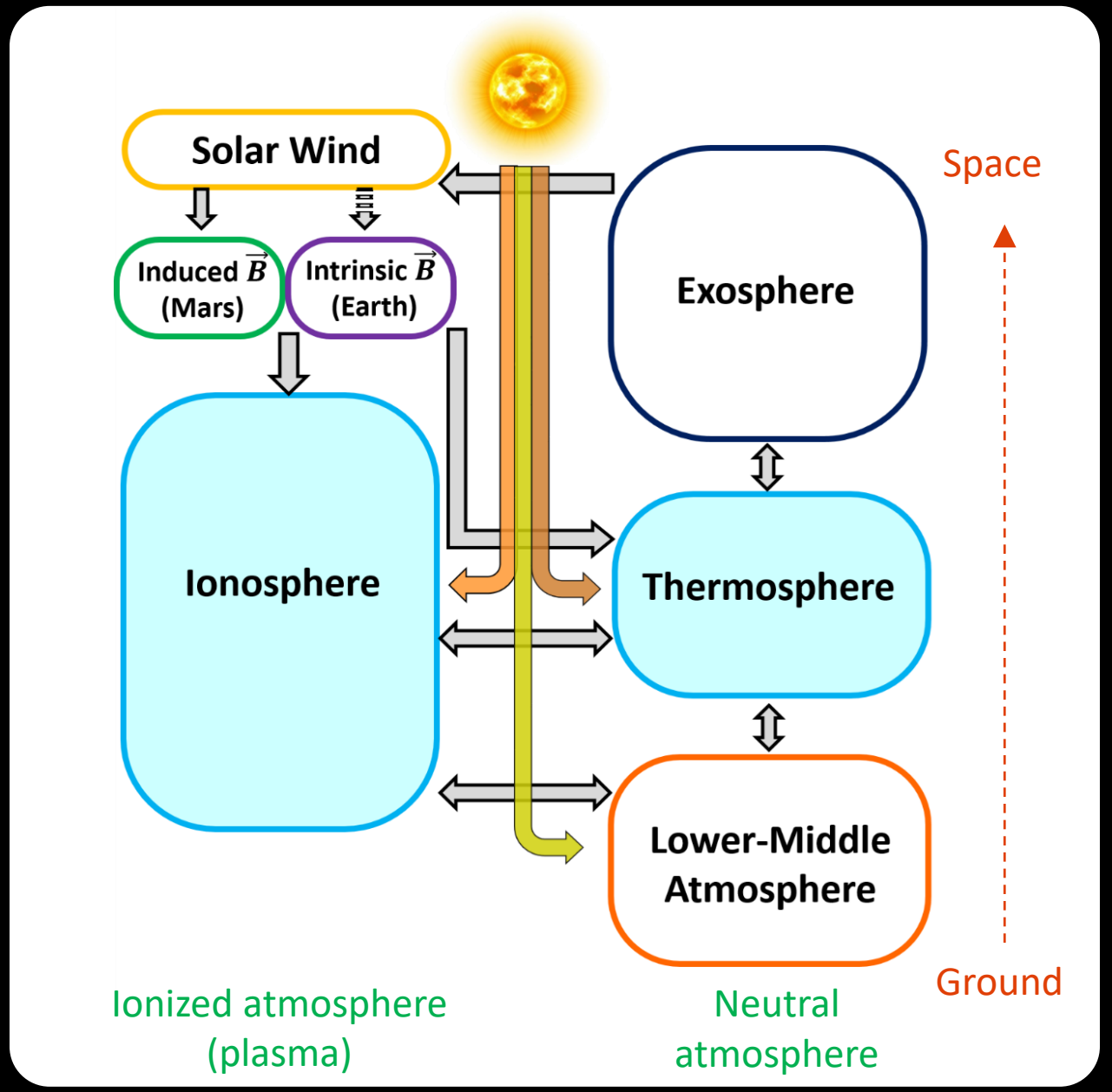
NASA/ESA

Mars today

NASA

Mars in the past

This is a key aspect to understand habitability as any planetary plasma system controls the dissipation of incoming energy from the solar wind, via e.g., atmospheric escape, auroral processes, incoming radiation, etc.



Our Solar System is an unique and natural laboratory!

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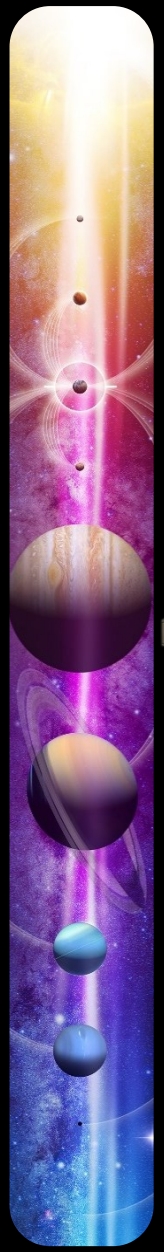
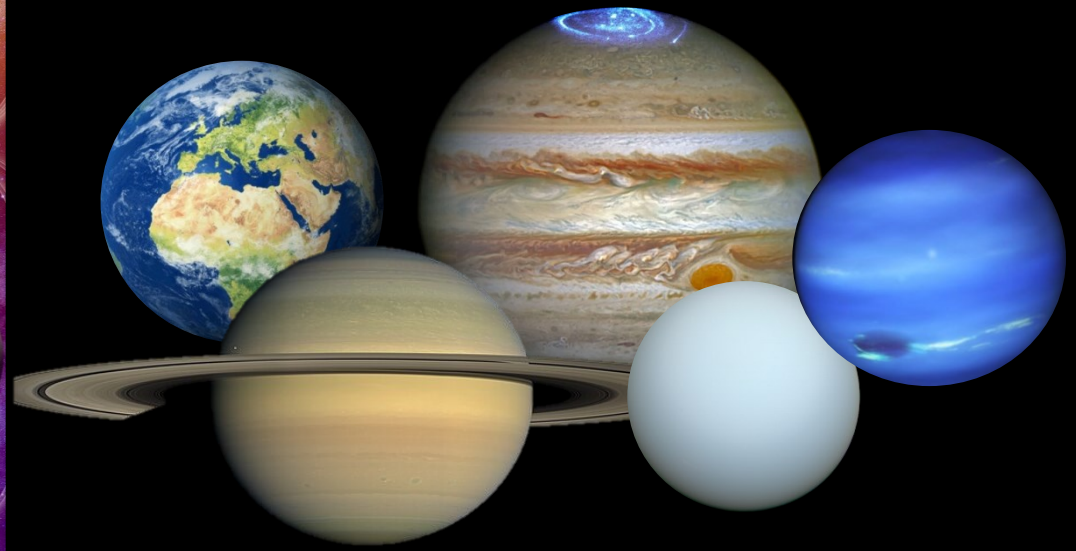


Bodies with an atmosphere and magnetic field



Bodies with atmosphere but no (or near-no) magnetic field

Bodies with/without atmosphere and with/without magnetic field in subsystems

Bodies with no atmosphere but magnetic field

Bodies with no atmosphere and no (or near-no) magnetic field

Different types of Sun-planet interaction

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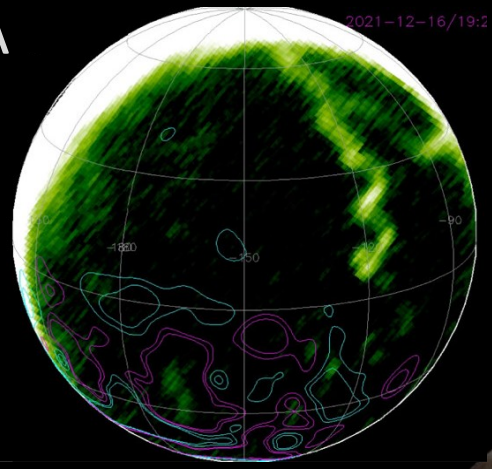
JUPITER'S AURORA

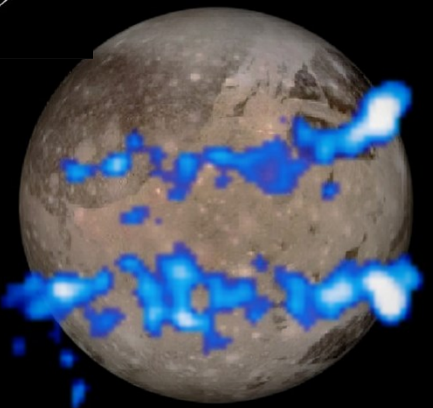
EARTH'S AURORA

SATURN'S AURORA

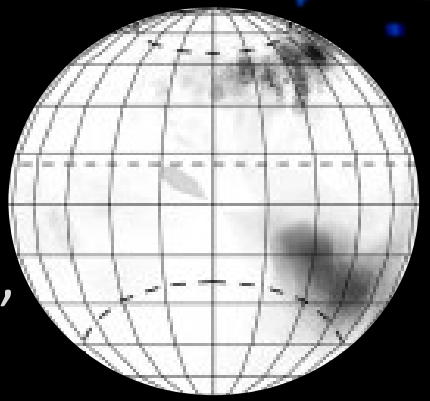
MARS' AURORA



GANYMEDE'S AURORA



MERCURY'S "AURORA"



The Sun

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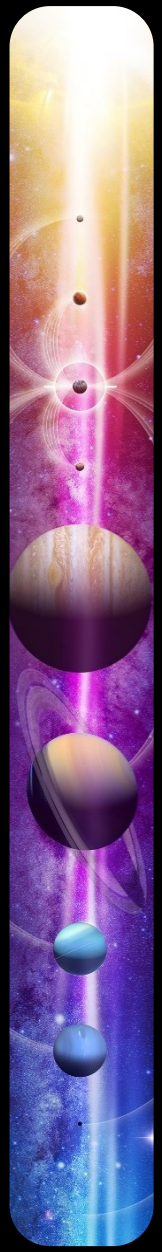
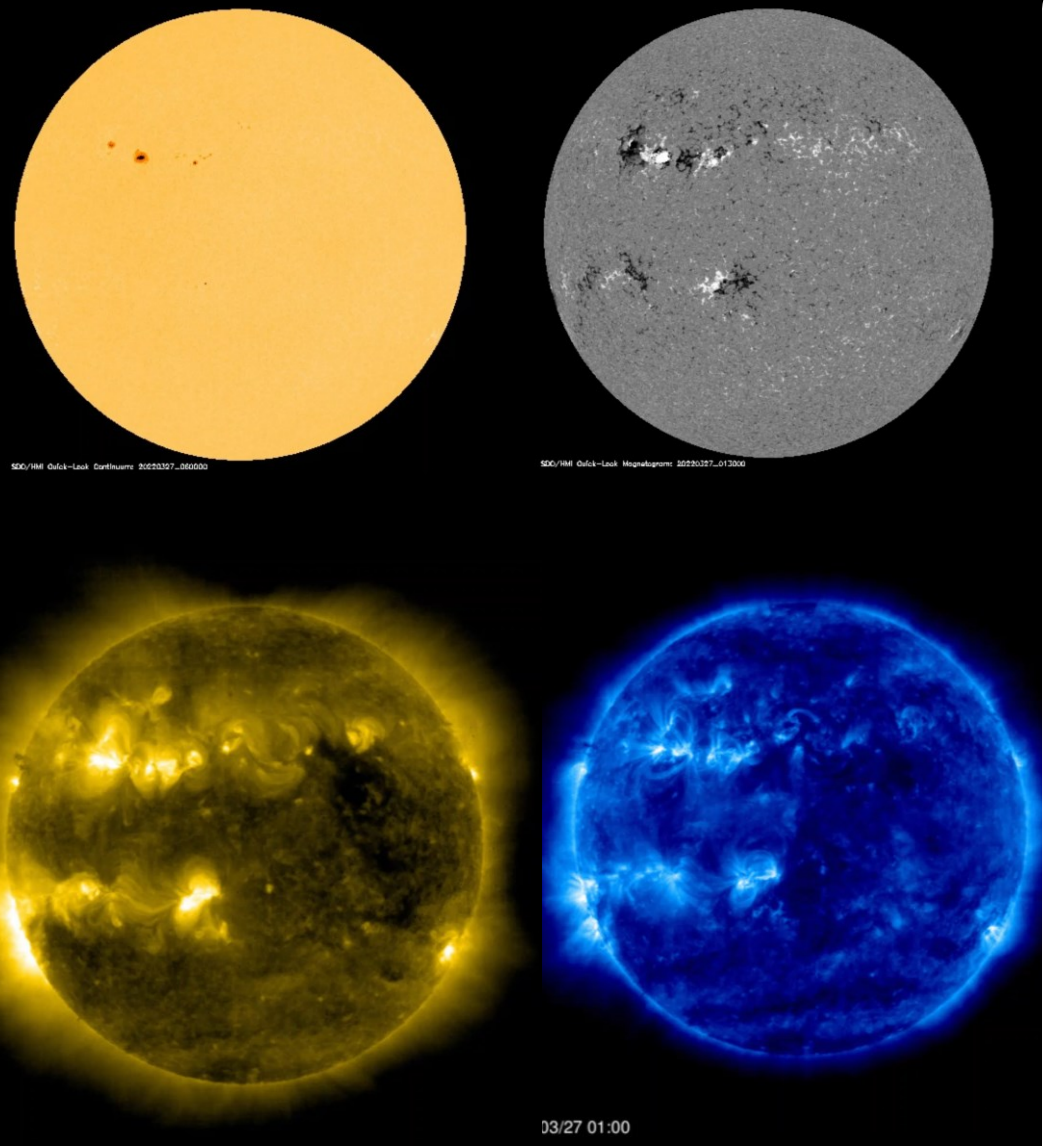
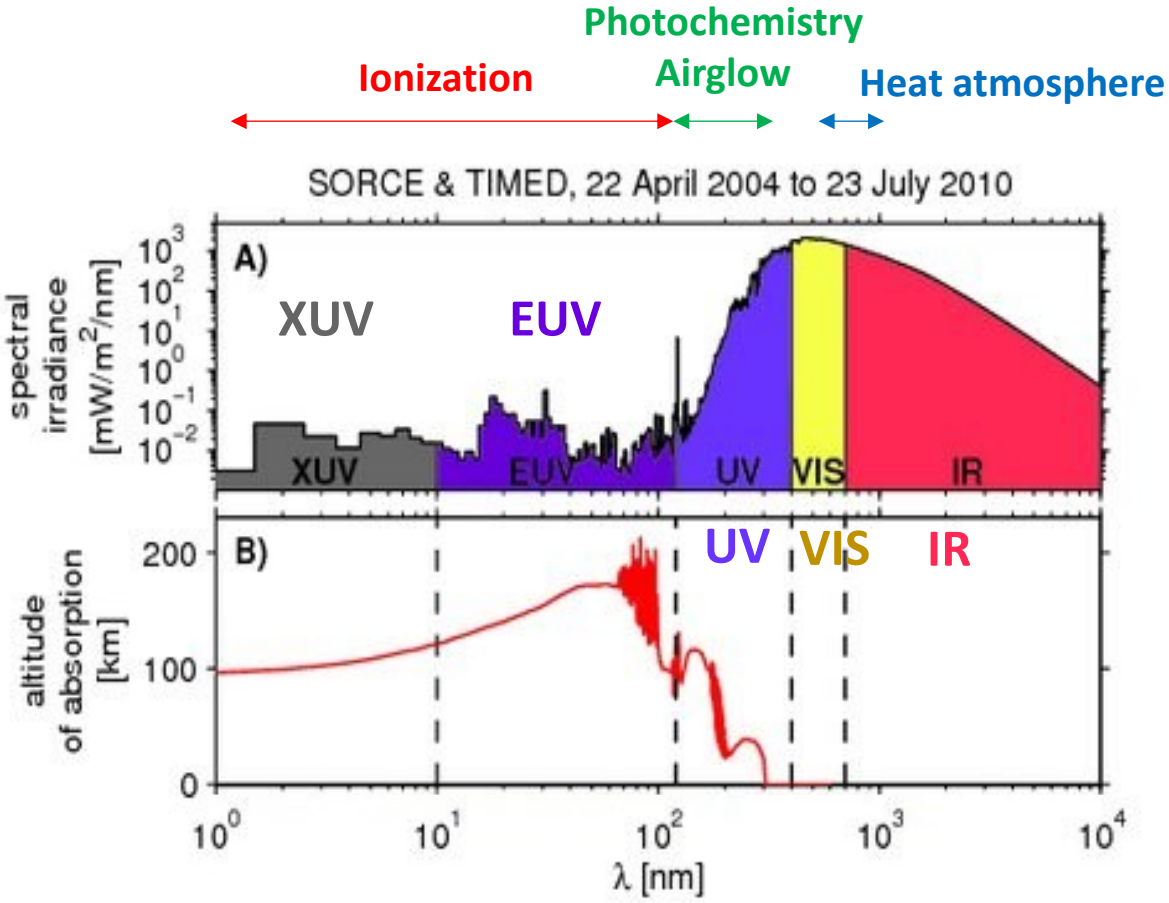




It behaves as a black body at wavelengths > UV, but not for shorter wavelengths



Ermolli et al., 2012

The ionosphere

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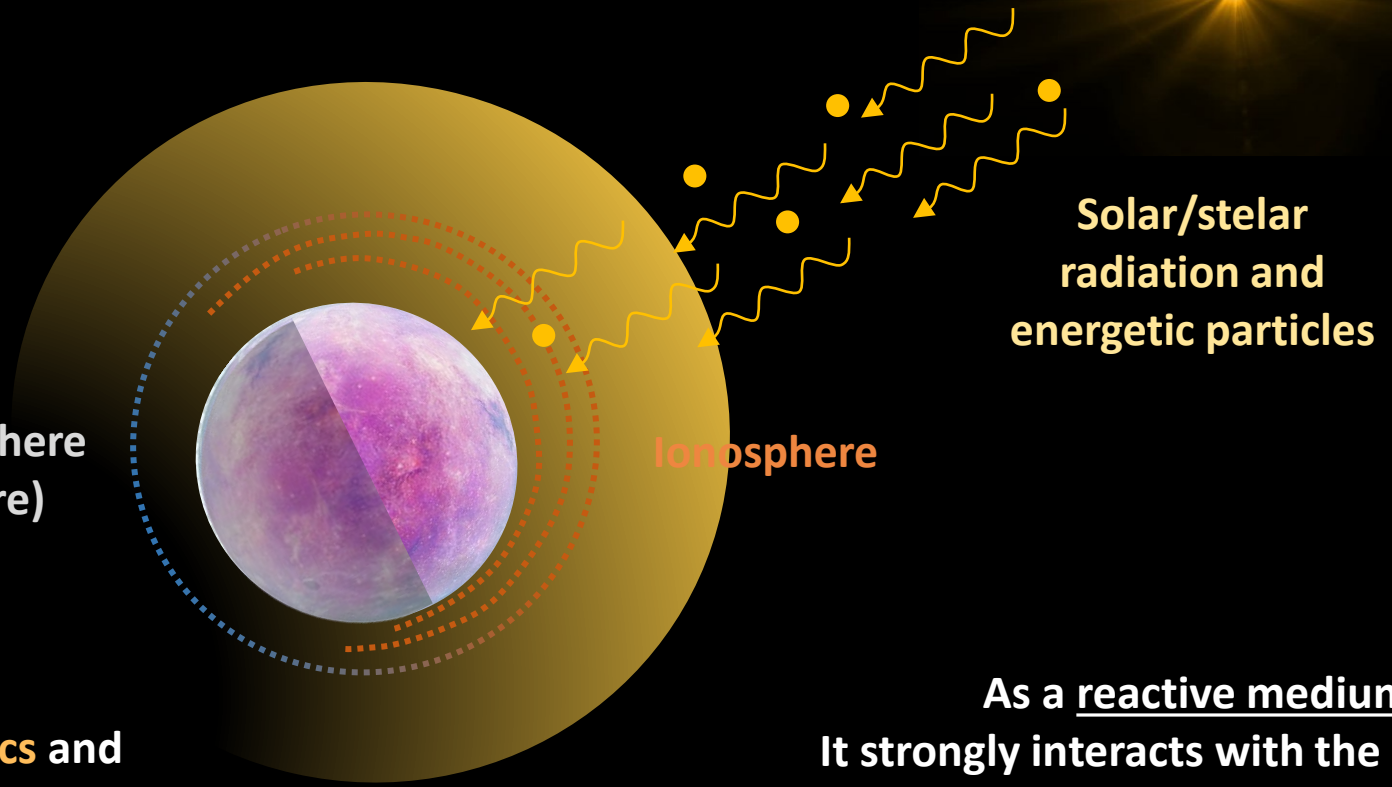
The ionosphere is the region of the upper atmosphere that is ionized by the Sun's radiation and **couples the neutral atmosphere** (the so-called **thermosphere**) **with space**. It can be considered as a **tracer** for atmospheric dynamics and also, for the solar wind-atmosphere coupling.



As an <u>ionized medium</u>:
It is sensitive to electrodynamics and magnetic fields

As a <u>reactive medium</u>:
It strongly interacts with the chemistry of the neutral atmosphere

The solar wind & Parker spiral: FROZEN IN plasma

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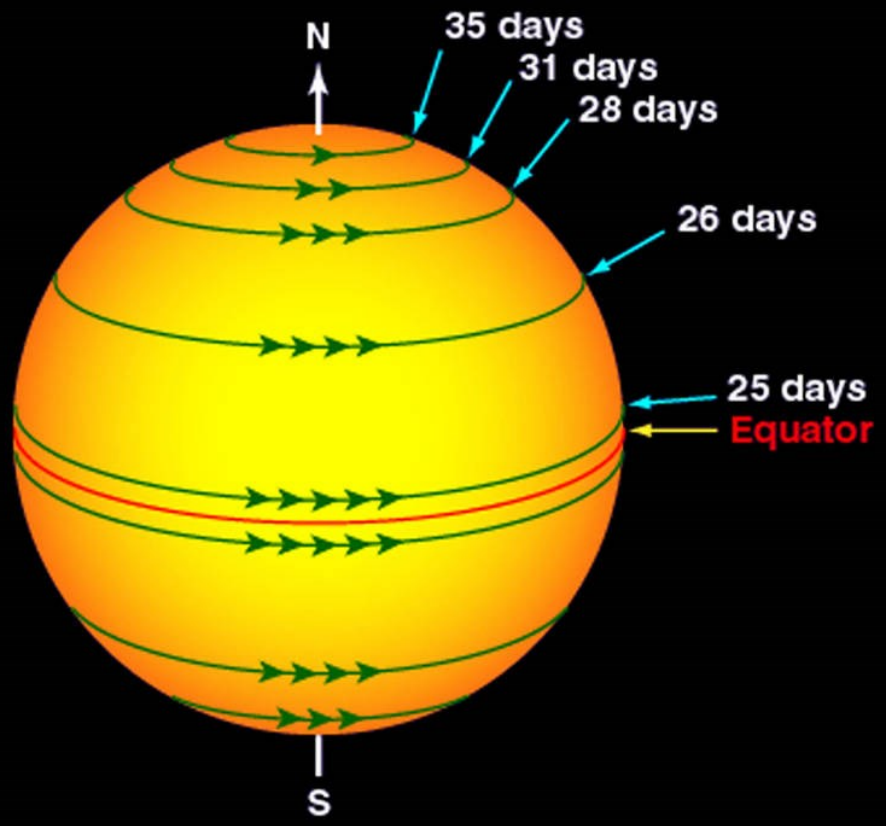
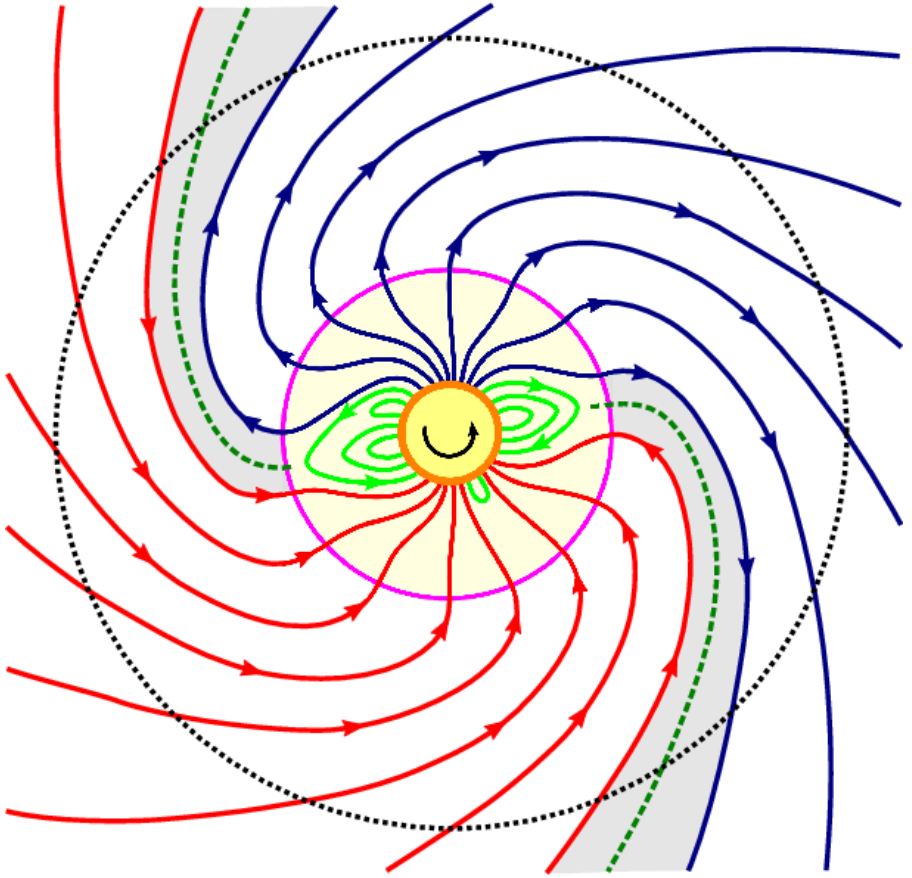
The Sun is constantly emitting charged particles, the so-called solar wind, which carries the solar coronal magnetic field to the outer parts of our solar system. Although the solar wind is constantly present, it is variable in strength, as the Sun periodically ejects more mass during active than during quiet periods.



Sun's differential rotation



Zhilkin and Bisikalo, 2019

Solar wind – planet interaction: planetary shocks

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Supersonic solar wind
~500 km/s average

Credits: NASA/MAVEN

Solar transients: space weather

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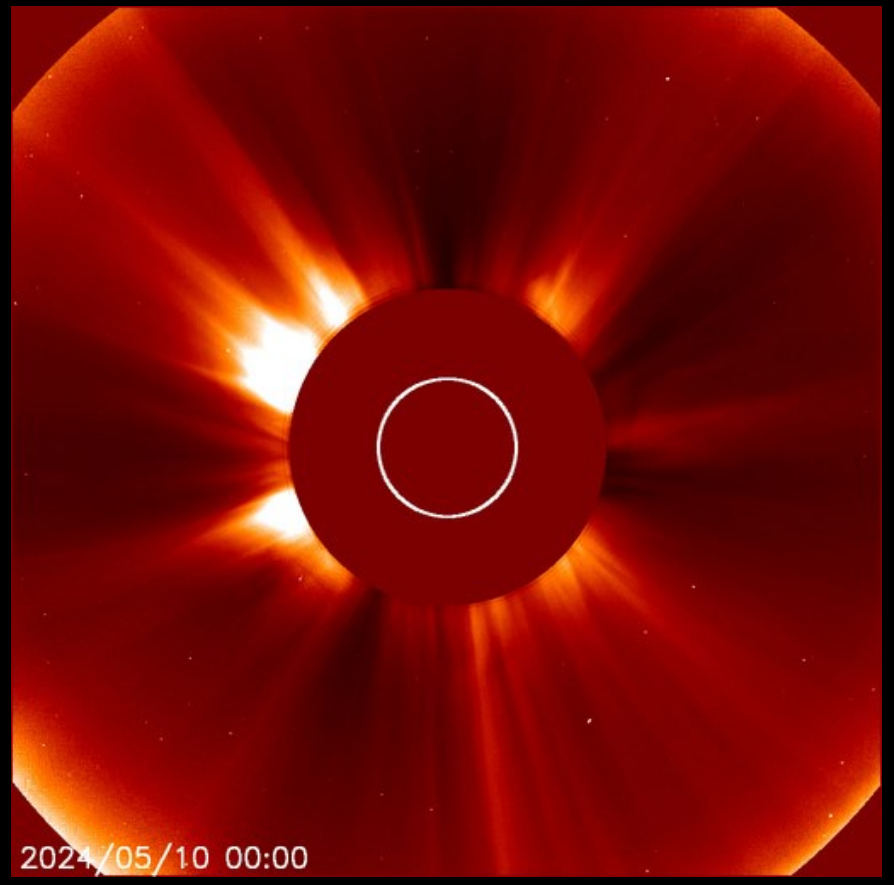

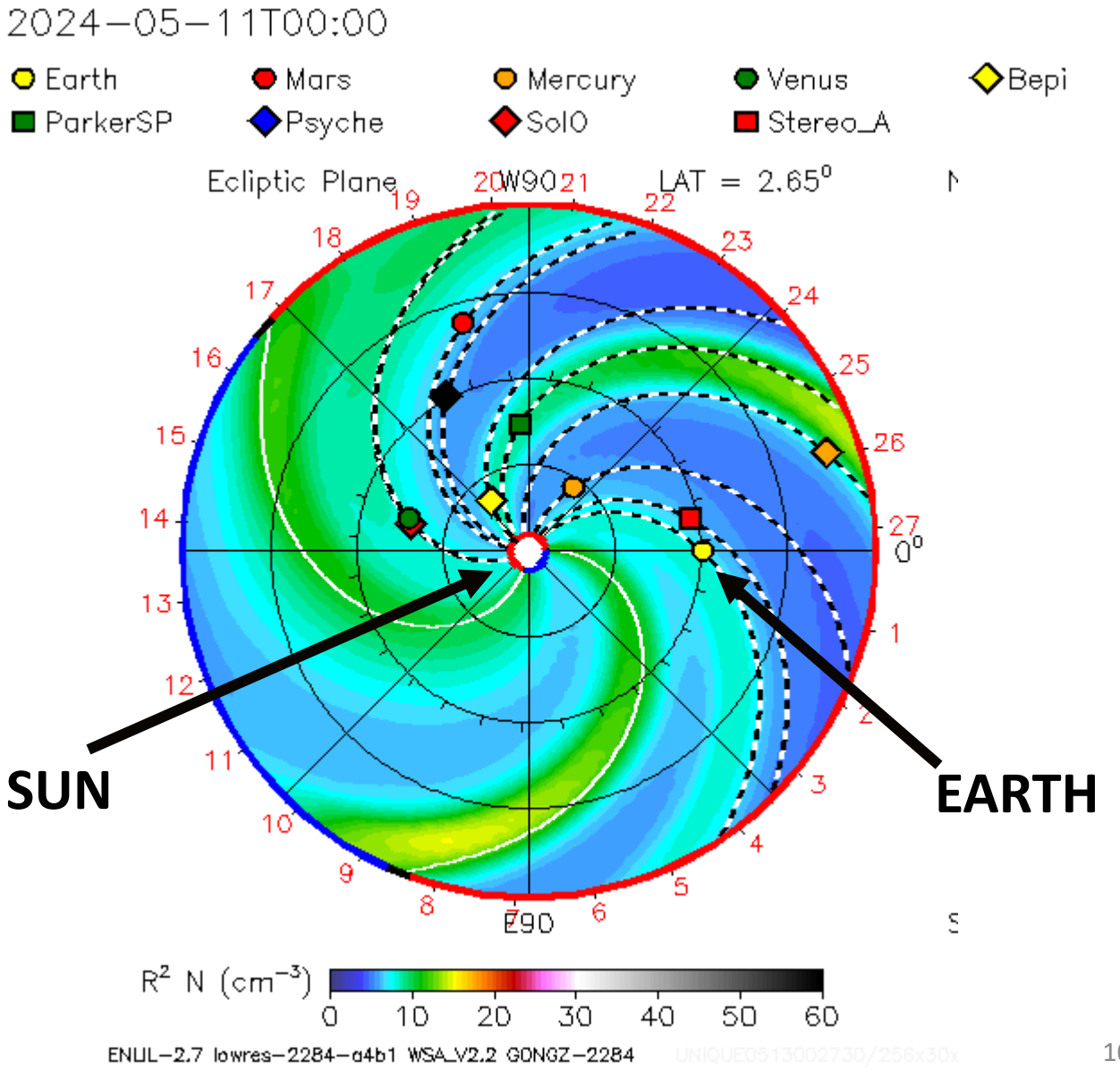

The magnetosphere: The Dungey cycle

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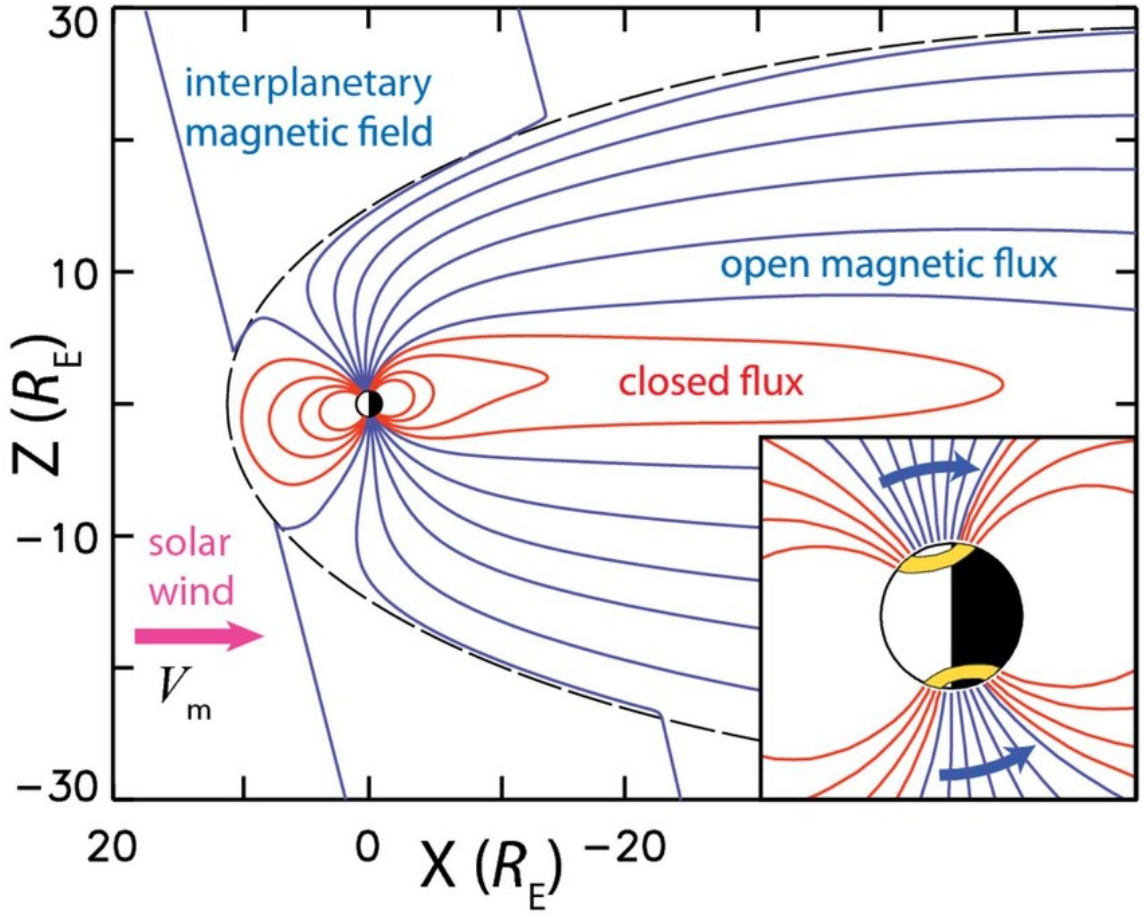
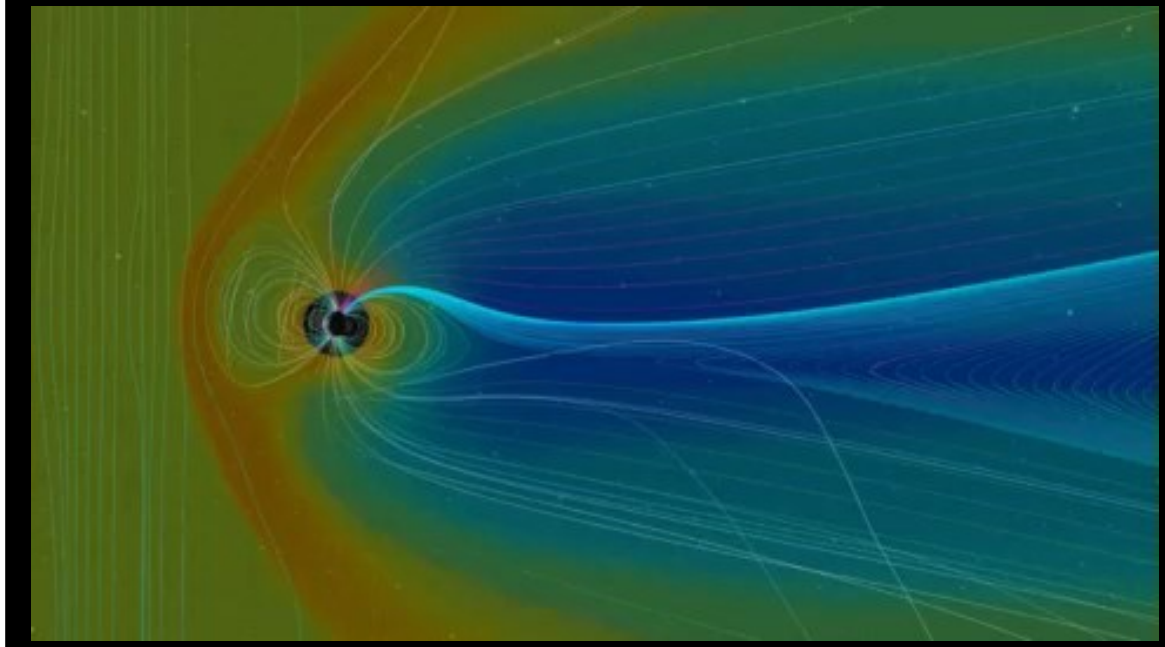
Classic scheme of a magnetosphere



Milan et al., 2009



NASA

Magnetosphere:
The region of space influenced by the planet's magnetic field.

Huge scales!

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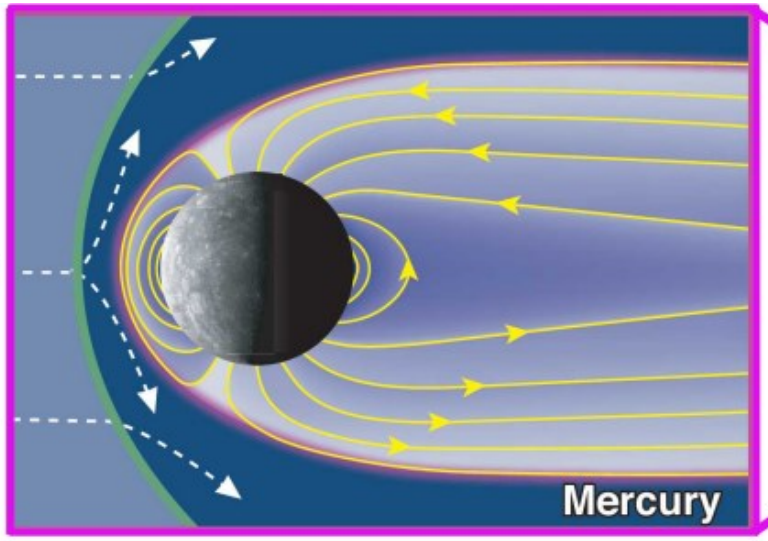
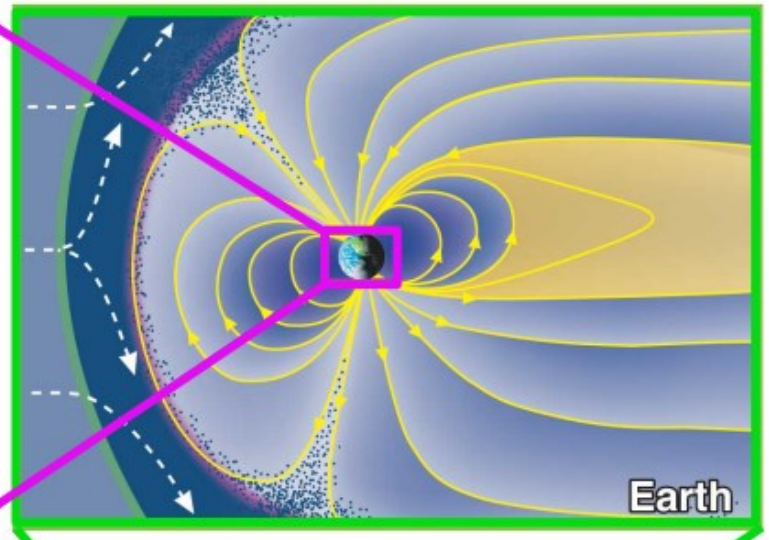
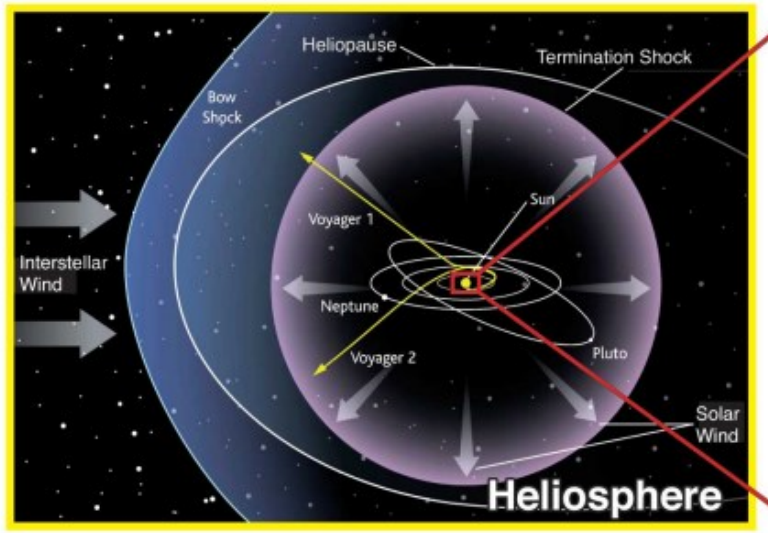
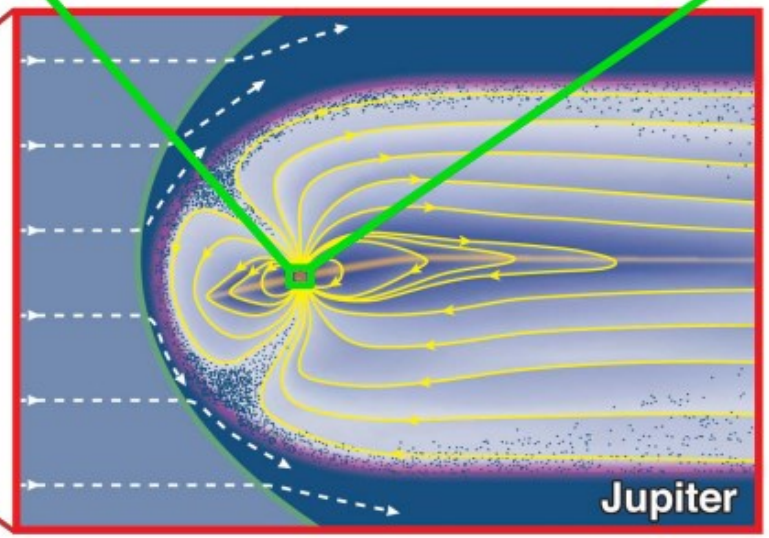
"Small/Mini"





"Medium"





"Large"

Bagenal+2013

Mercury: no atmosphere with magnetic field

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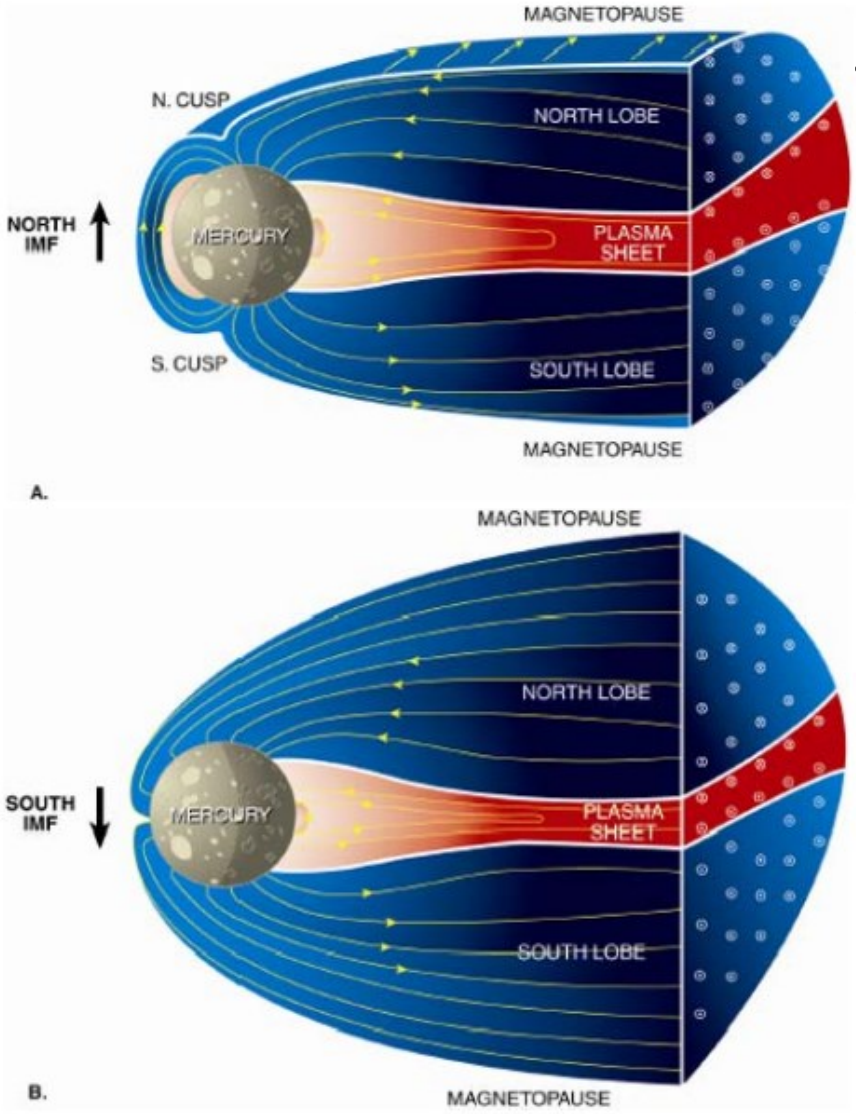


Slavin et al., 2007

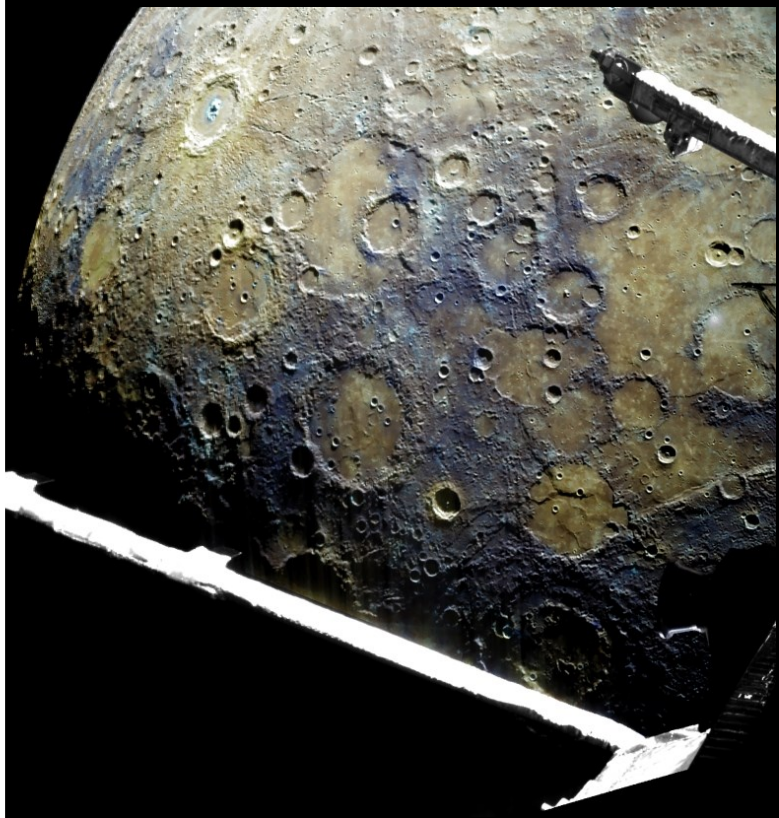
Planetary magnetic field is <1% of Earth's in strength.

Highly dynamical and compressed magnetosphere.

Dungey cycle is just a few minutes

Populated with solar wind and planetary heavy ions.

No atmosphere; tenuous exosphere.



BepiColombo view of Mercury

BepiColombo @ Mercury (finally!)

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- **September 3, 2026: Separation of the Mercury Transfer Module (MTM).**

- **November 21, 2026: Orbital insertion and official capture of the science orbiters by Mercury's gravity.**
- **December 9–10, 2026: Separation of the Mercury Planetary Orbiter (MPO, ESA) and the Mercury Magnetospheric Orbiter (Mio, JAXA).**
- **April 2027: Official start of nominal scientific operations in their respective polar orbits.**

BepiColombo flyby: ring current??

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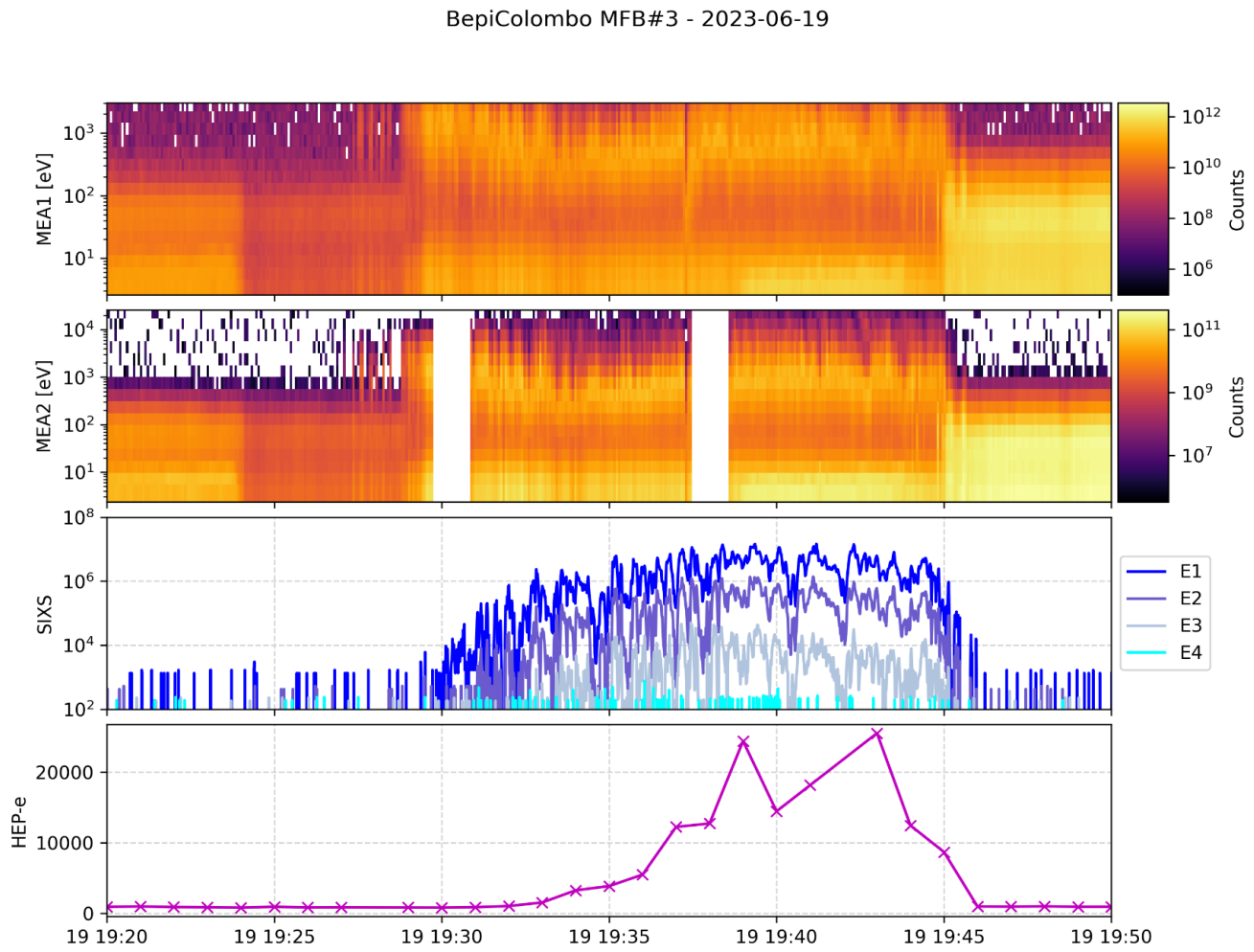
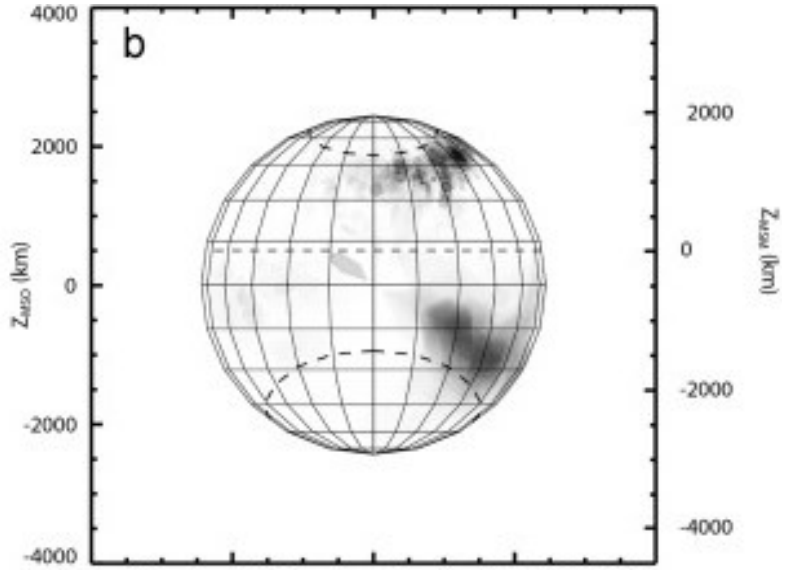


Aizawa et al., in prep

Energetic particle precipitation, specially during SEPs, seems to correlate with X-ray “auroras”

Work ongoing in preparation for orbit insertion



Lindsay et al., 2016

BepiColombo flyby: ring current??

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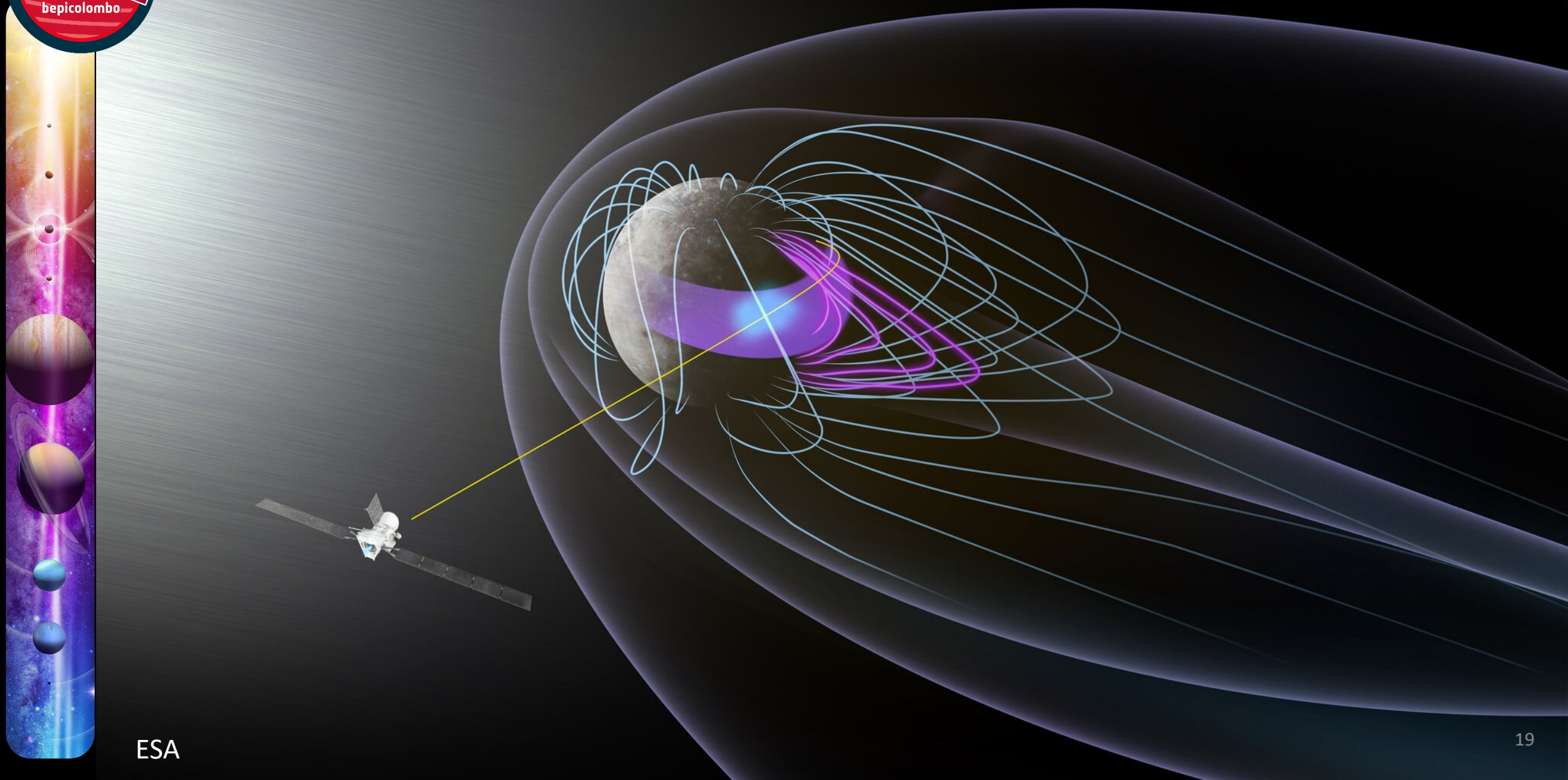

ESA

Venus and Mars' induced magnetospheres

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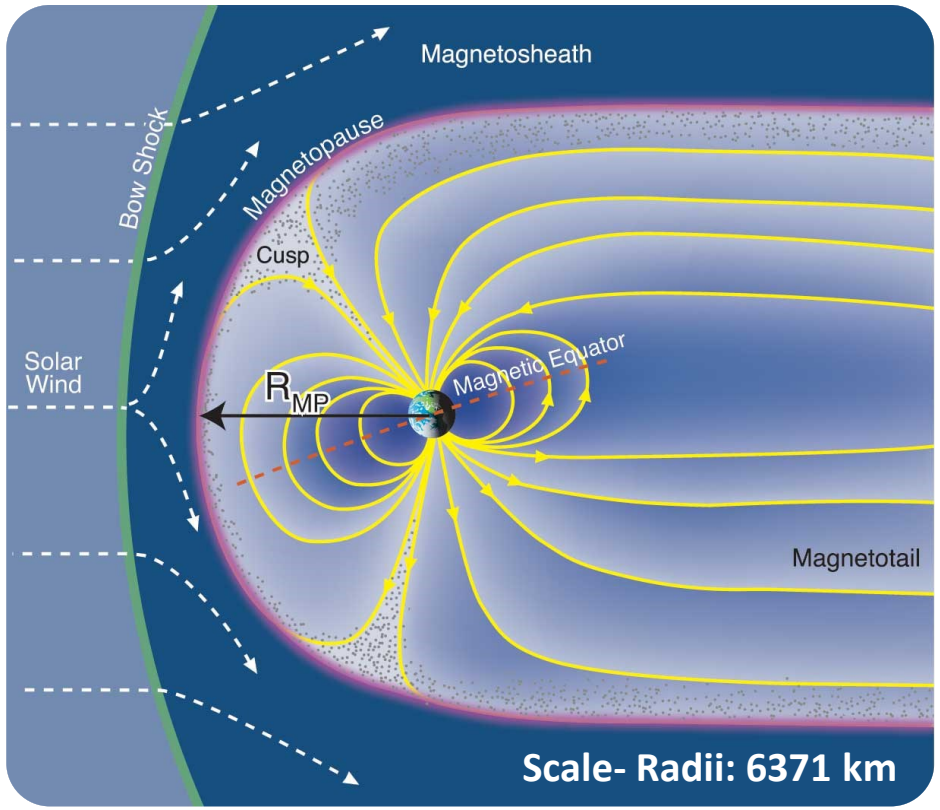
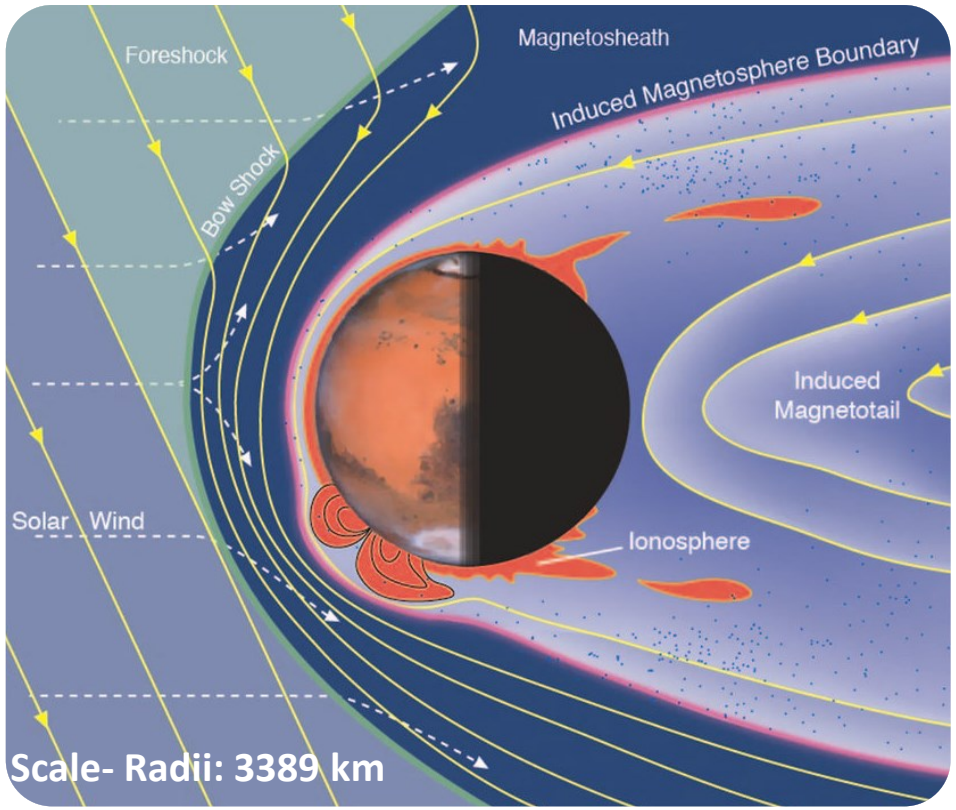
EARTH



Indirect coupling between the solar wind and the ionosphere

MARS (~Venus)



Direct coupling between the solar wind and the ionosphere

Mars' induced magnetospheres

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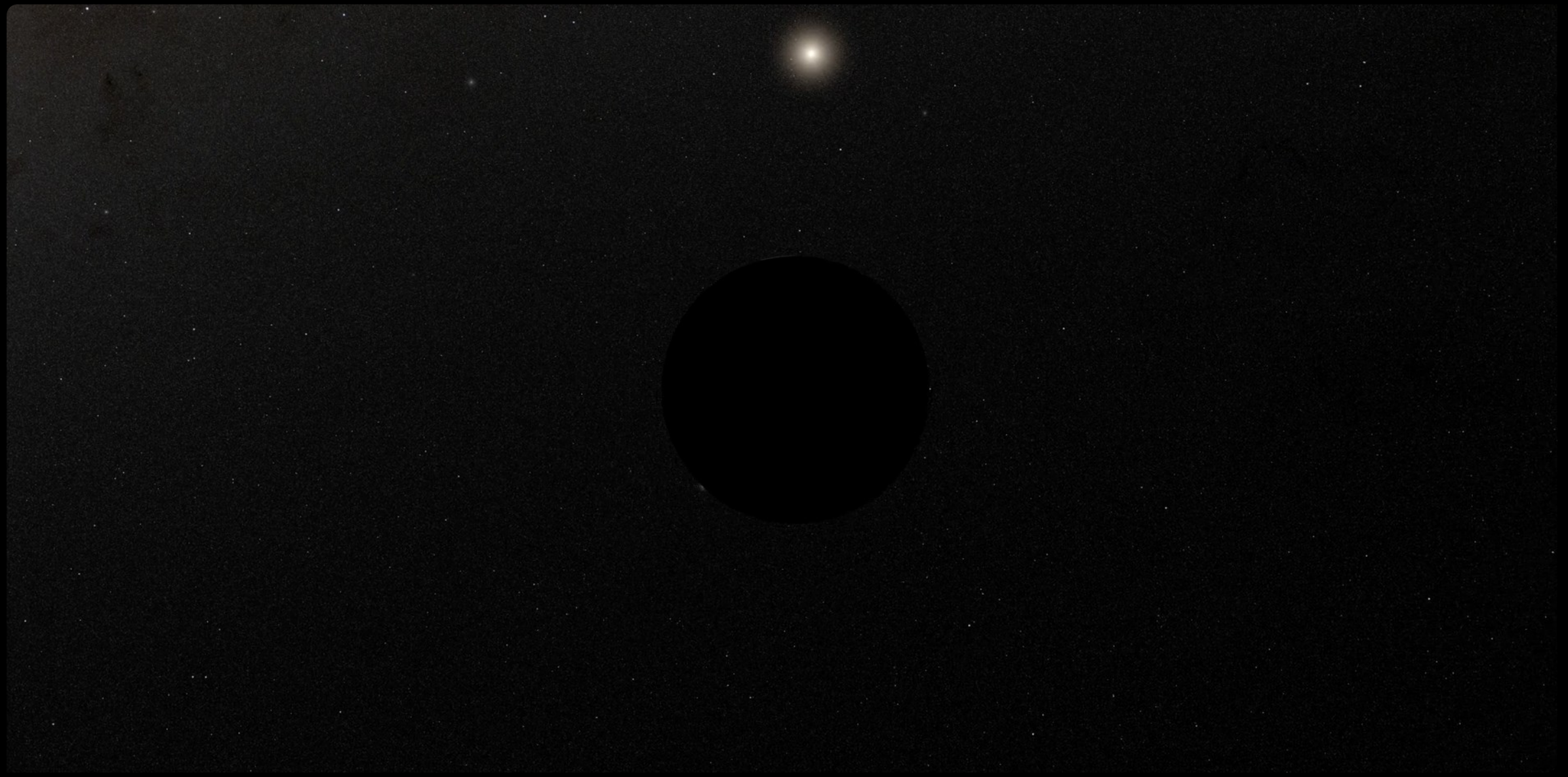

Solar cycle and orbital effects

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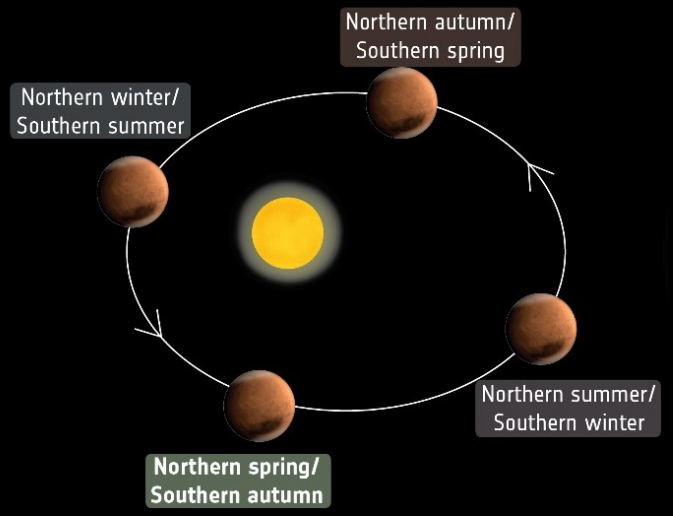
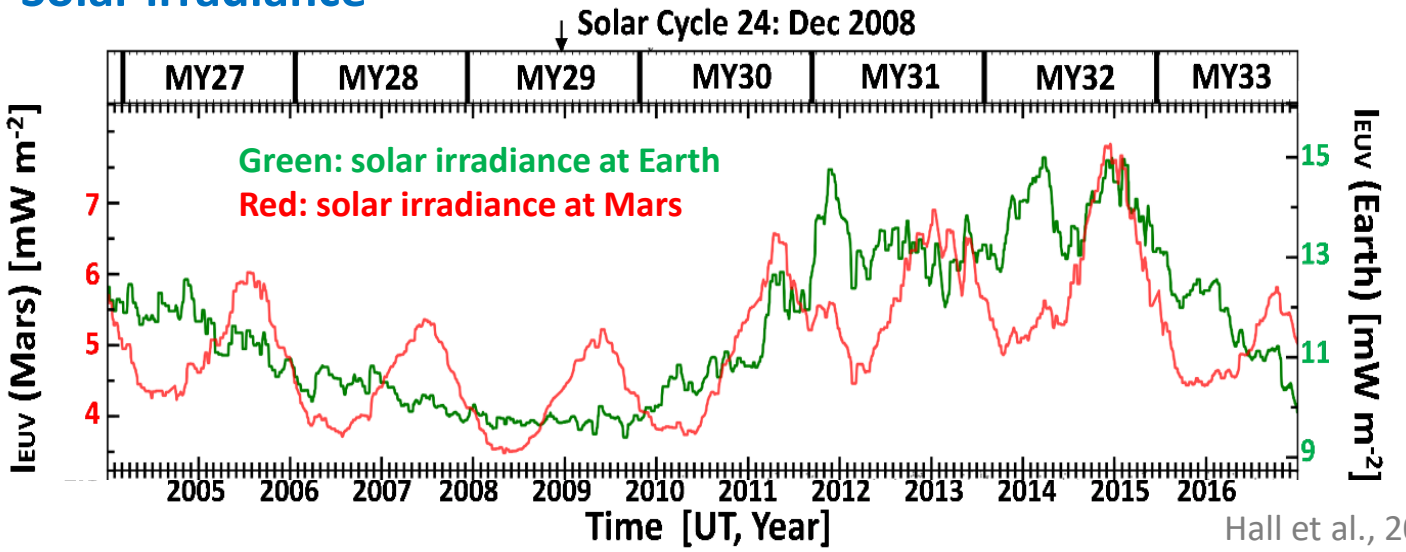


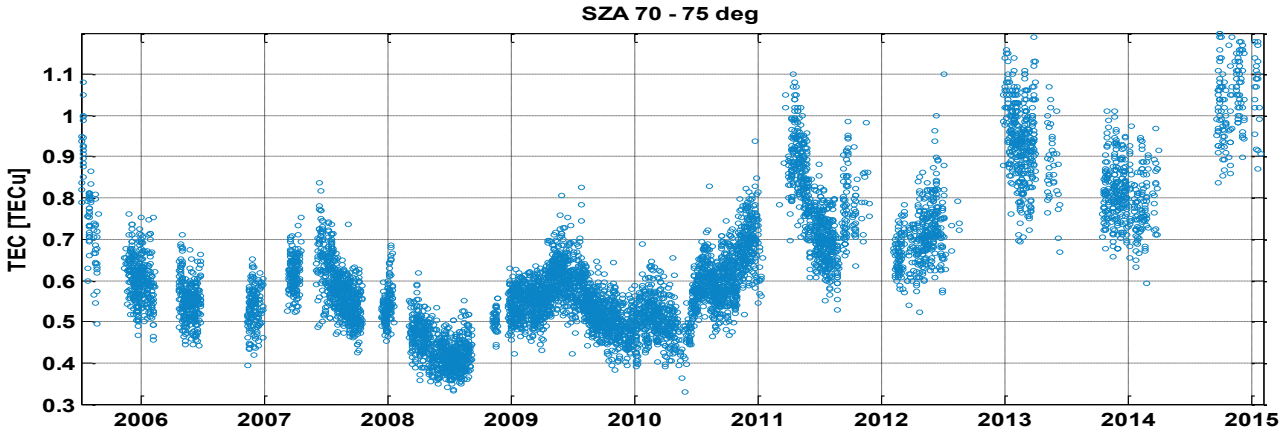
Solar EUV flux is the main source of ionization. At Mars, the large orbit eccentricity dominates the amount of solar radiation that reaches Mars, and so, has an effect on the ionosphere.

→ Solar irradiance



Hall et al., 2019

→ Total Electron Content in the ionosphere



Sanchez-Cano et al., 2016a

Solar cycle and orbital effects

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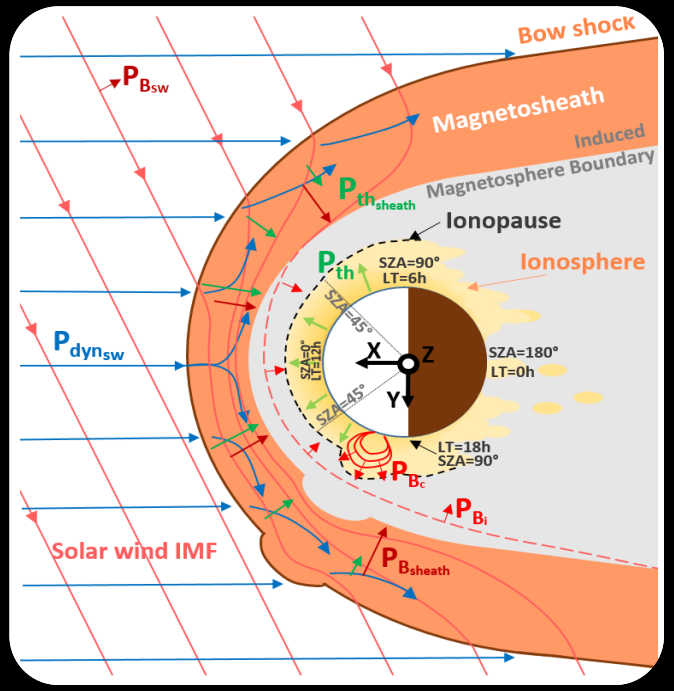
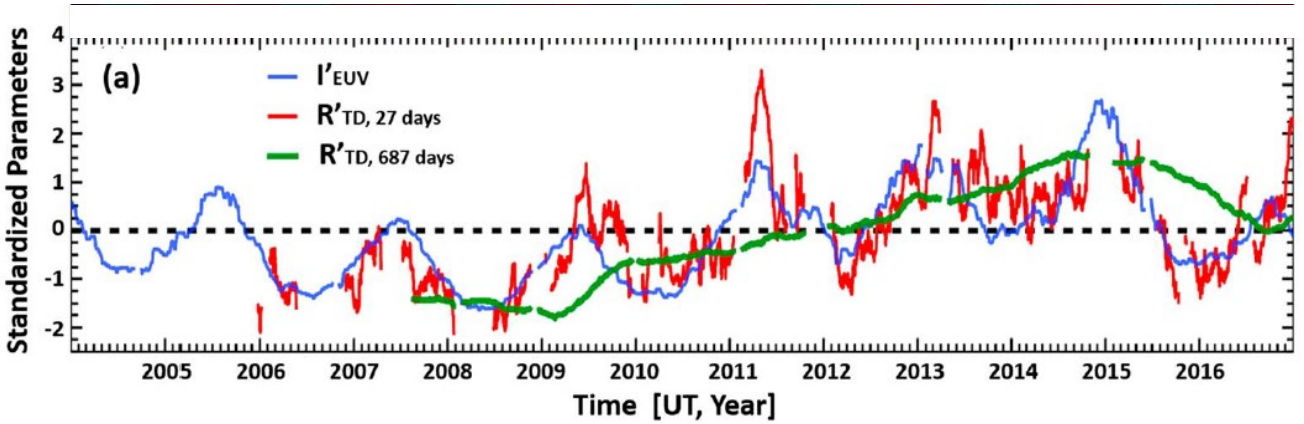


While most planetary bow shocks are controlled by the solar wind, at Mars the solar EUV flux is equally important, and so, the ionosphere.

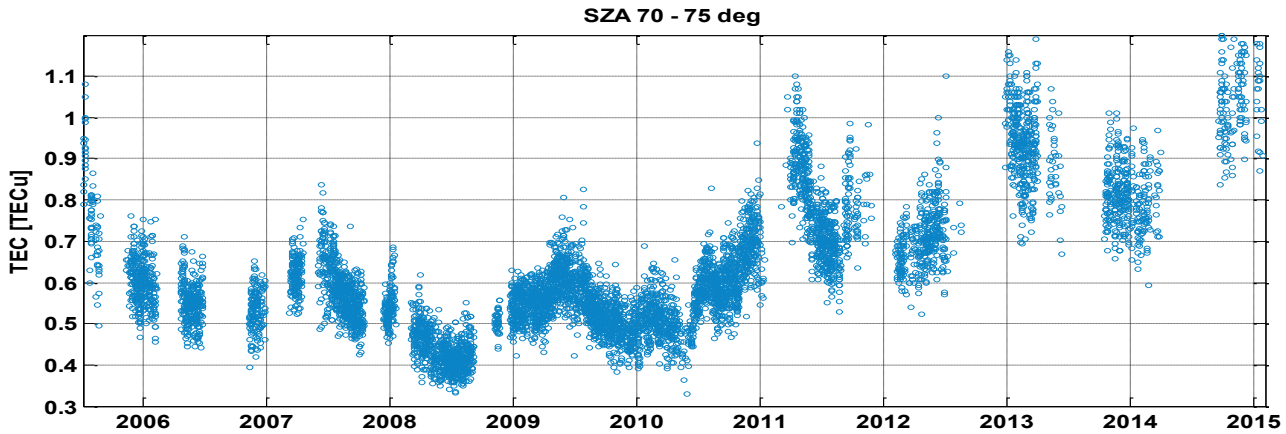
At Earth, the solar EUV control of the bow shock is negligible.

→ Bow shock location



Hall, Sanchez-Cano et al., 2019

→ Total Electron Content in the ionosphere



Sanchez-Cano et al., 2016a

Mars crustal fields

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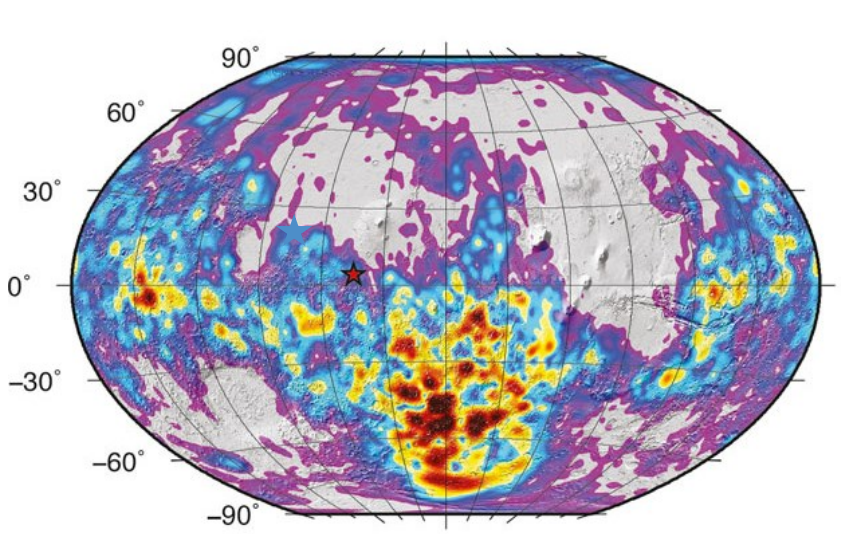
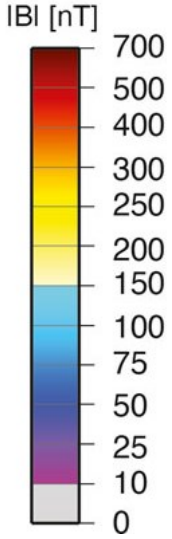
The crustal magnetic fields are mainly located at the Southern hemisphere. However, they can reach the solar wind and rotate with time. Therefore, they play a large (and quite still unknown) role on the Mars-solar wind interaction, even under quiescent solar wind conditions.

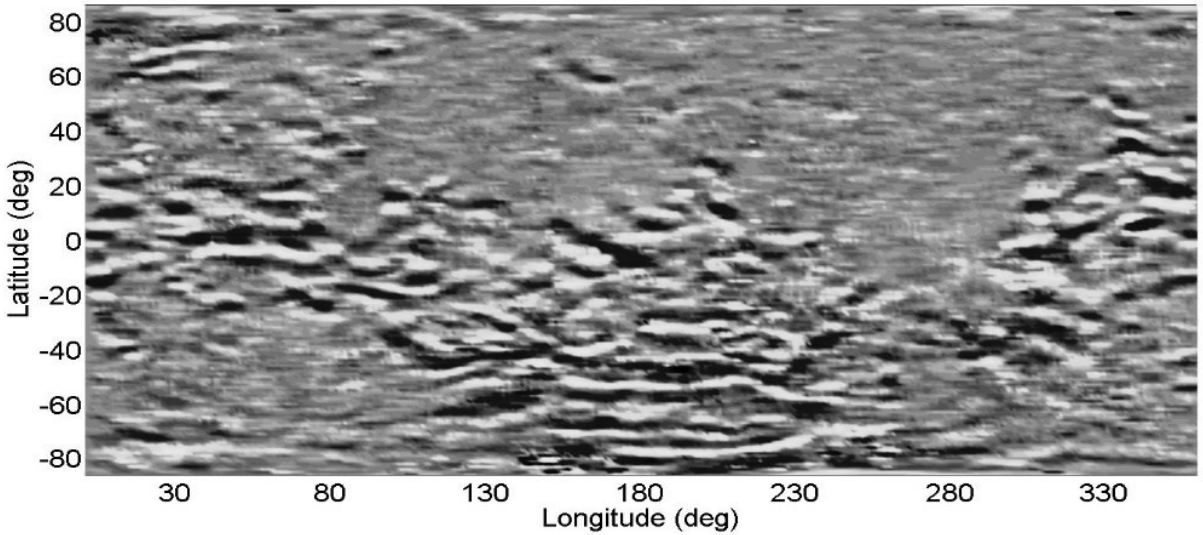
→ Crustal fields





Mittelholz et al., 2022 Langlais et al., 2019

→ Total Electron Content (nightside)



Cartacci et al., 2013

Mars' party auroras ☺

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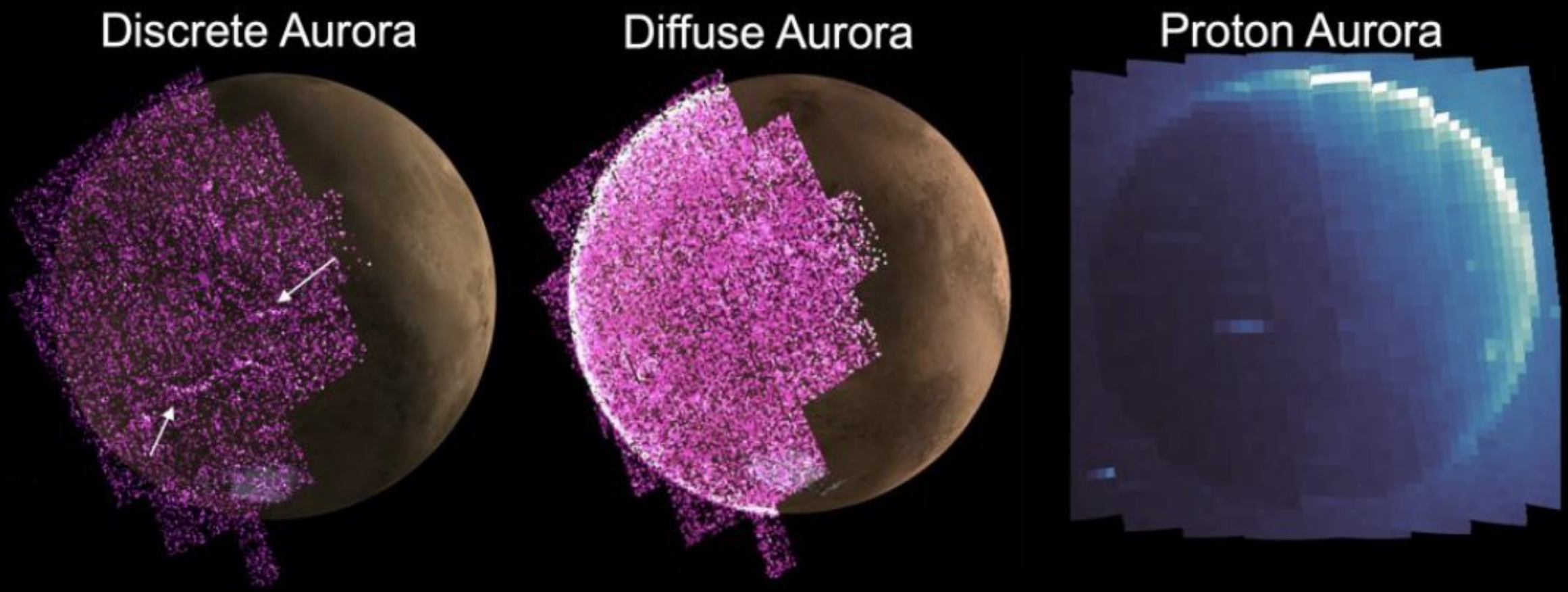

Image courtesy of N. Schneider (RAS discussion meeting February 2021)

Recent discovery of a new type of aurora

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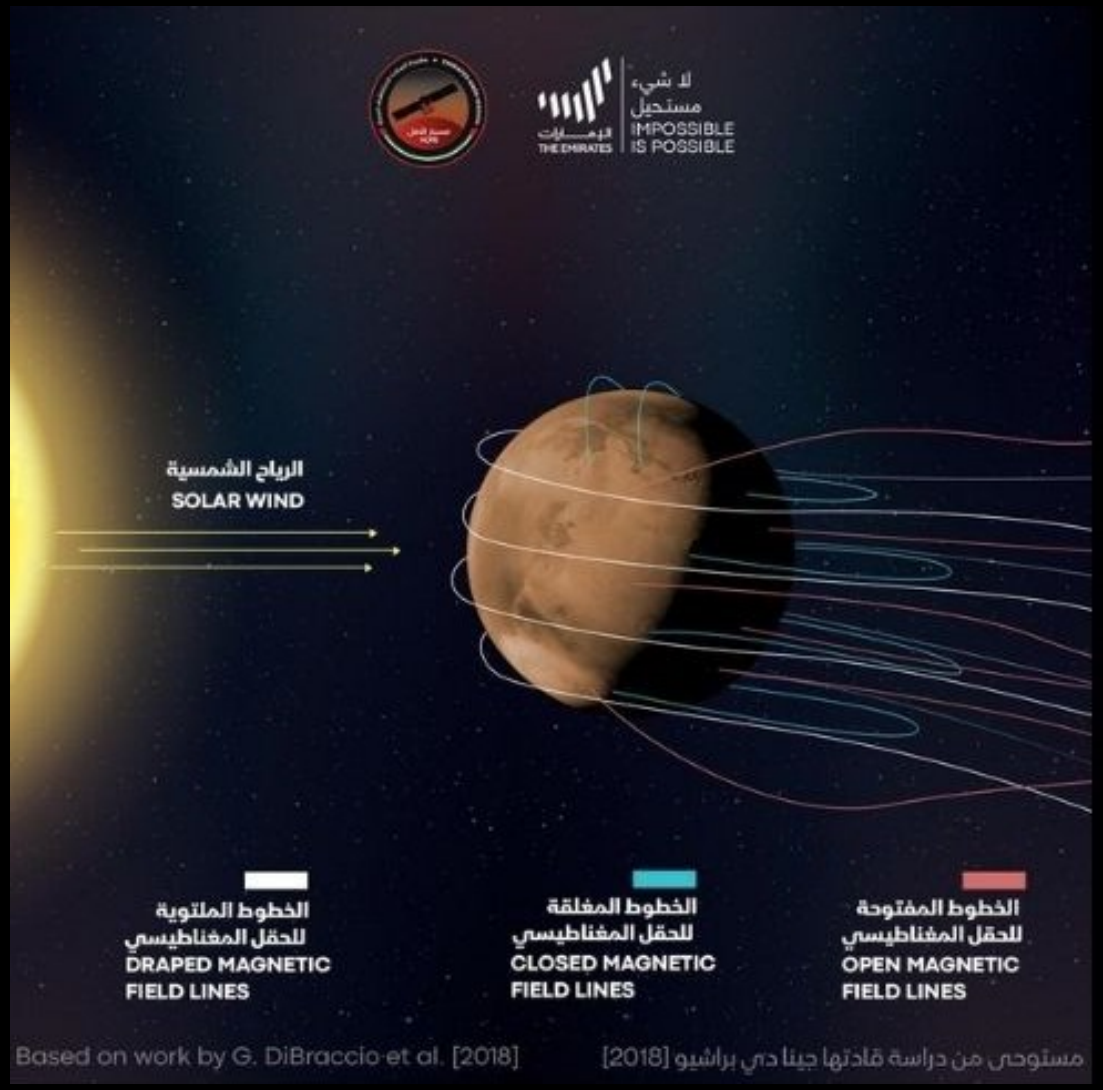

EMM mission, Lillis et al., 2022

Tail activity: solar wind door to reach the ionosphere

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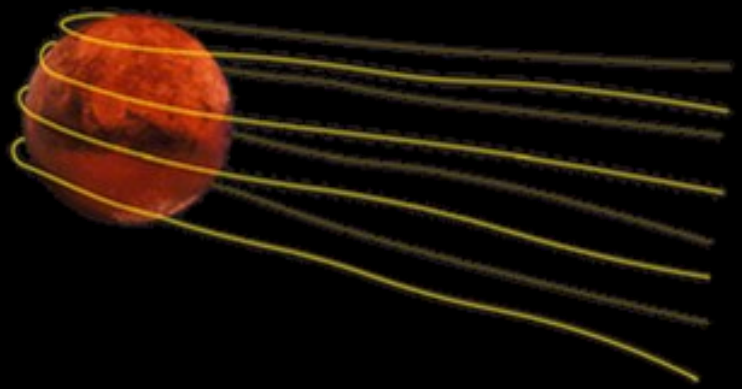
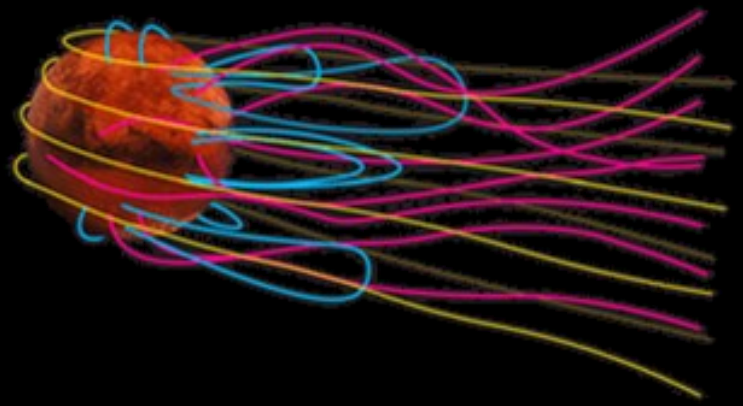
Venus-like

Induced magnetosphere



Mars-like

Hybrid magnetosphere



open magnetic field topology (magenta),
closed magnetic field topology (cyan),
draped magnetic field topology (yellow).

DiBraccio et al., 2018

Comets: large gaseous structures

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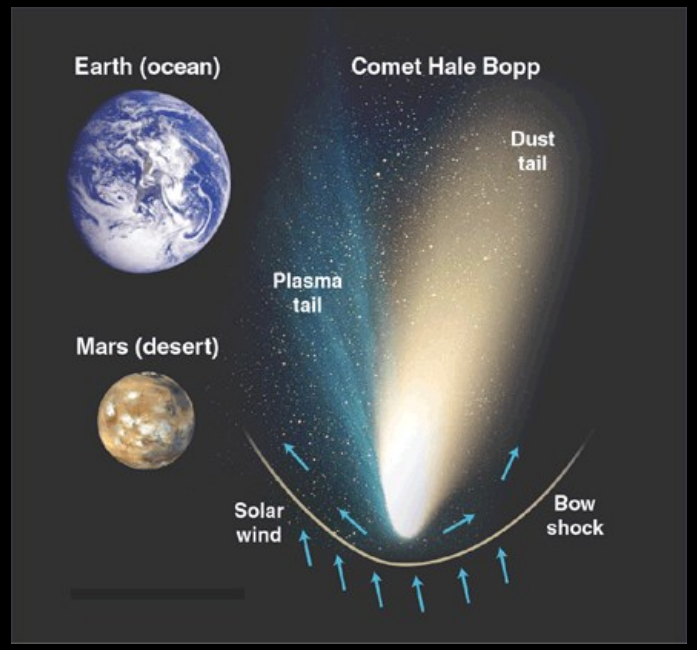
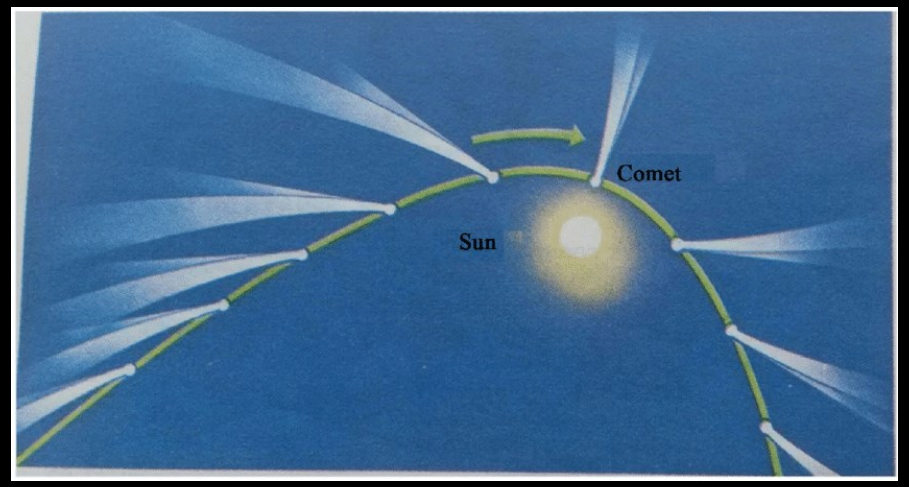
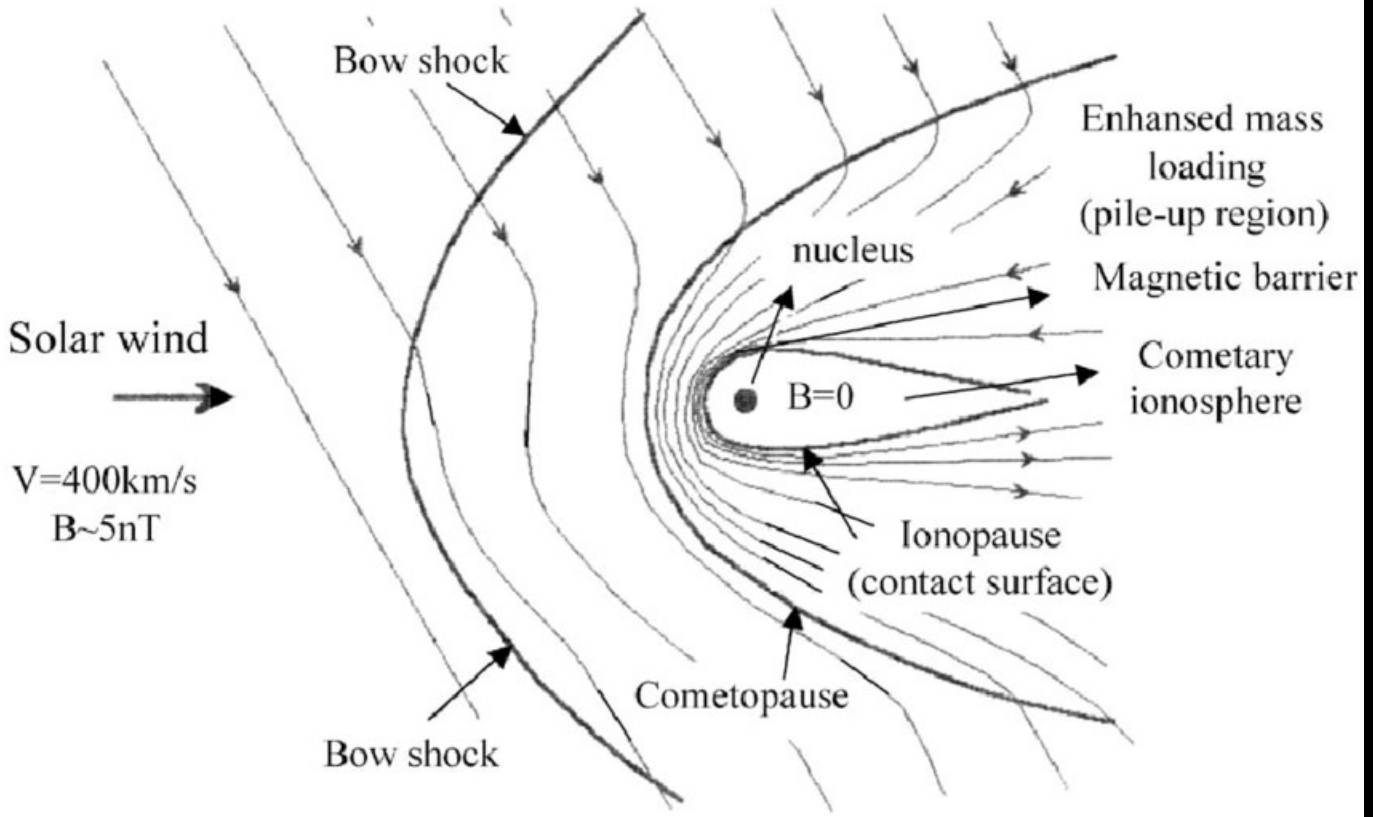




No gravity, comet's activity change with heliocentric distance



Interstellar object: 3I/ATLAS

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- The comet was releasing 70 Olympic swimming pools of water vapour every day
- This interstellar comet looks… just like a normal comet!
- Most of this water vapour was being released in the direction of the Sun

Moon interaction with the solar wind

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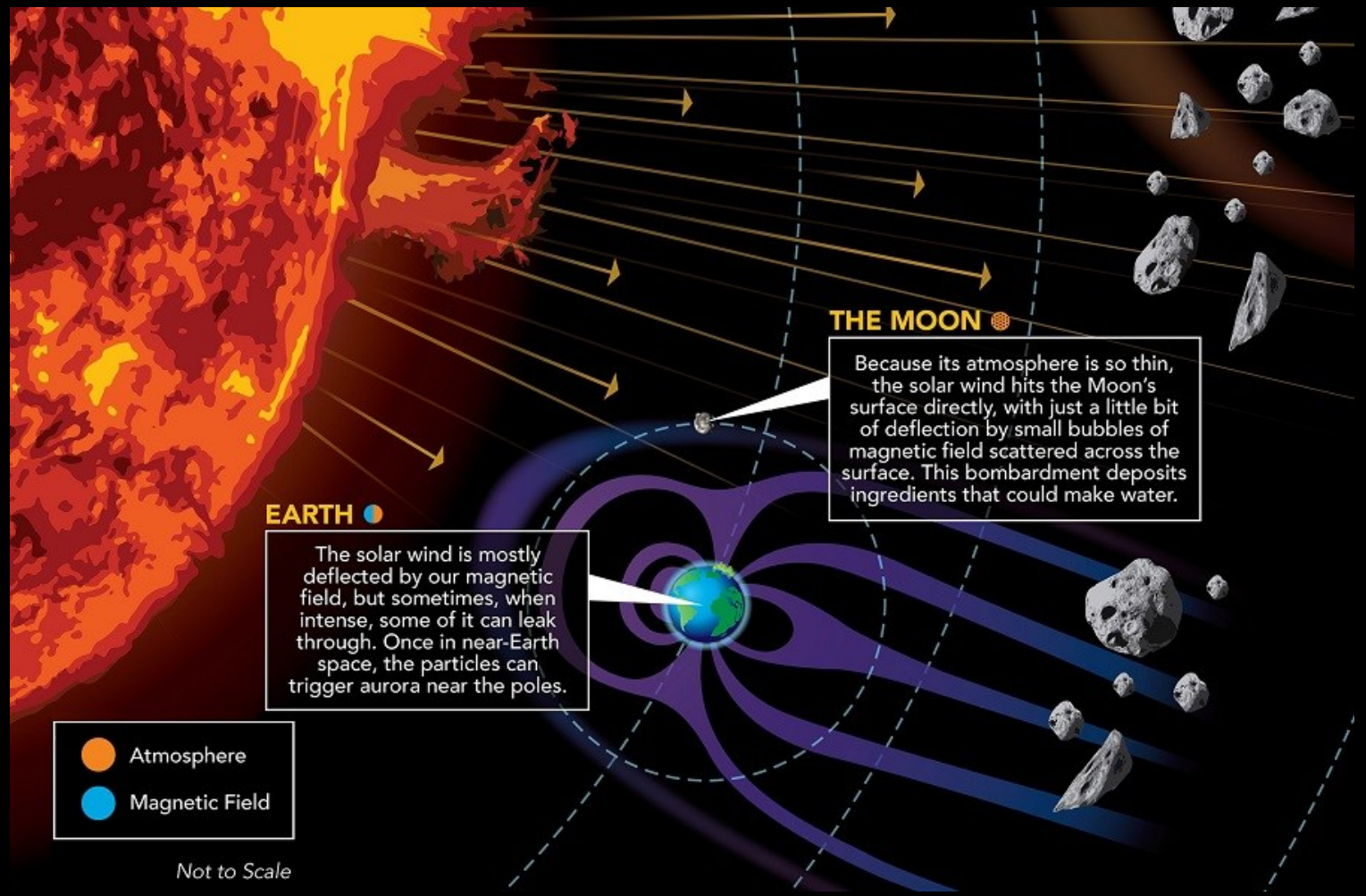
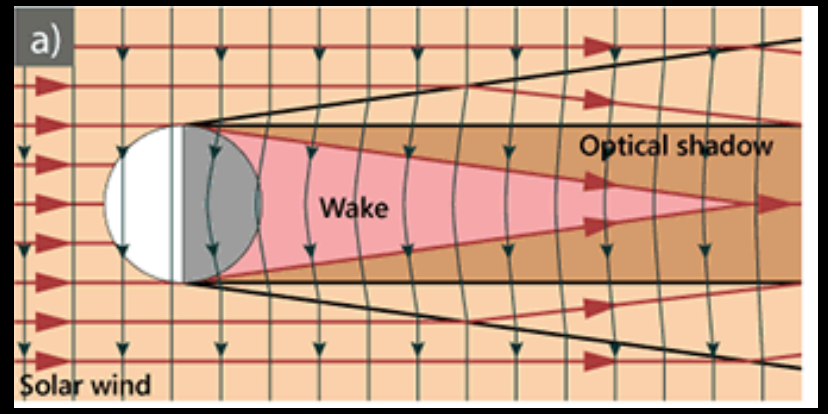
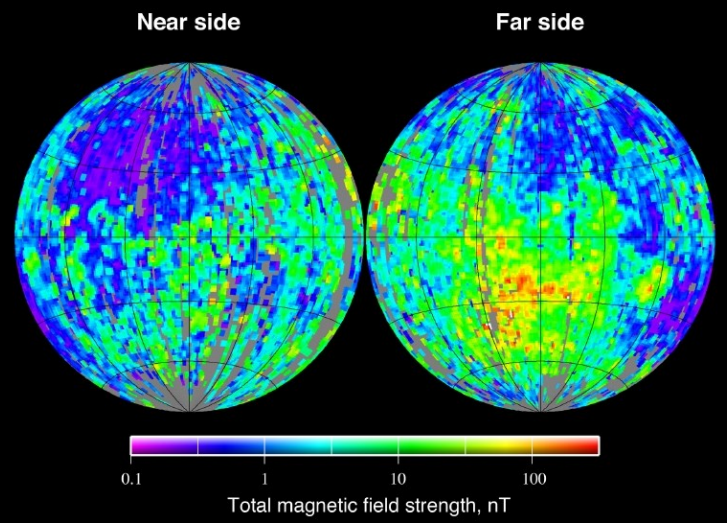
No atmosphere, no magnetic field, but crustal fields







Giant planets: Jupiter

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Size of Jupiter's magnetosphere as seen from Earth: the largest object in the Solar System

Giant planets: Jupiter

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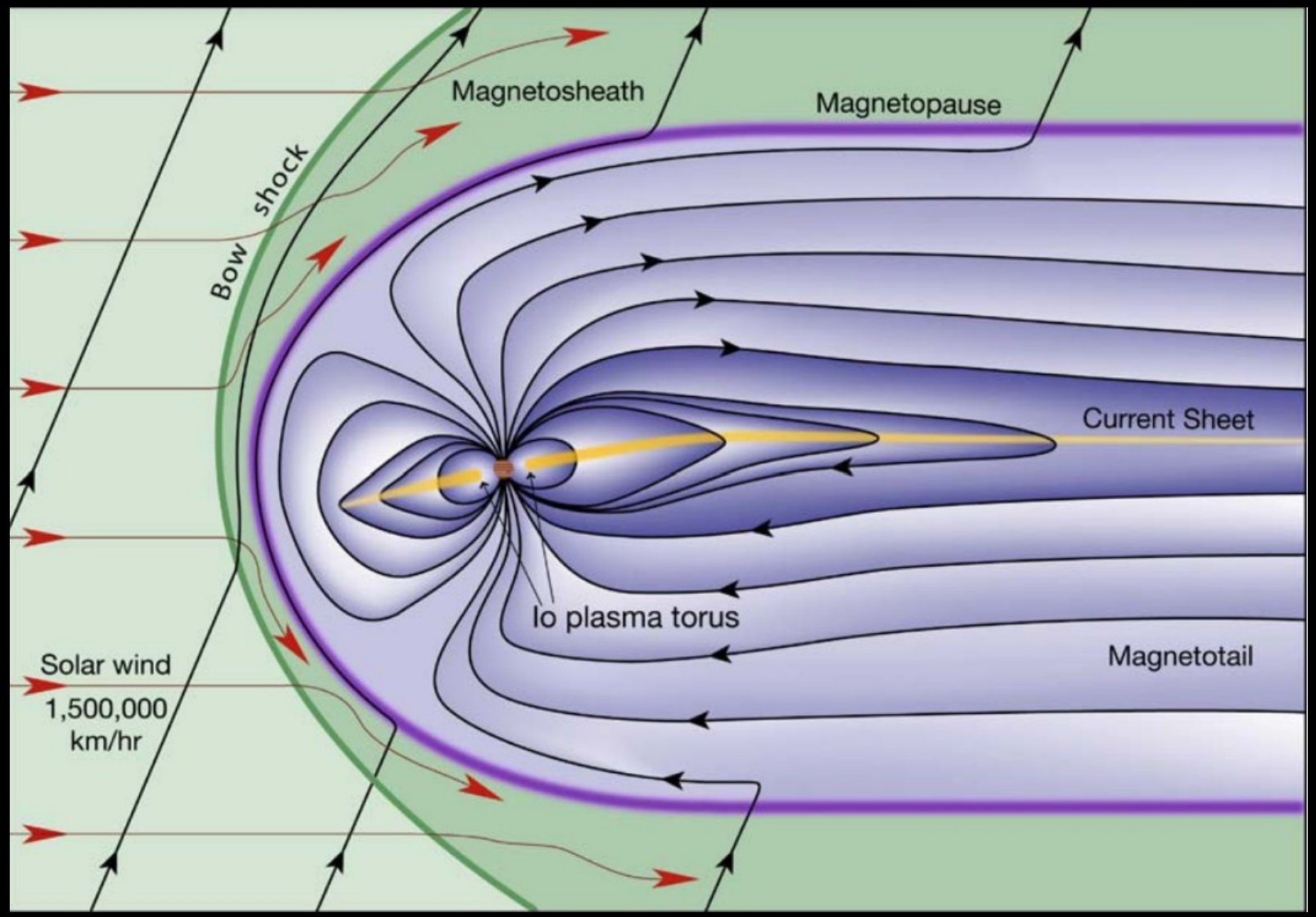

Credit: Fran Bagenal and Steve Bartlett

It has a magnetic field 20,000 times Earth's.

It feels a solar wind pressure of only 4% of the pressure at Earth.

Jupiter rotates incredibly fast (every 10 hours) but the plasma can't keep up. The plasma then precipitate into the atmosphere along a flux tube, creating the brightest aurorae in the Solar System.

Jovian coupled system

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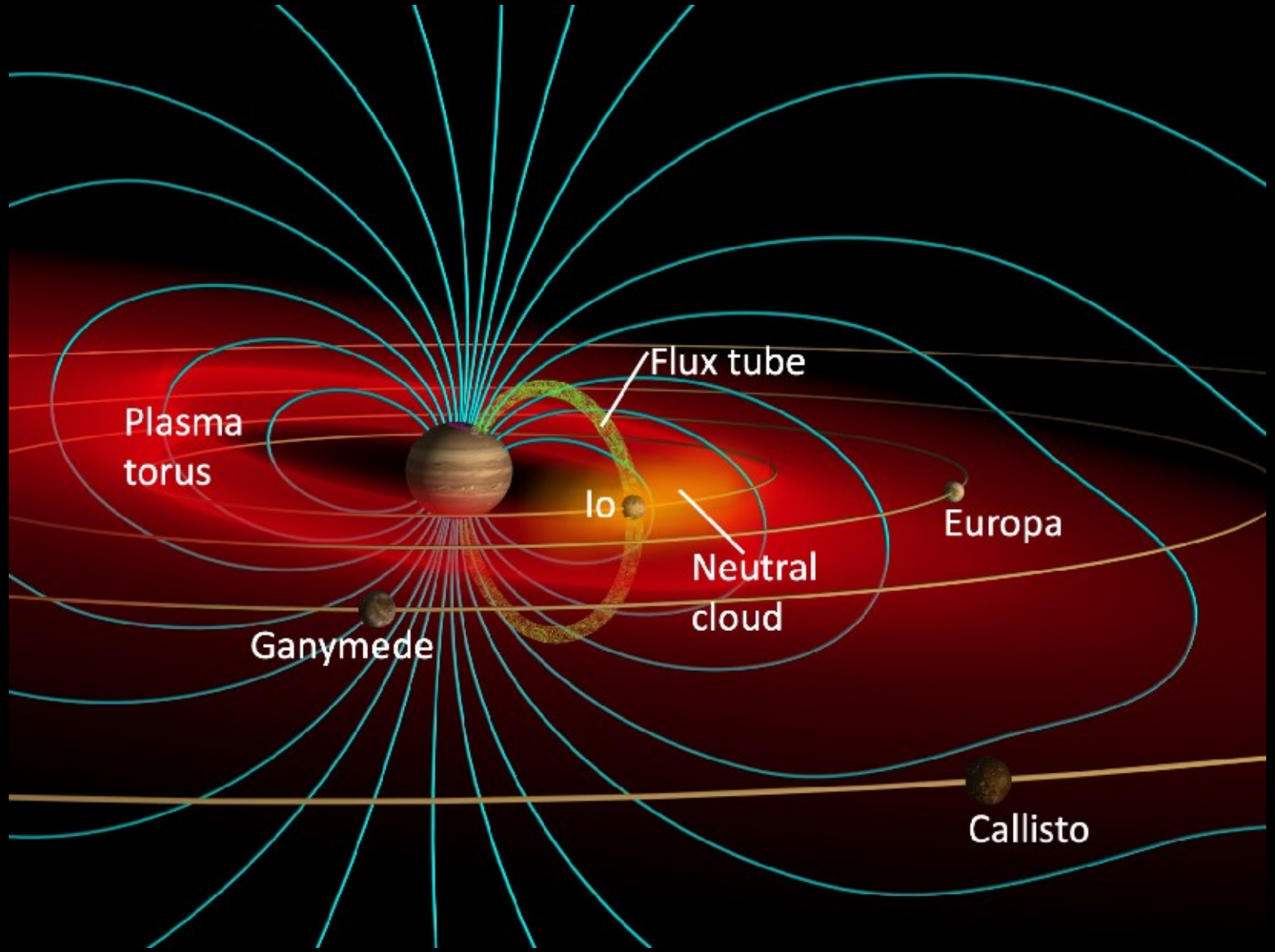

Credit: John Spencer, Southwest Research Institute

Io source of plasma corotates with the magnetosphere.

Io is volcanically active but has no atmosphere.

Every second, roughly a ton of neutral atoms from Io's atmosphere are ionized and become part of the plasma torus that encircles the planet and feeds the magnetosphere.

Jovian aurora

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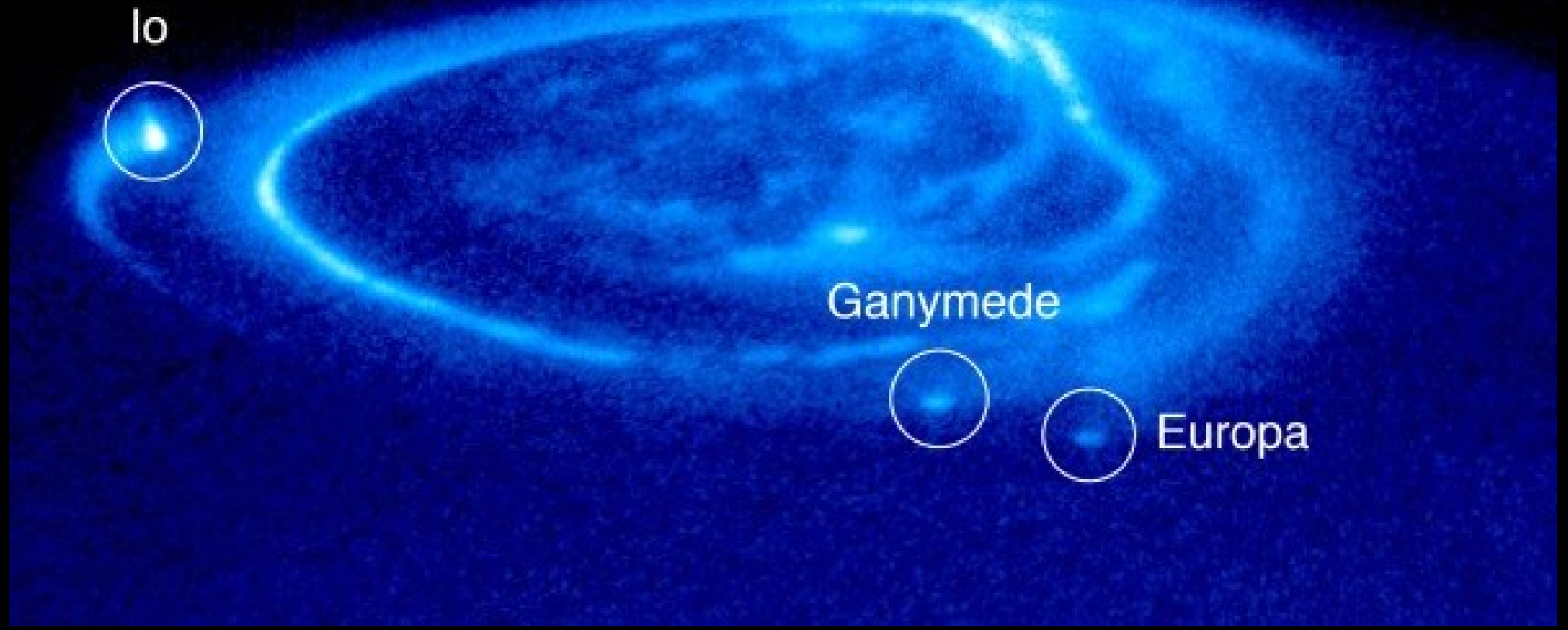

Credit: NASA and the Hubble Heritage Team

Ganymede: the special moon

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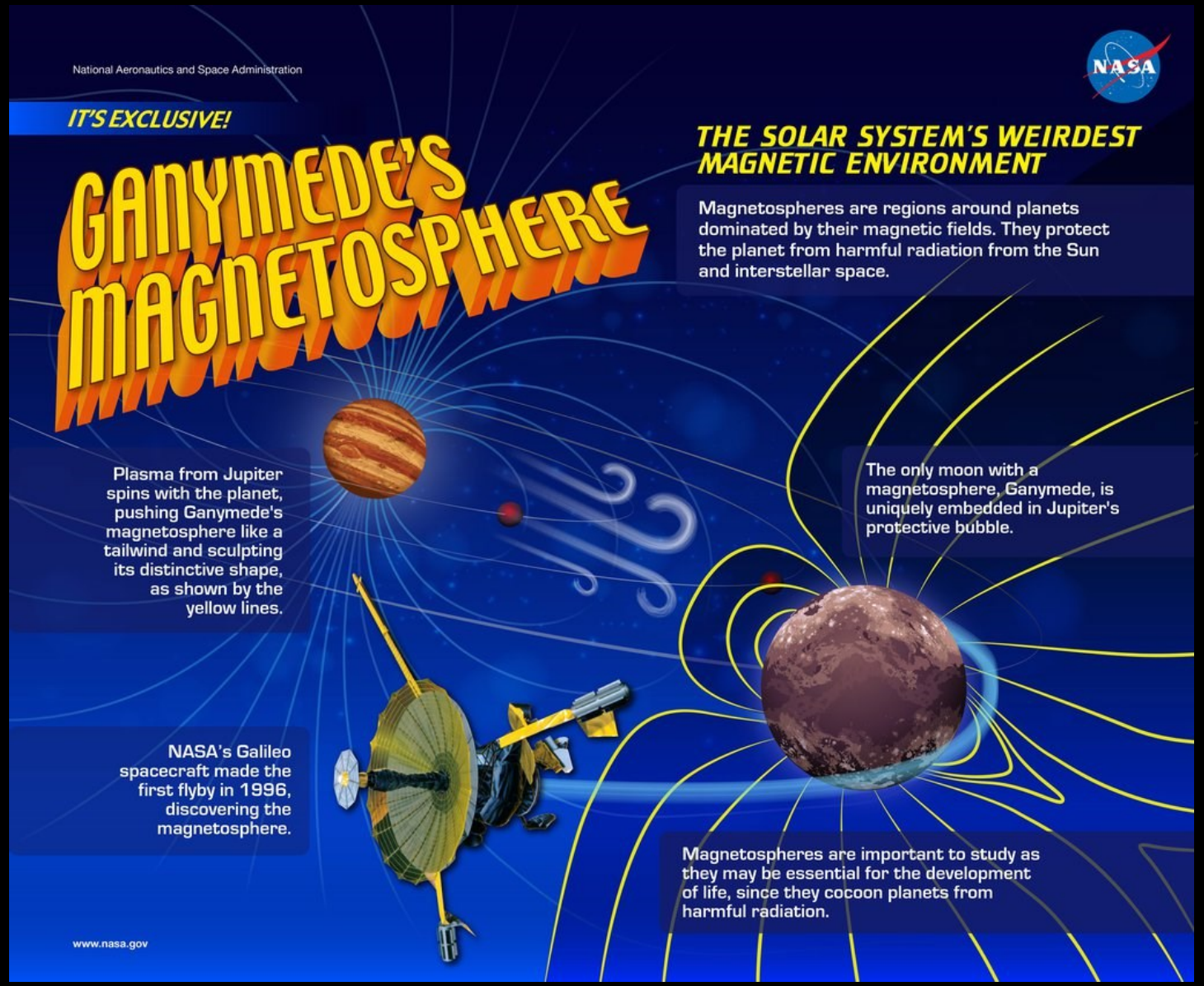

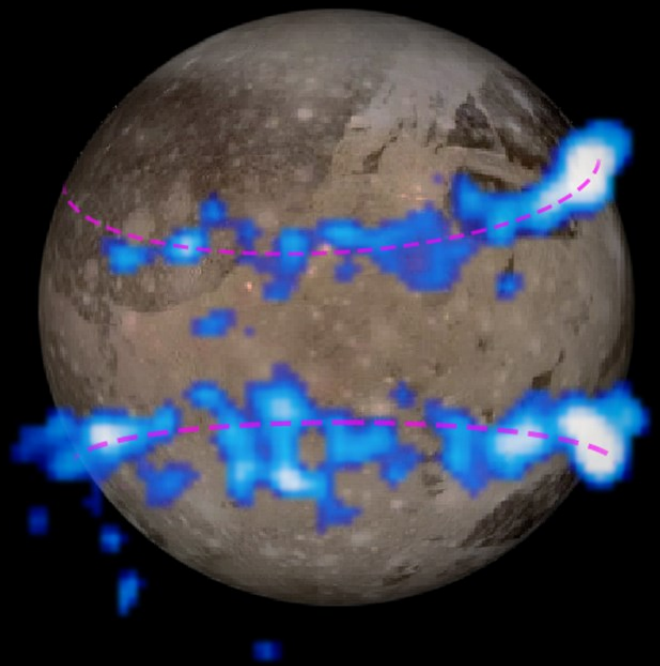

The largest moon in our solar system, bigger than Mercury, and the only one with a global magnetic field. Potential ocean under the surface.

Ganymede: the special moon

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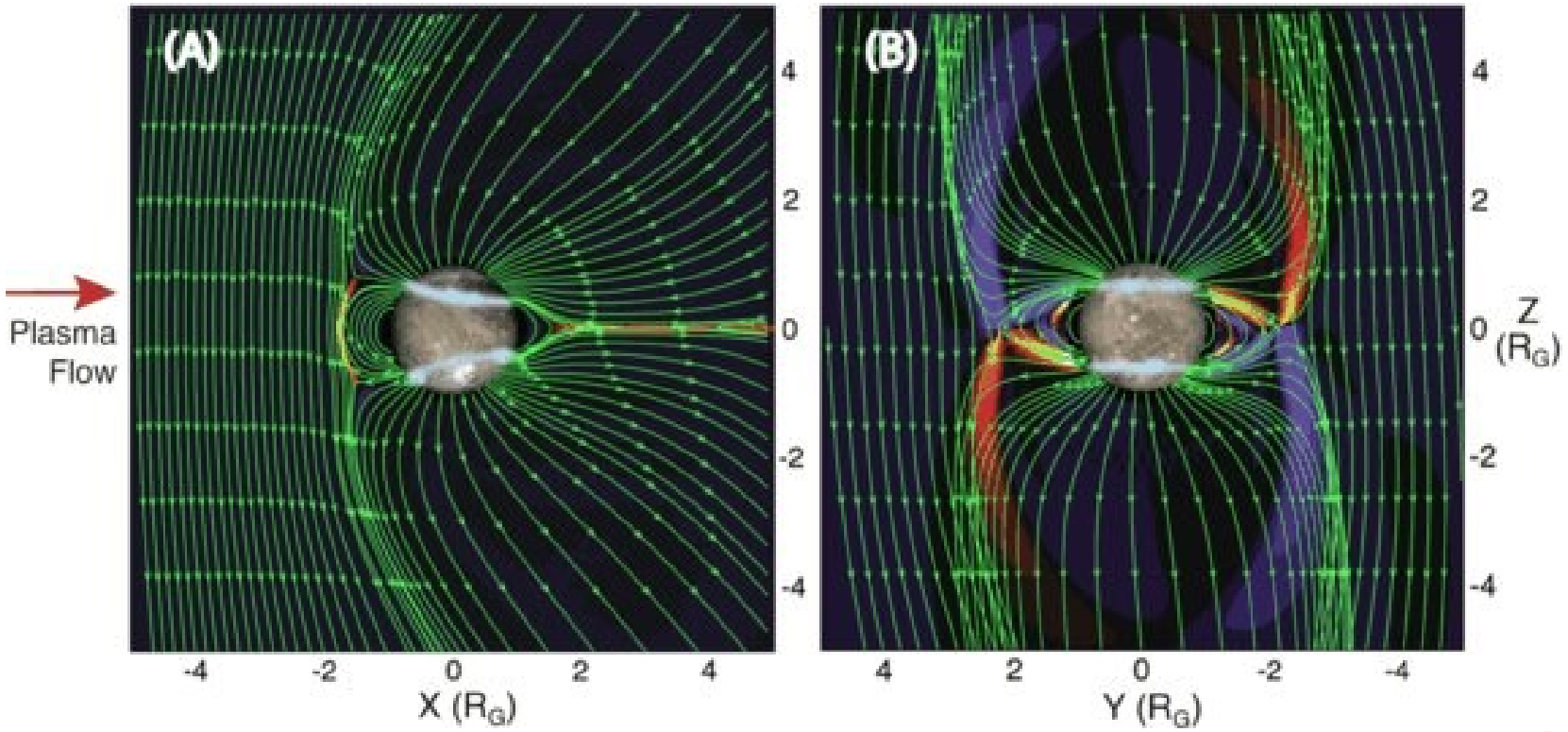
Numerical model of the magnetosphere of Ganymede. (A) The view looking at the anti-Jupiter side of Ganymede. (B) The view looking in the direction of the plasma flow at the upstream side (orbital trailing side) of Ganymede, with Jupiter to the left. The shaded areas show the regions of currents parallel to the magnetic field.



Bolton et al., 2015

The Jovian system as JUICE will see

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esa juice

esa
→ THE EUROPEAN SPACE AGENCY

Saturn

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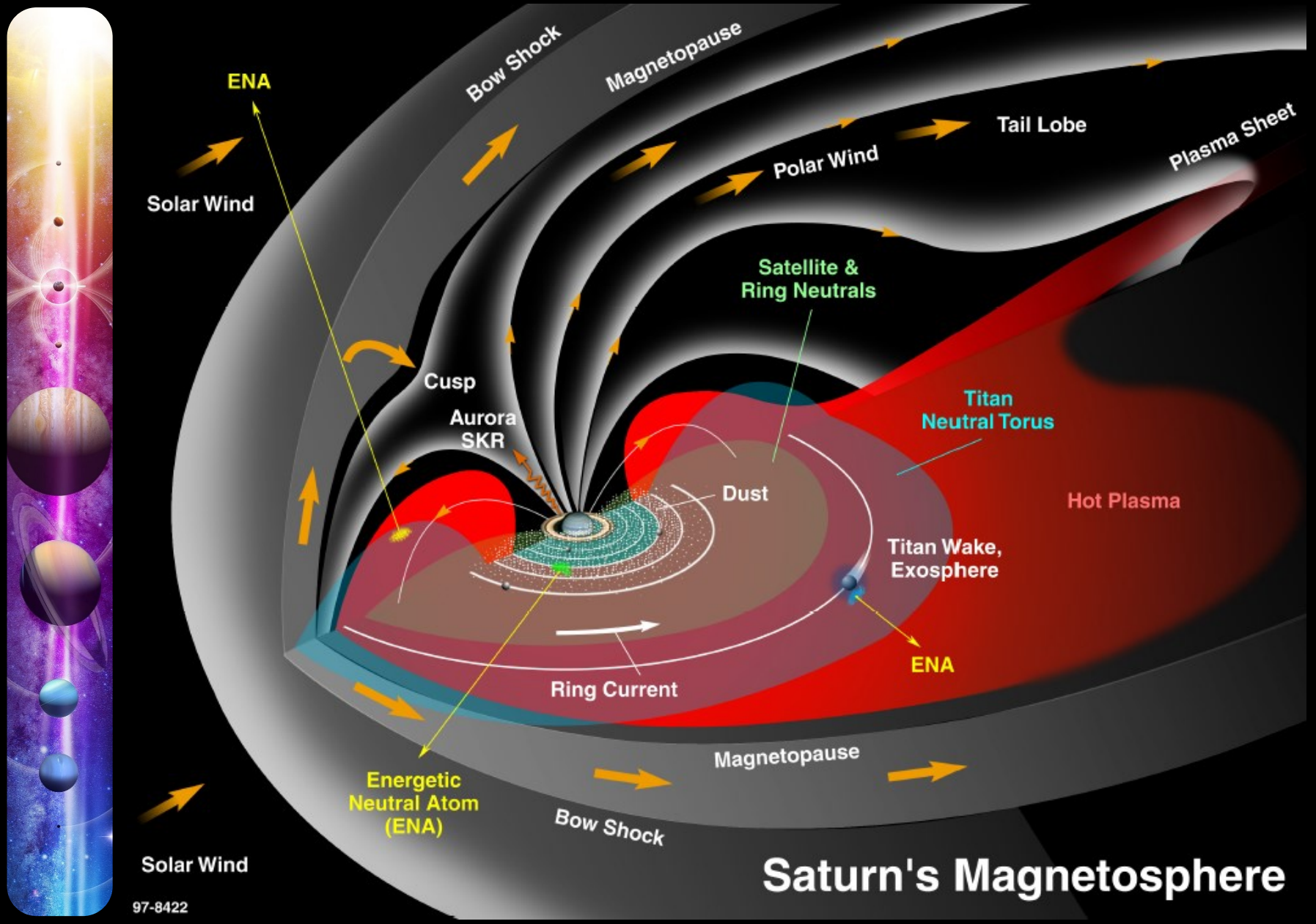

Magnetic field 600 times stronger than Earth's

Super fast rotation

The moon Enceladus is the source of most of the plasma in Saturn's magnetosphere

→ **L4 ESA mission!** ☺

Planetary period oscillations drive the motion of the magnetosphere

Saturn-Titan-solar wind interaction

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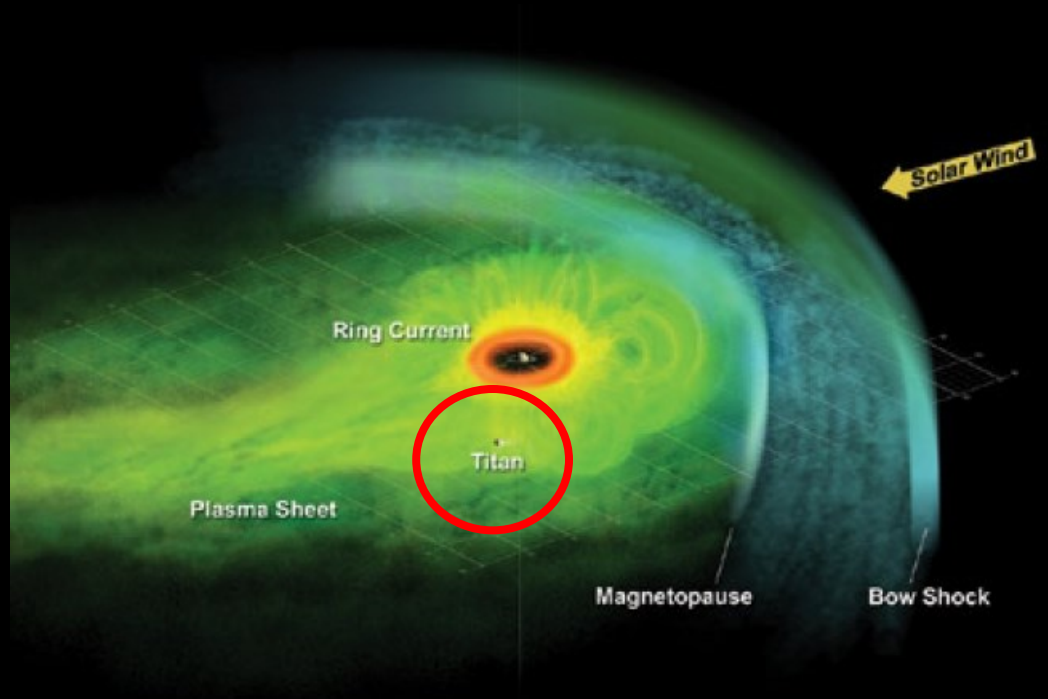
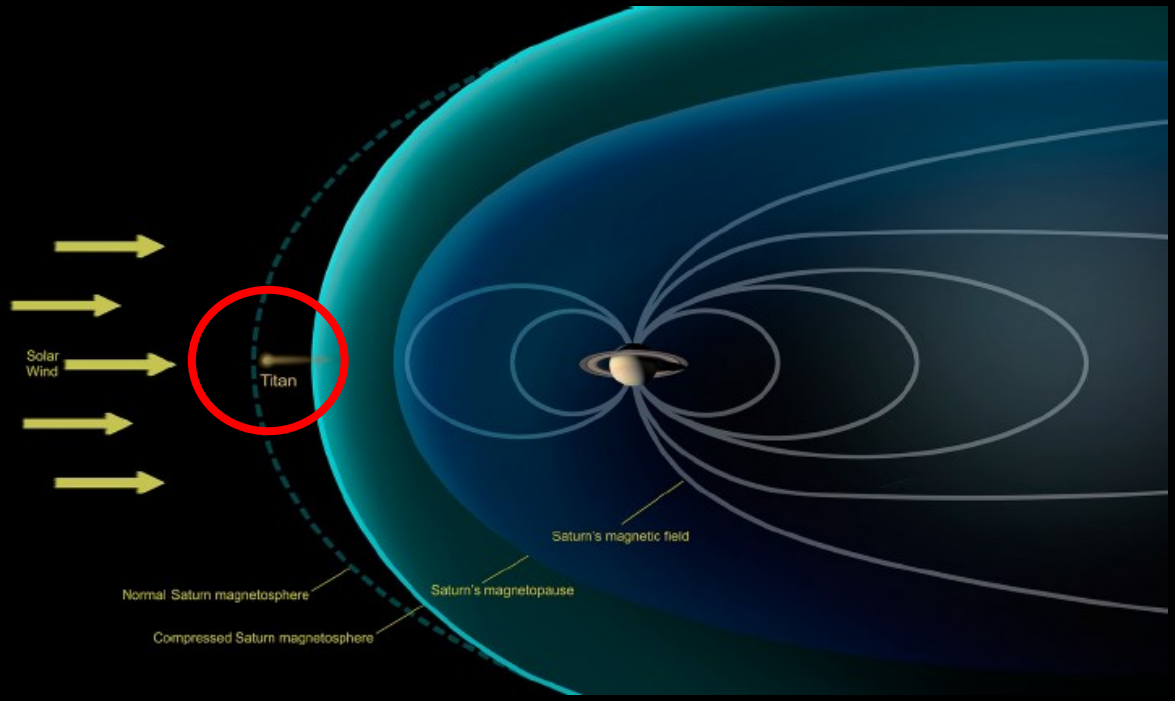
Under typical solar wind conditions



Under significant increase of solar wind dynamic pressure



Titan orbits Saturn fully inside its magnetosphere at ~20 Rs (1 Rs=60,268 km). It interacts with the planetary plasma in a subsonic regime)

Titan has been observed just a few times in Saturn's magnetosheath and only one time in the solar wind (during Cassini's T96 flyby, 01/12/2013)

Titan's interaction

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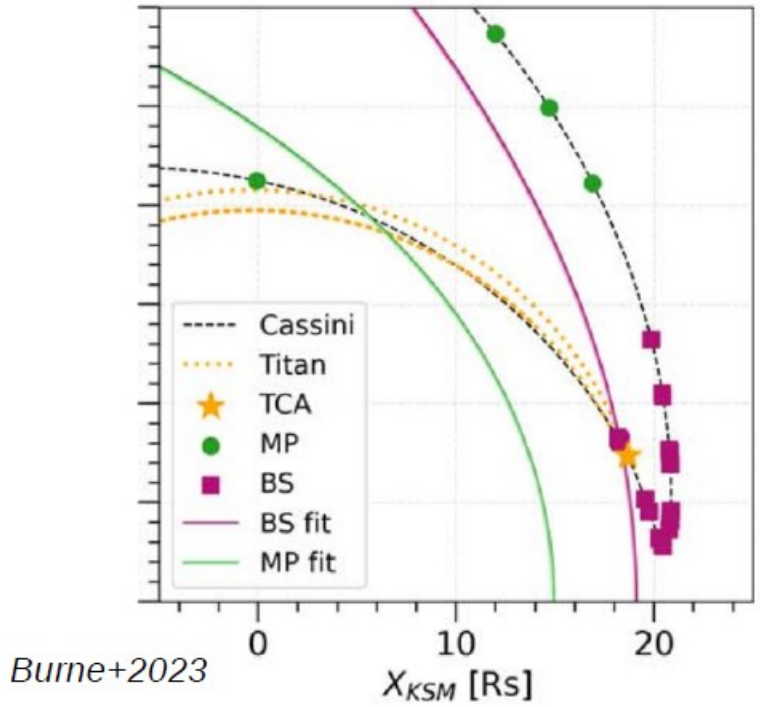
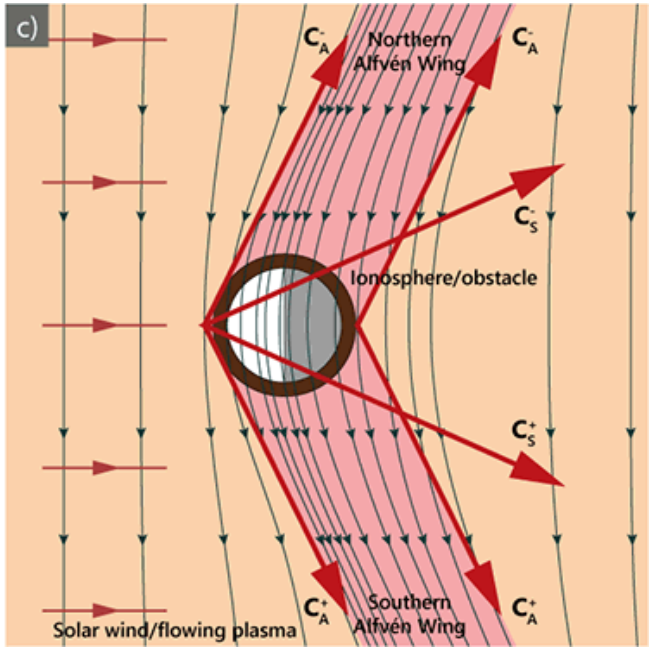
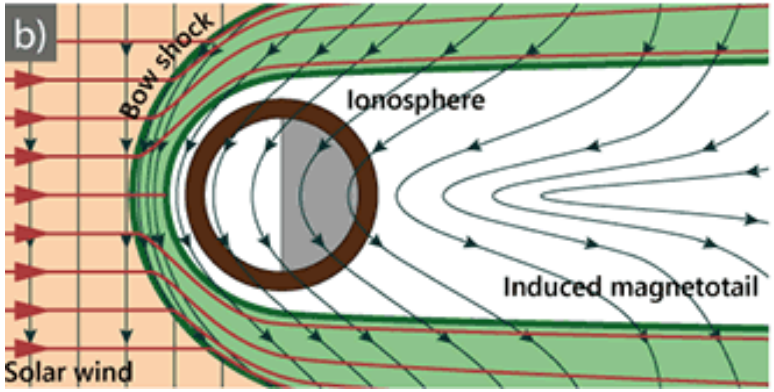
- Unique observations of Titan's interaction with Supersonic solar wind
- First detection of supercritical bow shock
- Induced magnetosphere similar to Mars and Venus





Under typical solar wind conditions



Under significant increase of solar wind dynamic pressure

Arridge et al., 2020

Uranus (and Neptune) highly irregular magnetosphere!

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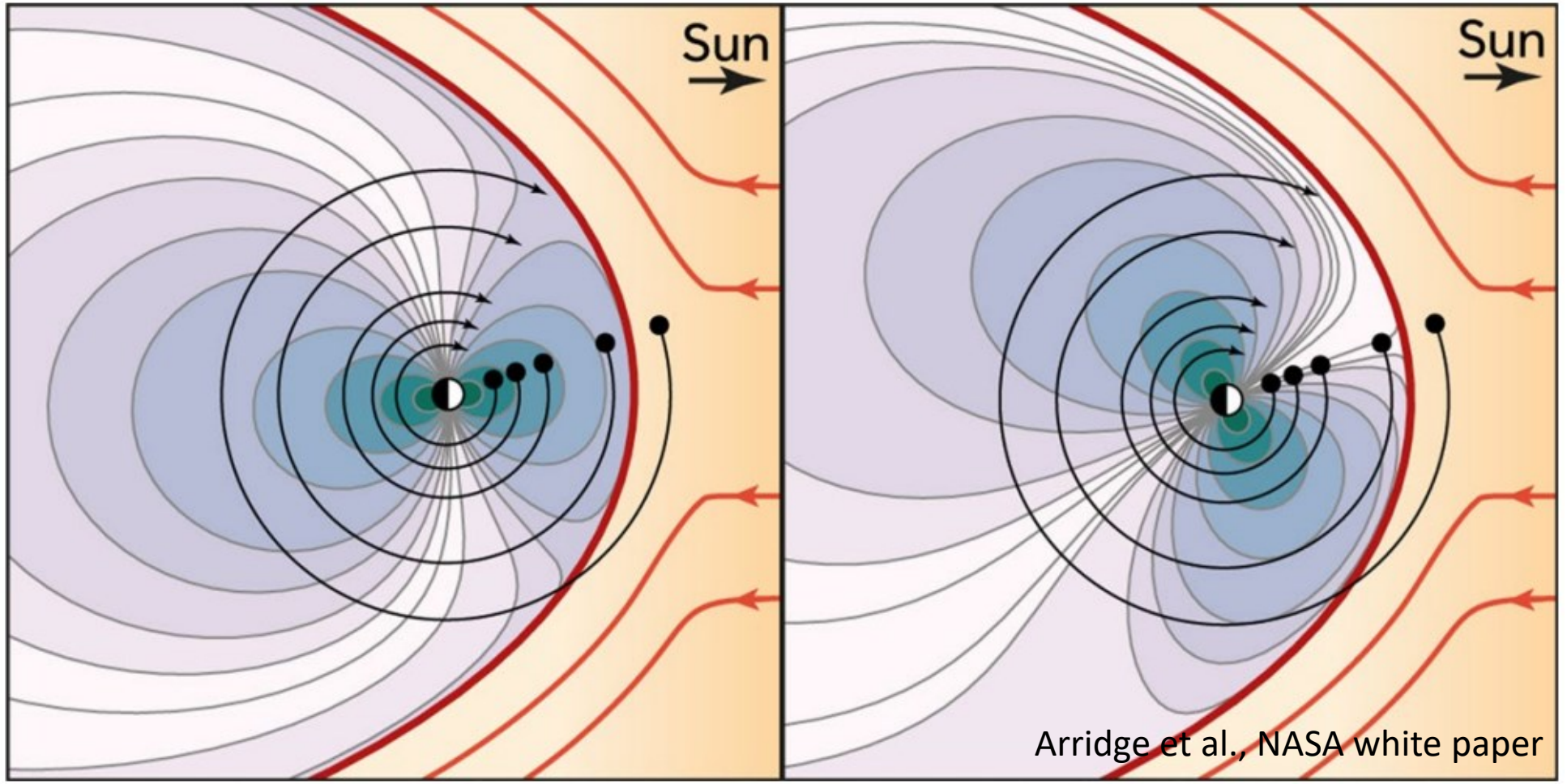

Magnetosphere at equinox. The configuration alternates between pseudoterrestrial (left) and pole-on (right) in one Uranus day (diagrams drawn ~ 4 hours apart).

Magnetic configuration of Uranus

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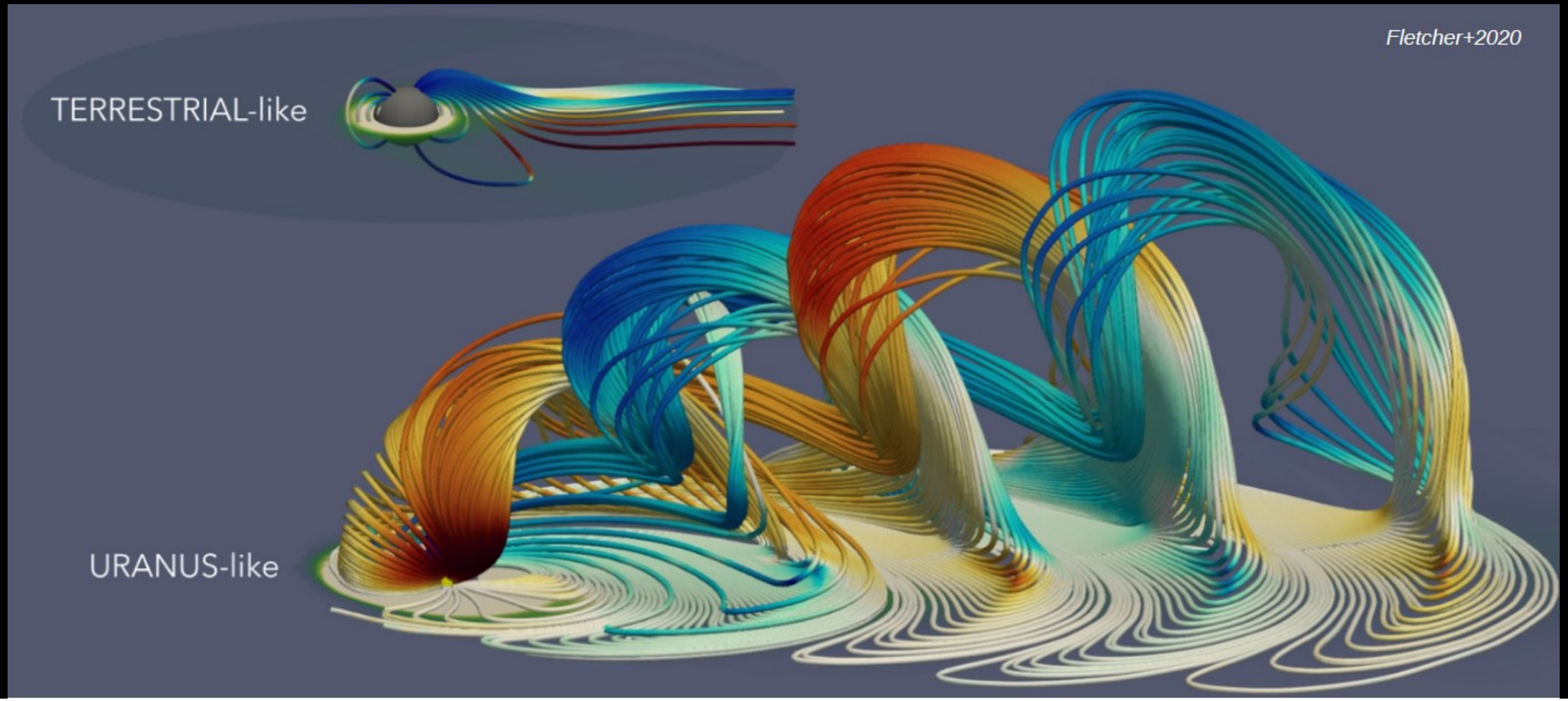

Magnetic field lines in the roughly cylindrical magnetotail to be wound into a helical shape

How does plasma move radially in this type of Configuration ?

Take home message

- The solar system is a unique and natural laboratory
- Planetary- Heliophysics are intimately linked
  - ➢ Same for any exoplanet system
- Plasma systems are a key to unravel planetary evolution and habitability
- Good luck in your PhDs!! ☺

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(Photo: NASA/Jenny Mottar)