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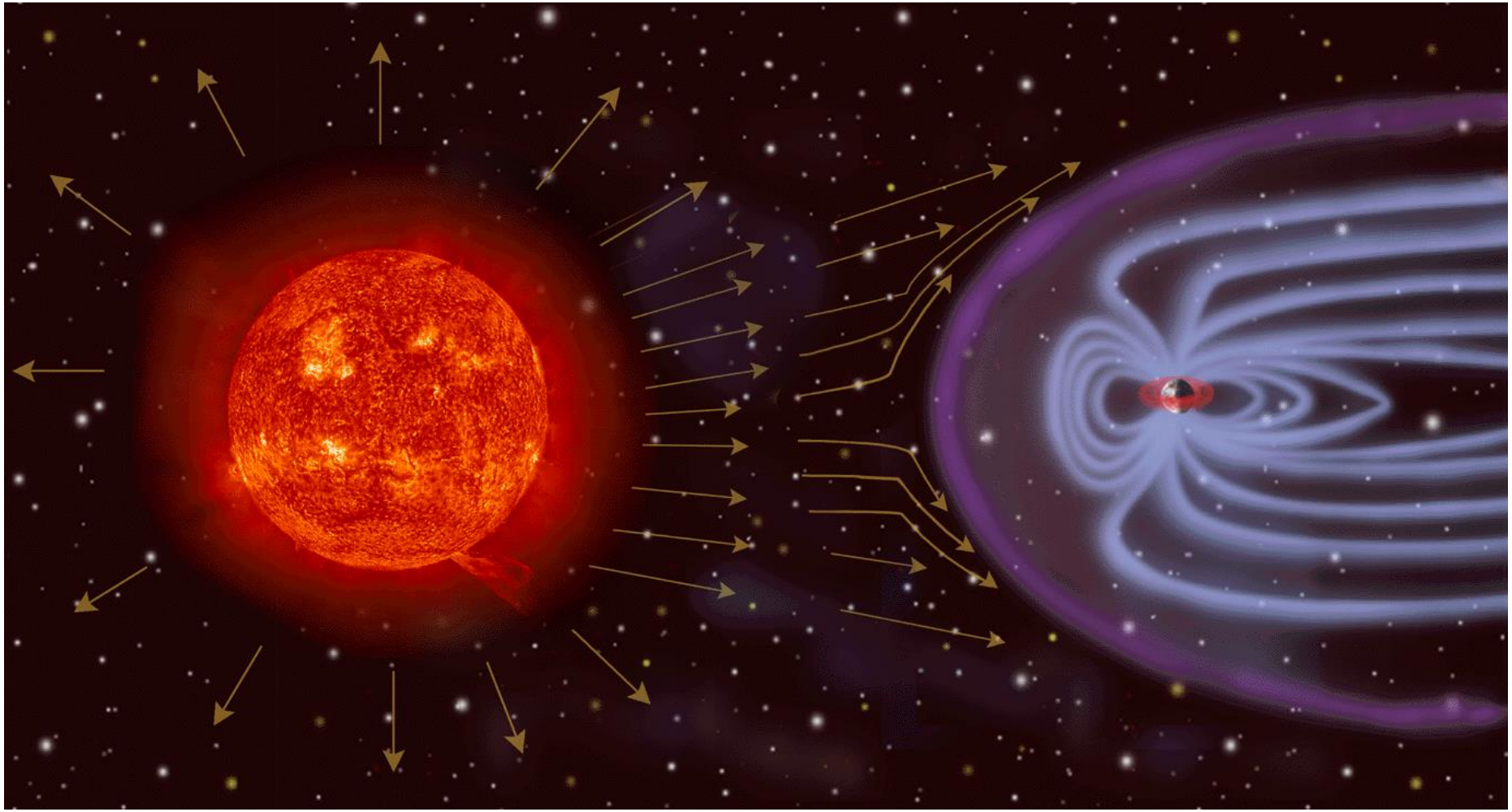
- Please let me know if you have any questions!

The scope of space physics

Solar-Terrestrial Relations



Solar-Terrestrial Relations (cont'd)

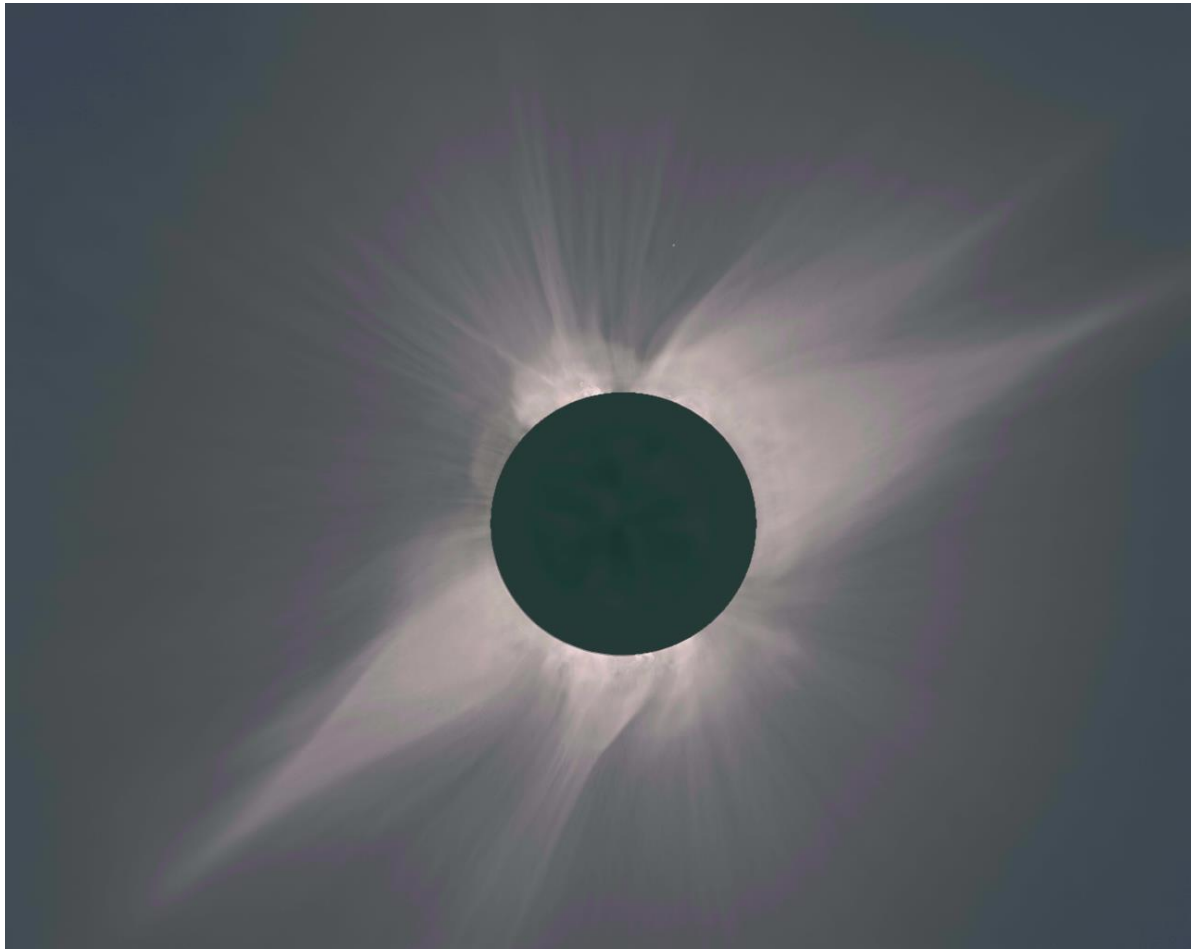
Strong coupling between the Sun, the solar wind and Earth's magnetic field

Influence of the Sun on Earth:

- solar radiation (photon flux): leads to the formation of Earth's *ionosphere*

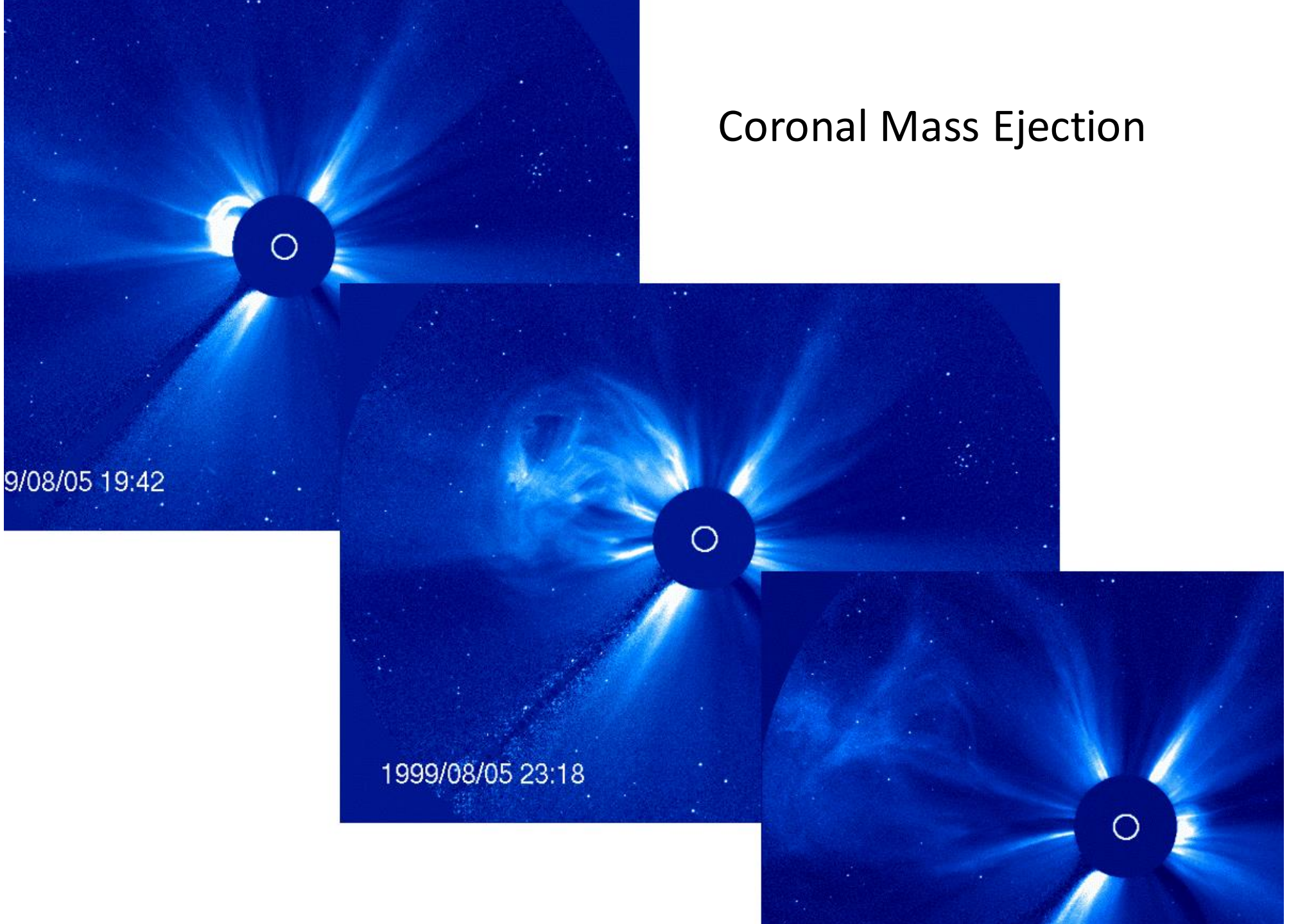
- solar wind (mass flux): leads to the formation of Earth's *magnetosphere* and aurorae, generates magnetic storms

Solar-Terrestrial Relations (cont'd)



The Sun

Coronal Mass Ejection

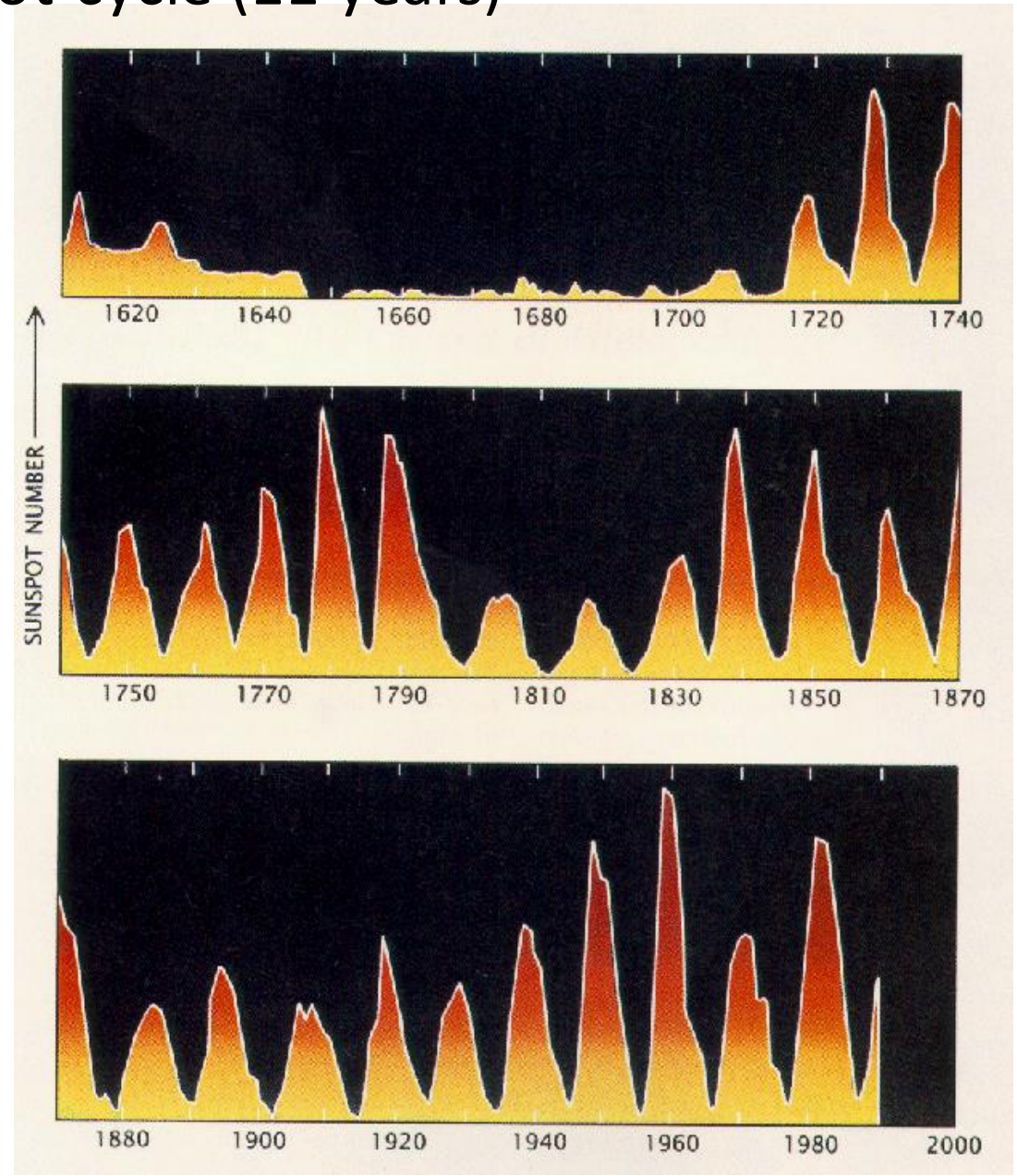


Consequences of coronal mass ejections:

- power failure
- disruption of telecommunication networks
- damage to spacecraft
- increased auroral activity

Sunspots, close-up

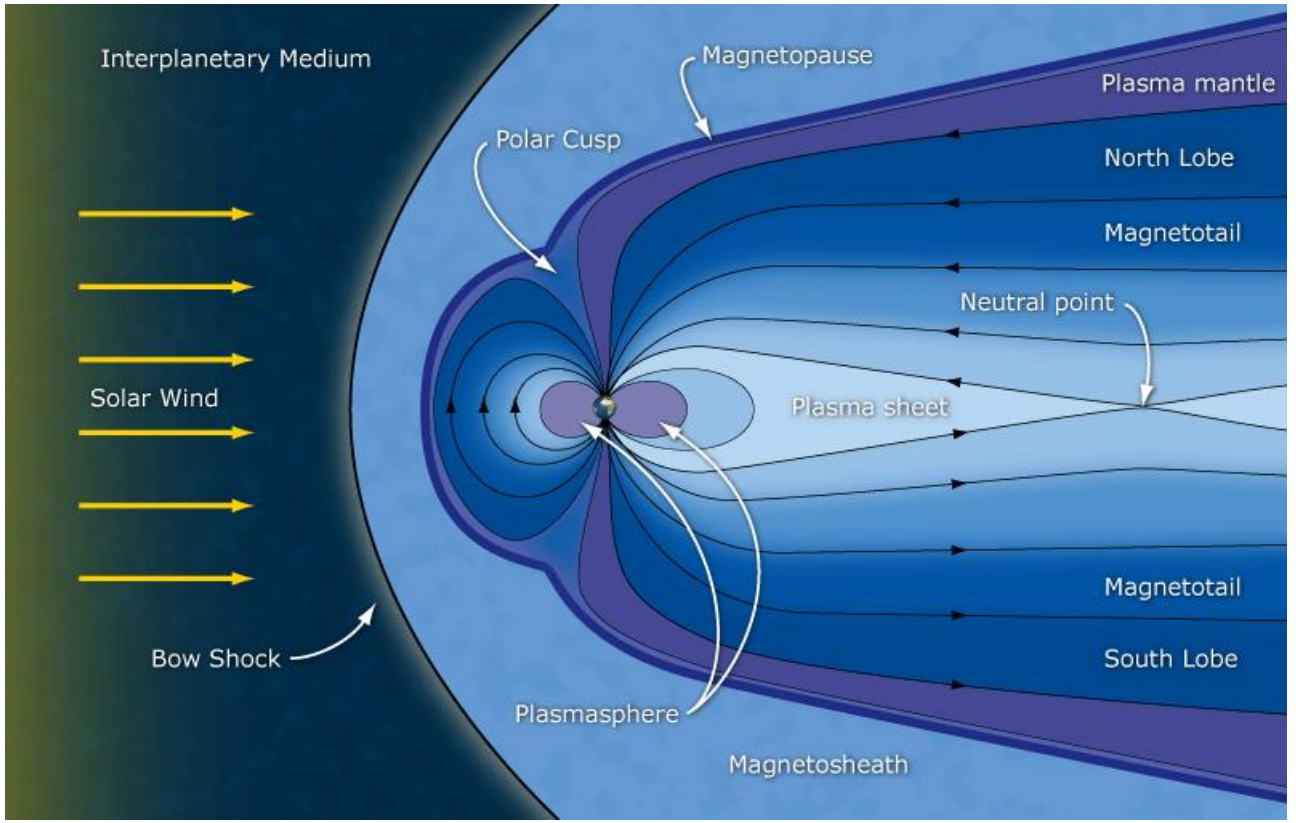
Sunspot cycle (11 years)



Observation: Cometary tails are directed away from the Sun
=> discovery of the solar wind (1951)

Earth‘s magnetosphere

- cavity in the solar wind that is controlled by Earth‘s magnetic field
- “outermost part of Earth’s atmosphere”
- The magnetosphere is filled with plasma.



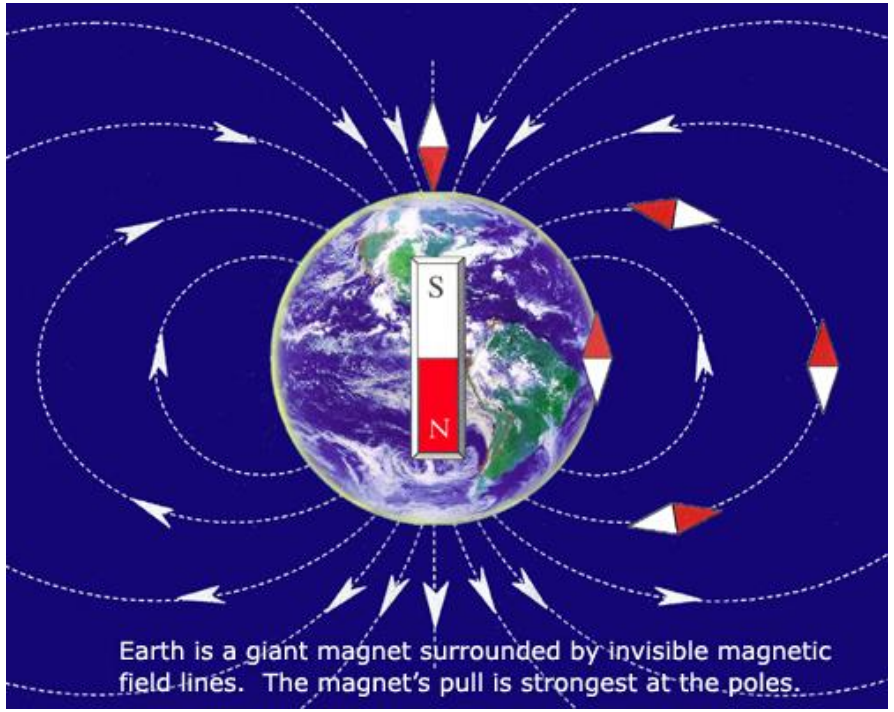
Earth‘s magnetosphere (cont’d)

The magnetosphere is generated by the superposition of the magnetic fields from two types of electric currents:

- currents in Earth’s core which generate the planetary magnetic field
  (dynamo effect: kinetic energy of fluid motion is transformed into magnetic energy)

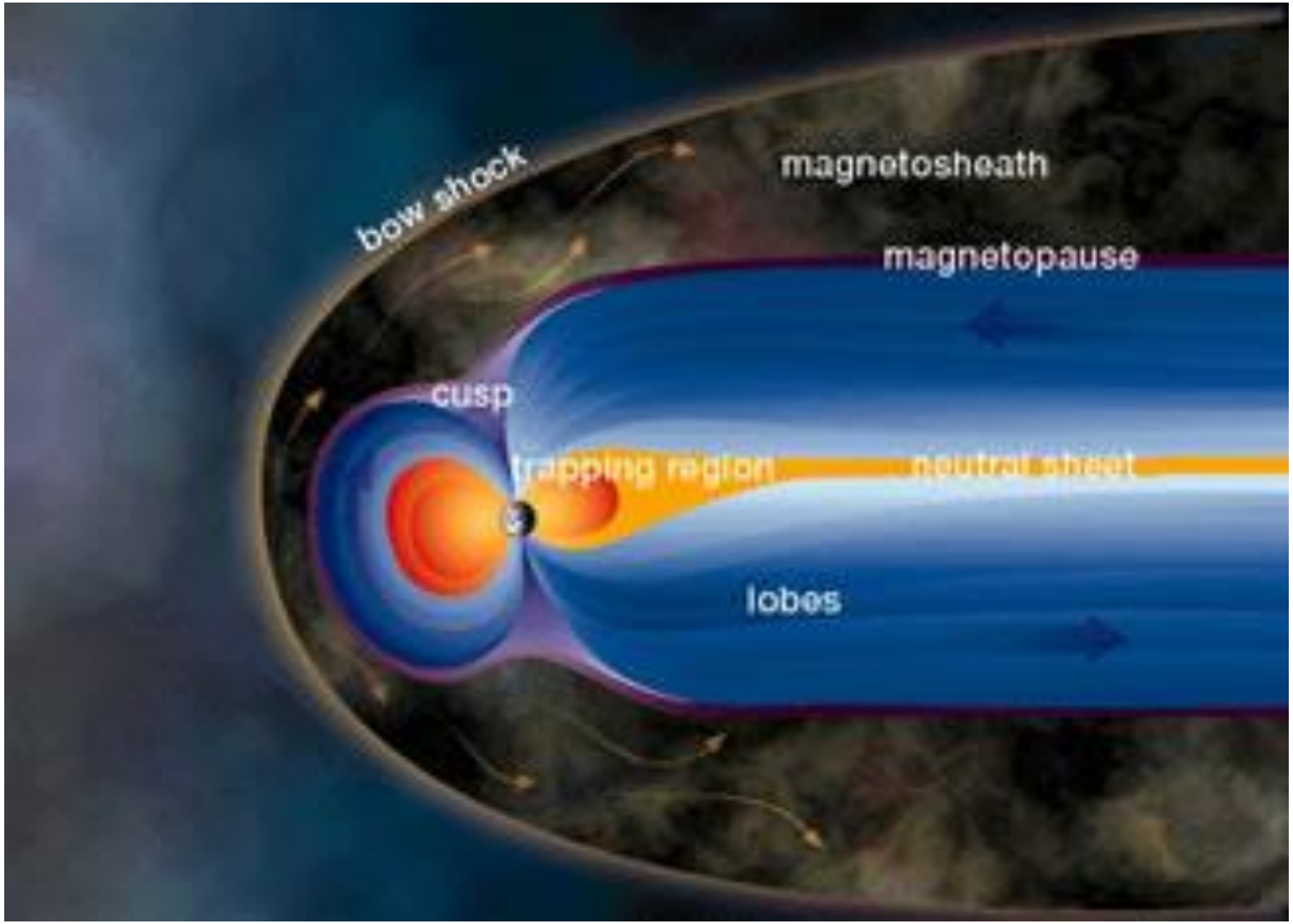
- currents in Earth’s space environment (generated by the interaction between Earth’s magnetic field and the solar wind)

Earth‘s magnetic field



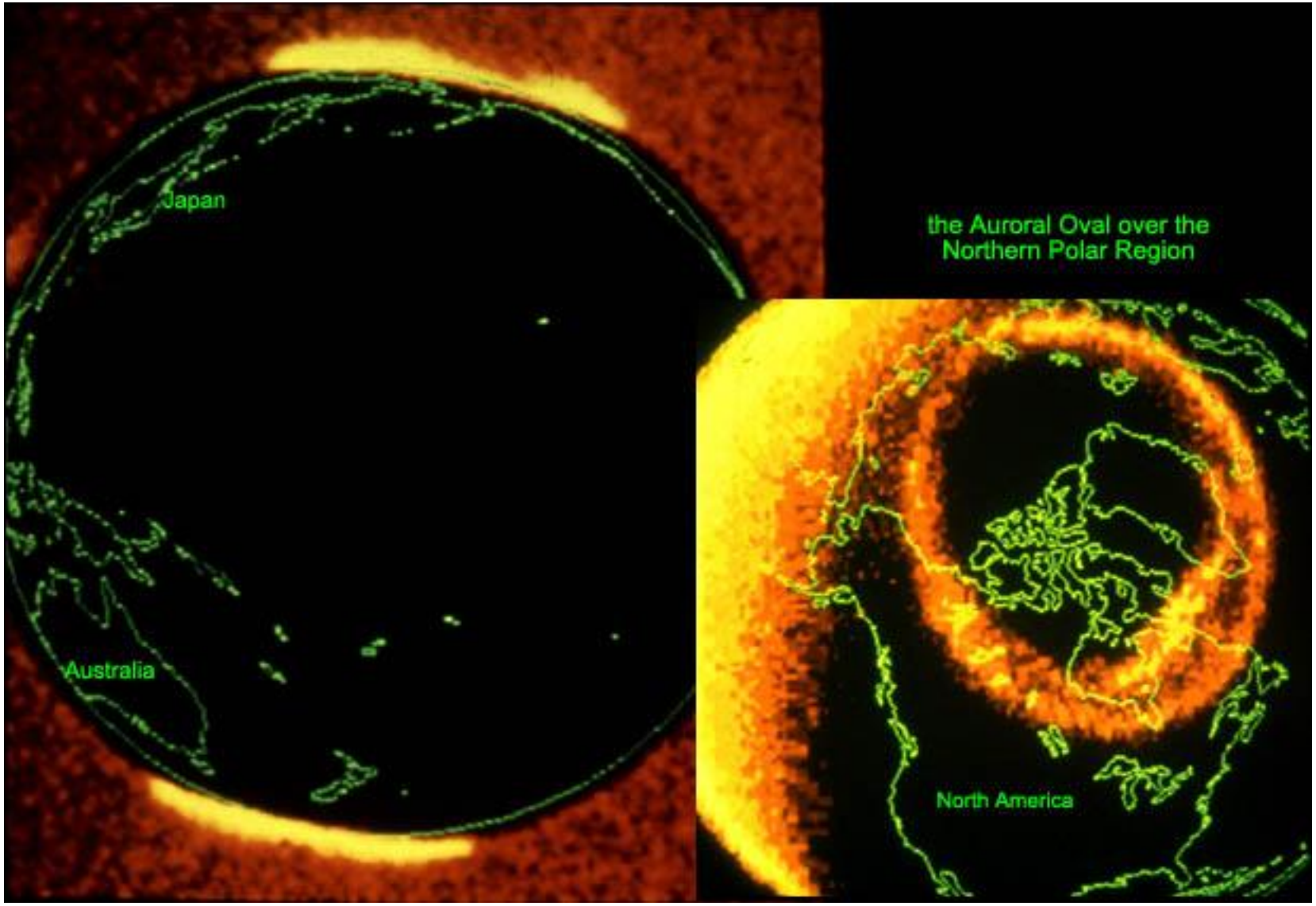
- Earth’s intrinsic magnetic field B is roughly dipolar
- north magnetic pole (point on the surface of Earth’s northern hemisphere where B points vertically downward): ~ 86° north, 147° west

Structure of Earth's magnetosphere:

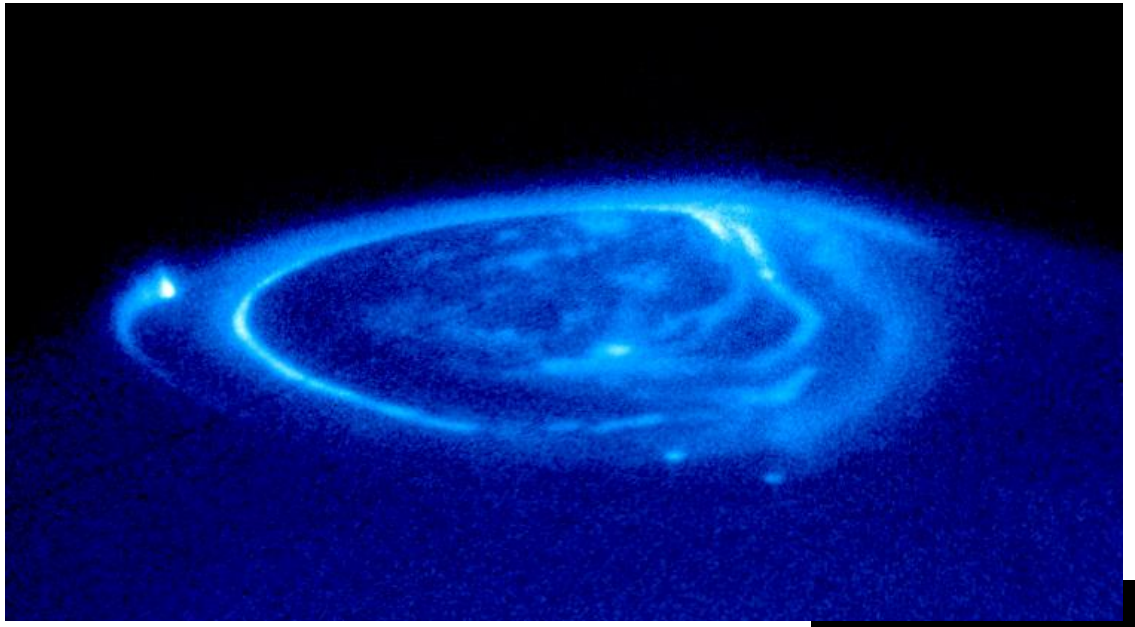


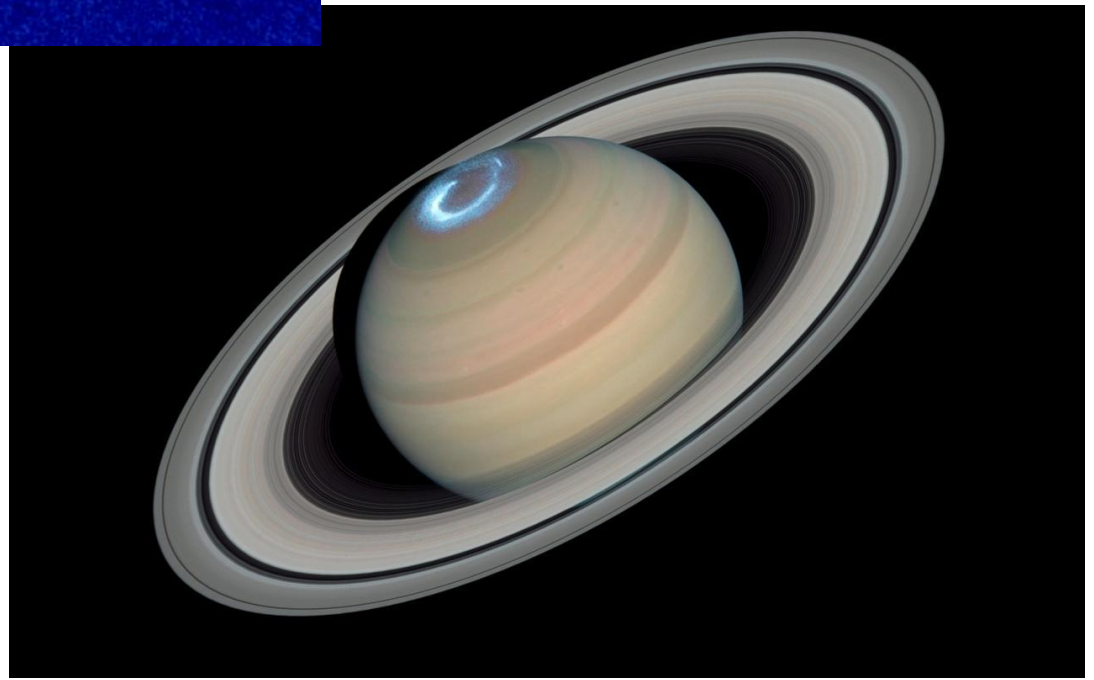
Aurora

Auroral oval



Aurora at Jupiter and Saturn





Characteristics of a plasma

Introduction

Preliminary definition:

- A plasma consists of free positive and negative charges (e.g., protons, electrons, …). It may also contain neutral particles.

- The properties of the plasma are mainly determined by the charged particles.

- On average, the plasma is electrically neutral.

Quasi-neutrality:

On average, a plasma is electrically neutral.

$\Rightarrow$ average over both, spatial scales and time scales!

- size of averaging volume defines a characteristic length scale (*Debye length*)

- length of averaging time interval defines typical time scale (inverse *plasma frequency*)

Below these length and time scales: No neutrality!

Collective behavior:

- The dynamics of the plasma are not controlled by the interactions between individual particles (e.g., binary collisions)

- The dynamics of the plasma are determined by the particle system as a whole!

Question:

- **What are plasmas we encounter in everyday life?**

Occurrence of plasmas:

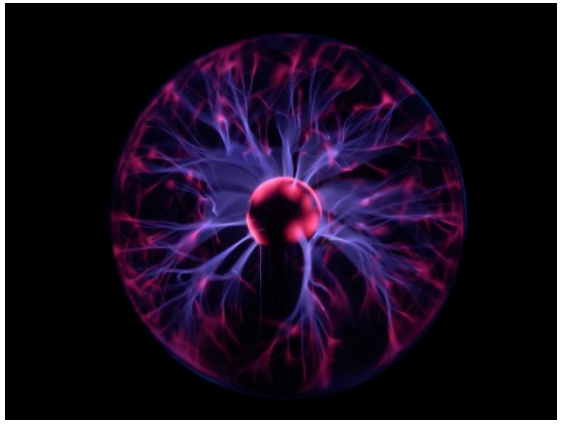
energy input →

solid | liquid | gas | plasma

- Plasma: “fourth state of matter”

- “exotic” under terrestrial conditions:

⇒ lightning, candle flame, electrons in metal, fluorescent lightbulbs

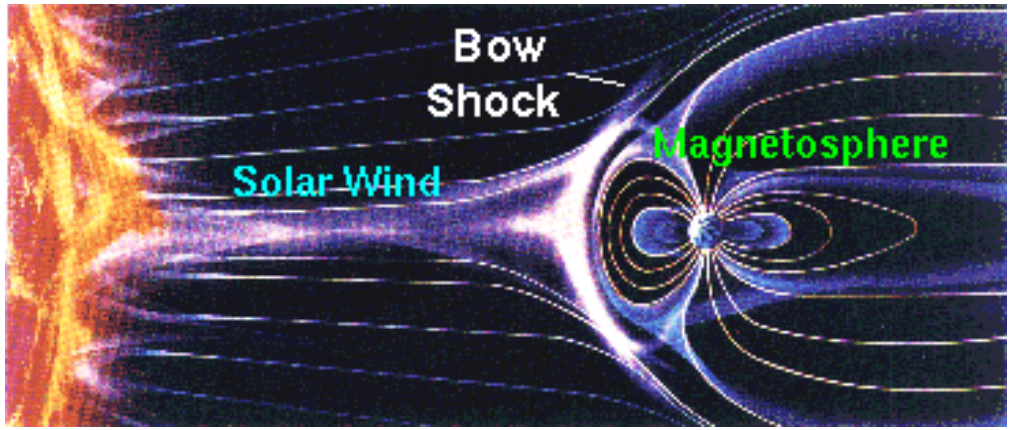


Occurrence of plasmas:

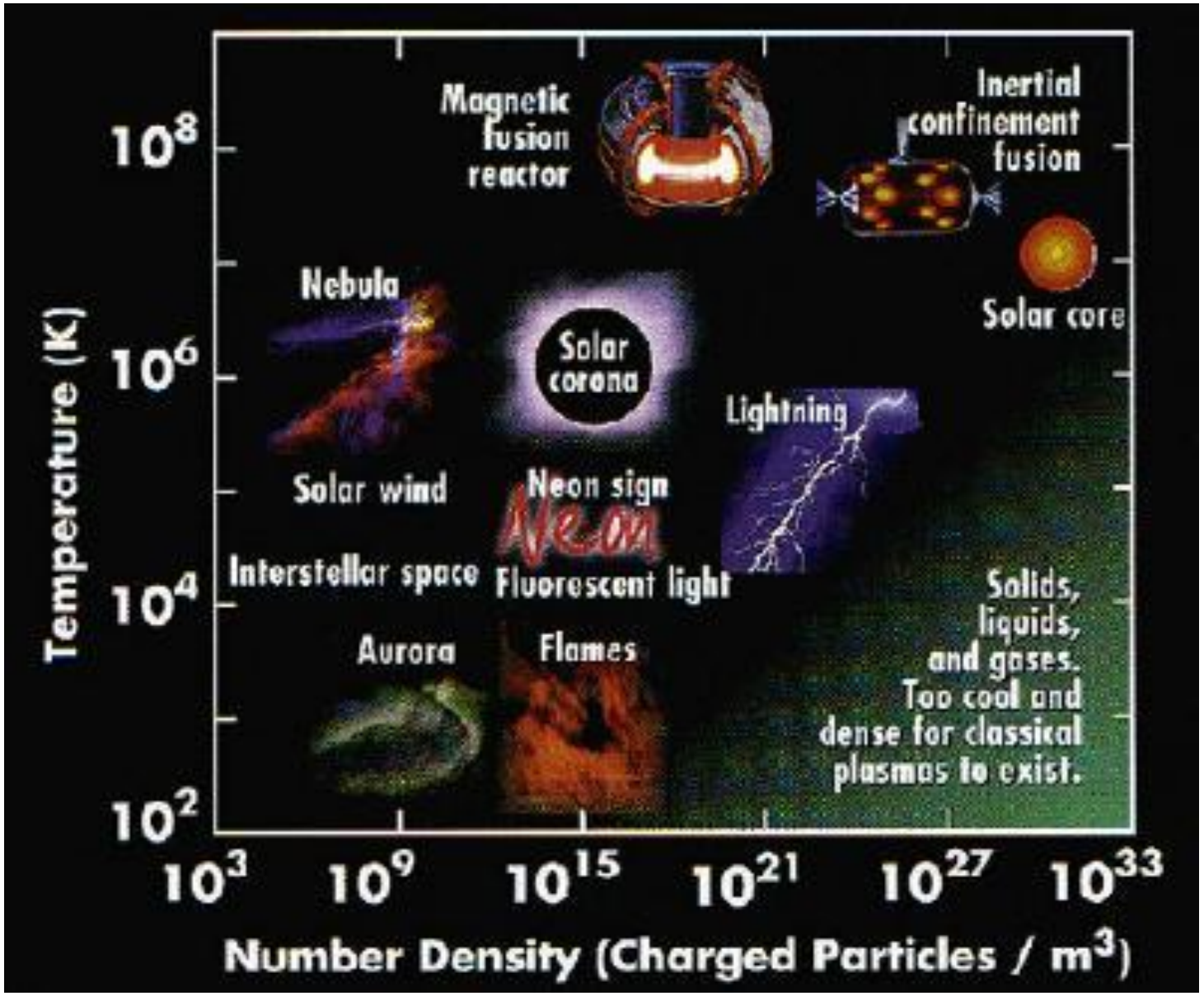
energy input →

solid | liquid | gas | plasma

- Omnipresent in space:
  > 99 % of the matter in the universe consist of plasma: stars, space in between the stars, …
  exceptions: comets, planets, asteroids, moons, …



Examples


Magnetic fusion reactor
Inertial confinement fusion
Solar core
Nebula
Solar corona
Lightning
Solar wind
Neon sign
Neon
Interstellar space
Fluorescent light
Aurora
Flames
Solids, liquids, and gases. Too cool and dense for classical plasmas to exist.
Temperature (K)
10^8
10^6
10^4
10^2
10^3
10^9
10^{15}
10^{21}
10^{27}
10^{33}
Number Density (Charged Particles / m^3)

Major difference between plasma and neutral gas:

neutral gas:

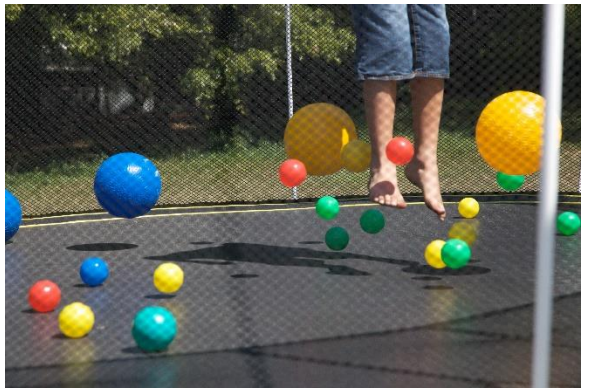
- particles interact only by means of collisions
- no interaction of particles between collisions

=> Interaction on short length and time scales!

plasma:

- short-scale interactions are irrelevant
- particles coupled by E&B fields on large scales

=> Collective behavior!



Debye length

- Solution of Poisson's equation is a shielded Coulomb potential.
- For large r the potential vanishes exponentially, i.e., the charge of the selected test particle is completely shielded.
- Debye length depends only on macroscopic quantities (density, temperature) => shielding is a collective effect

$$\frac{1}{\lambda_D^2} = \sum_\alpha \frac{1}{\lambda_{D,\alpha}^2} = \sum_\alpha \frac{n_{\alpha,0} q_\alpha^2}{\epsilon_0 k_B T}$$

$$\lambda_{D,\alpha} = \sqrt{\frac{\epsilon_0 k_B T}{n_{\alpha,0} q_\alpha^2}}$$

Notes:

- Debye shielding can occur only, if the Debye length is much larger than the average distance between the particles

  number of electrons in the Debye sphere: $\Lambda = \frac{4\pi}{3}\lambda_{De}^3 n_{e0}$

  => a plasma needs to fulfill $\boxed{\Lambda >> 1.}$

Electron Plasma Frequency:

- If electrons are slightly displaced with respect to the ions, then the Coulomb force pulls the electrons back.
- Results in an oscillation occuring with frequency:

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} \; [rad/s]$$

- This is the Electron Plasma Frequency.

Neutral gas in a plasma

- Plasma may contain neutral gas as well
  (example: planetary ionosphere => mixture of neutral particles from atmosphere and ionized particles)

- When neutral gas density is high:
  dynamics of the system are dominated by collisions between charged and uncharged particles
  => suppression of collective effects
  => "plasma" behaves like a neutral gas
  => condition for a plasma:

time between electron-neutral collisions	>>	1/(electron plasma frequency)

Definition of a plasma

A plasma is an ionized gas, consisting of free positive and negative charge carriers. It may also contain neutral gas.
A plasma is quasi-neutral and exhibits collective behavior.

Therefore, a plasma fulfills the following conditions:

1) The Debye length is large compared to the average distance between the particles (=> large number of particles in Debye sphere).

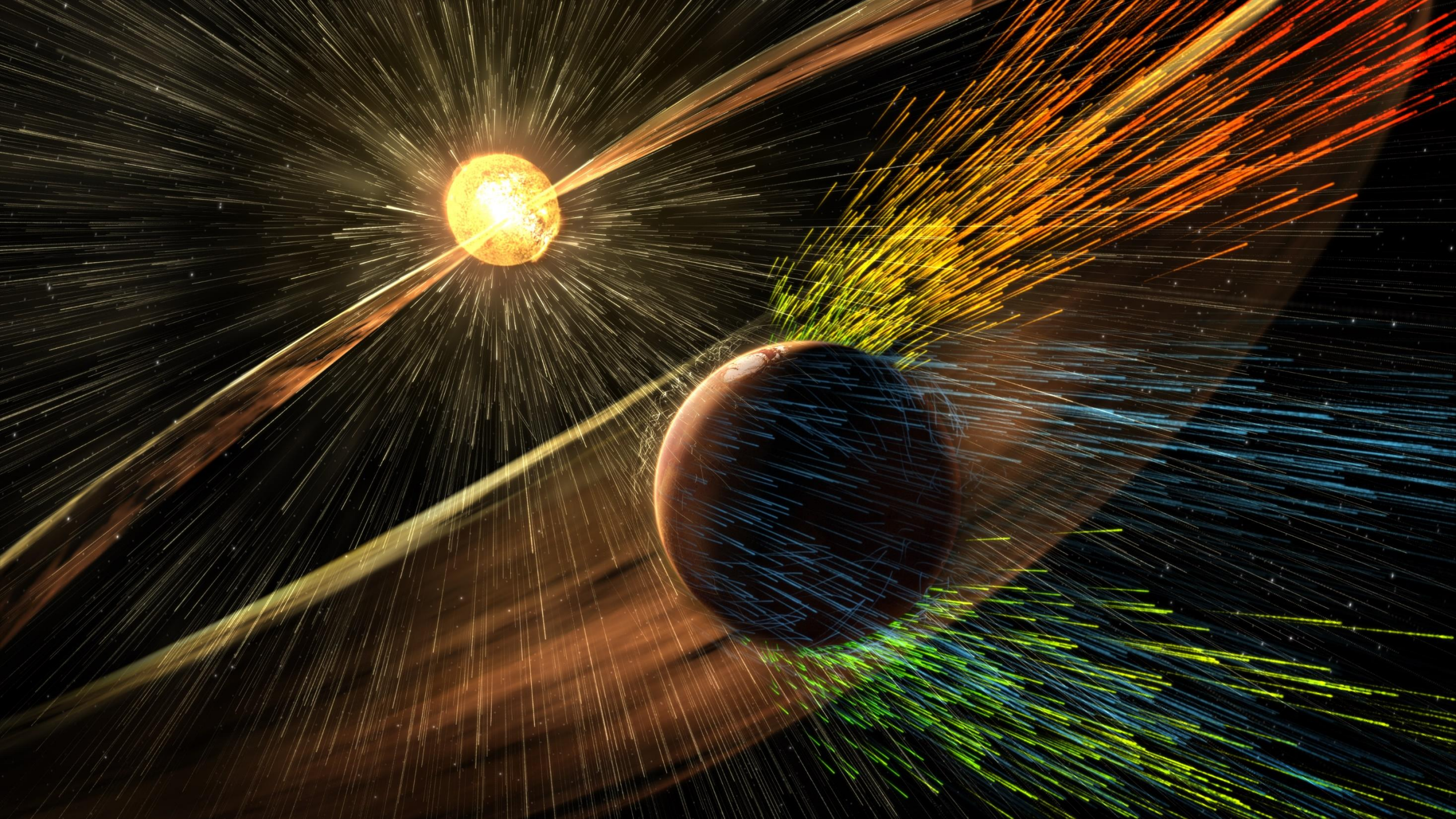
2) The Debye length is small compared to the spatial scales of the system.

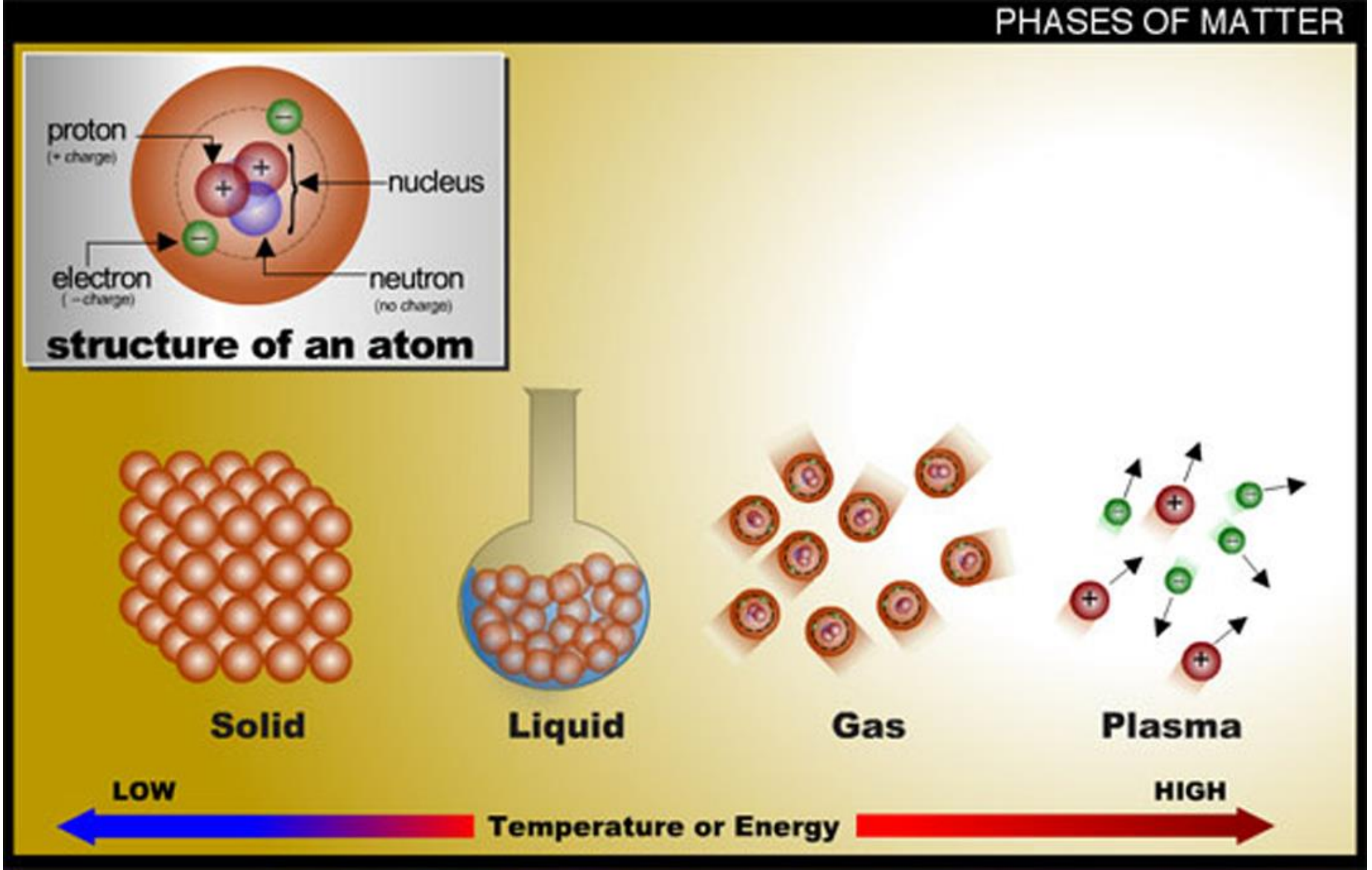
3) The characteristic time scales of the system are large compared to the inverse electron plasma frequency.

4) The time between electron-neutral collisions is large compared to the inverse electron plasma frequency and the characteristic time scales of the system.

Question:

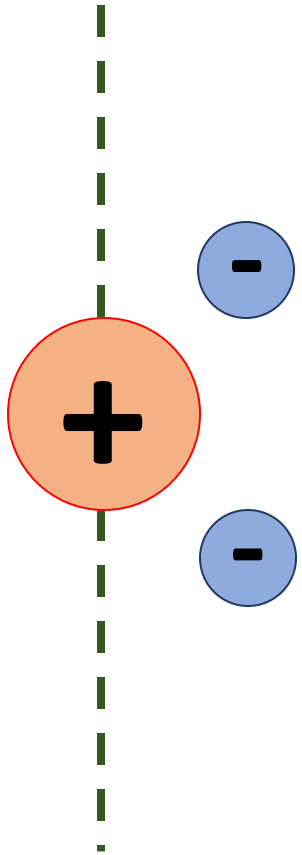
- **What were the main points of today's lecture?**
- **Are there any questions that you have?**



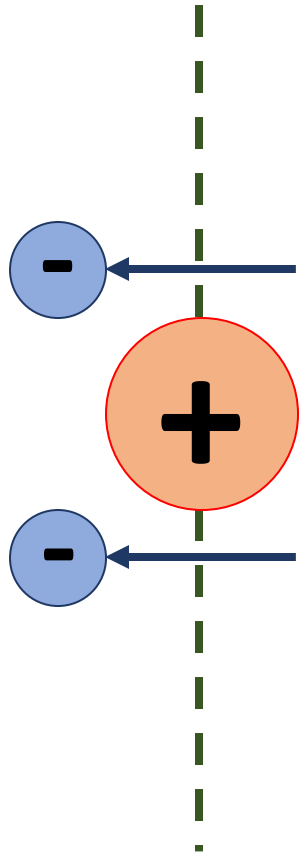


Courtesy of NASA.gov

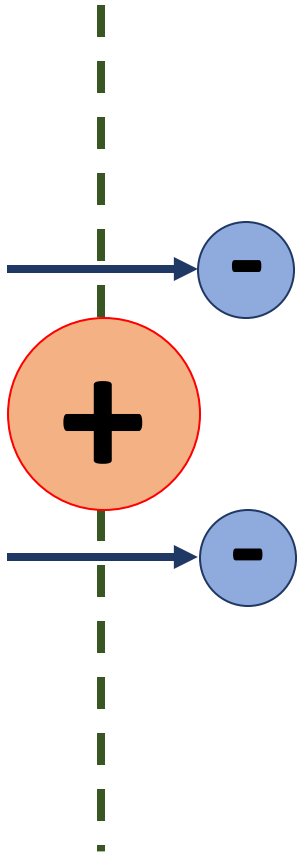
Electron Plasma Frequency:



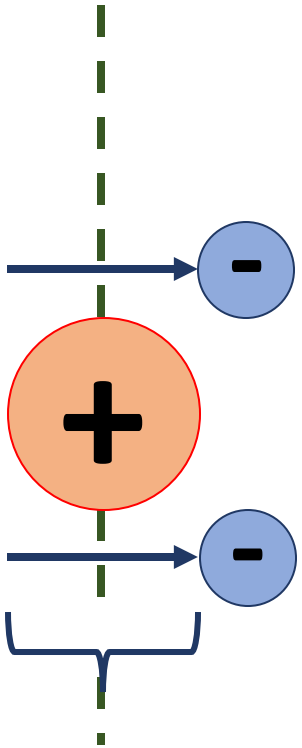
Electron Plasma Frequency:



Electron Plasma Frequency:

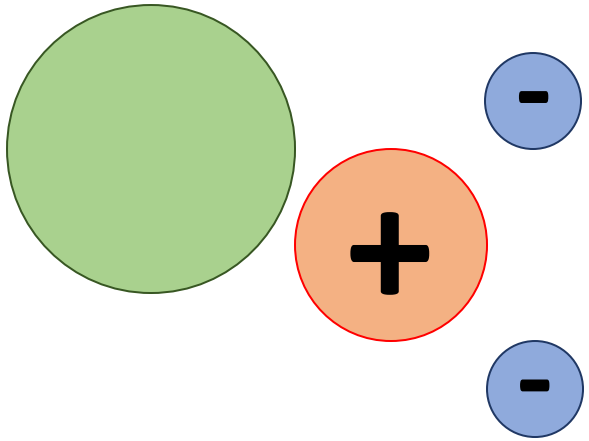


Electron Plasma Frequency:

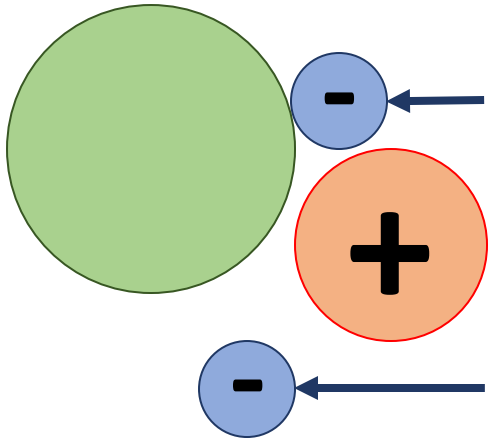


Oscillation of Electrons
-The time this oscillation takes is the **inverse electron plasma frequency.**

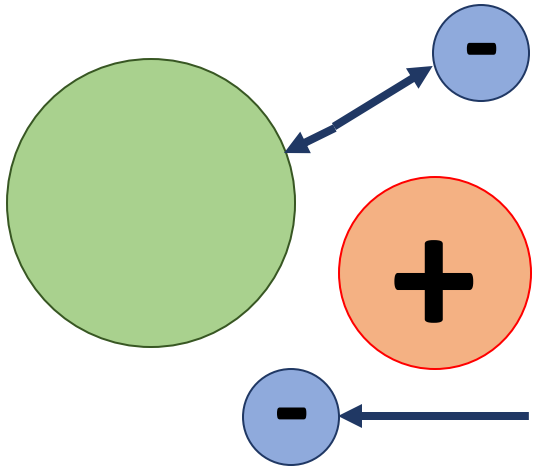
Electron-Neutral Interaction:



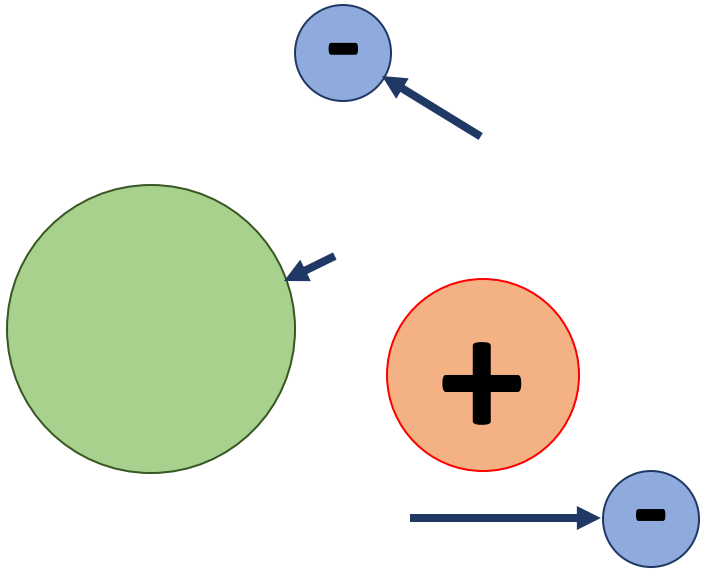
Electron-Neutral Interaction:



Electron-Neutral Interaction:



Electron-Neutral Interaction:

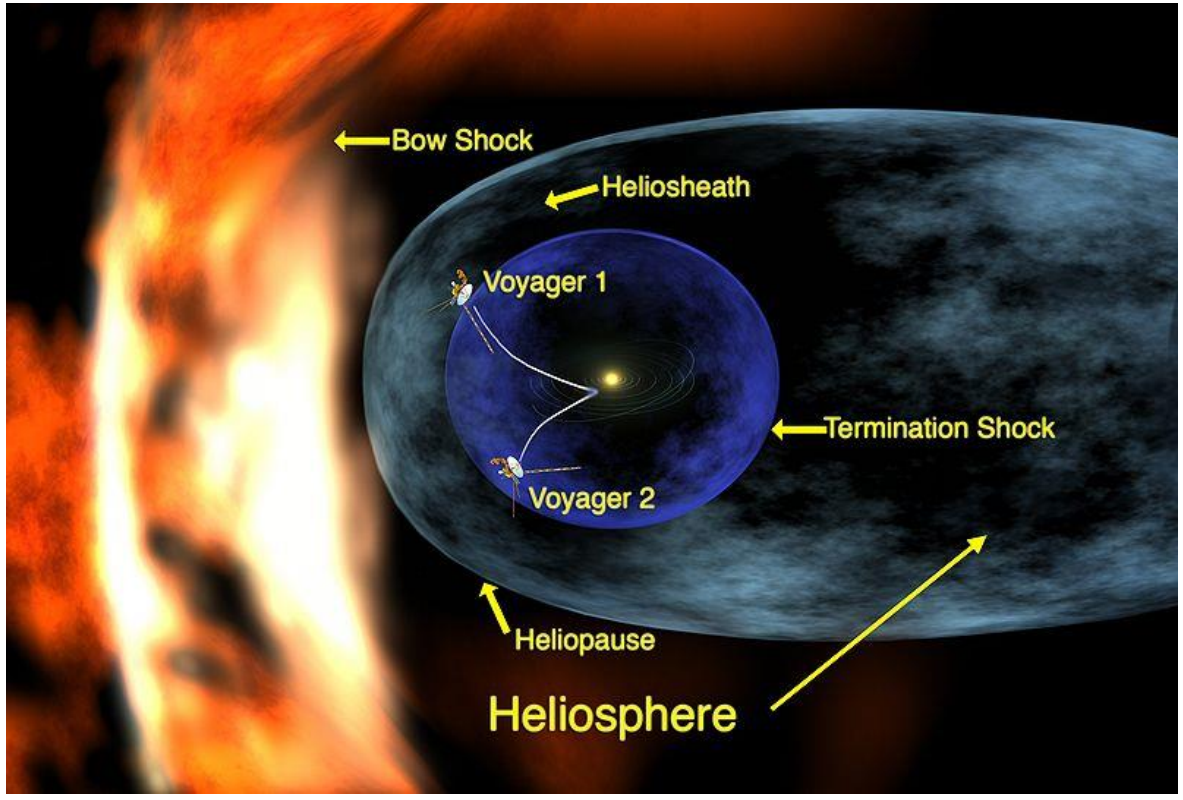


The Solar Wind and the Interplanetary Magnetic Field

The solar wind

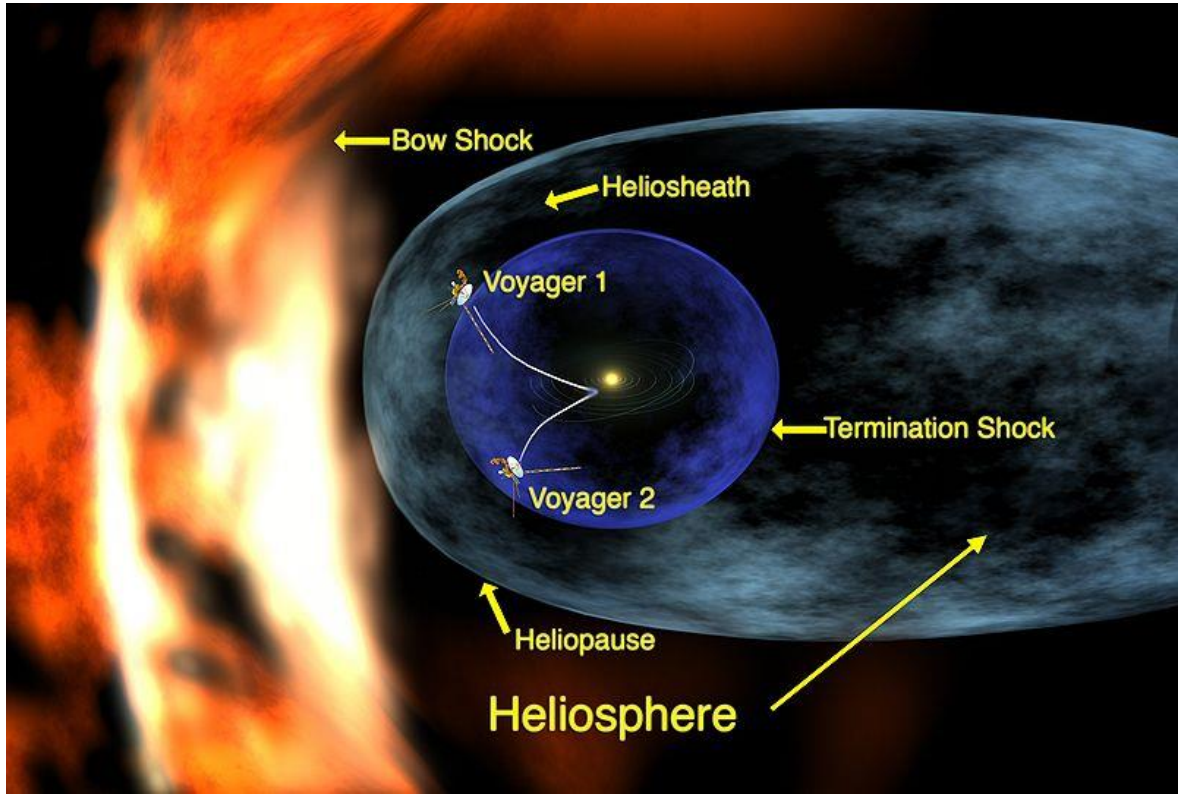
- solar wind: fully ionized plasma (mainly protons and electrons), streaming from the solar corona into interplanetary space

- the region filled with solar wind "ends" at about 100 AU (where 1 AU = 1.5 x 10^{11} m) when hitting the weakly ionized interstellar medium



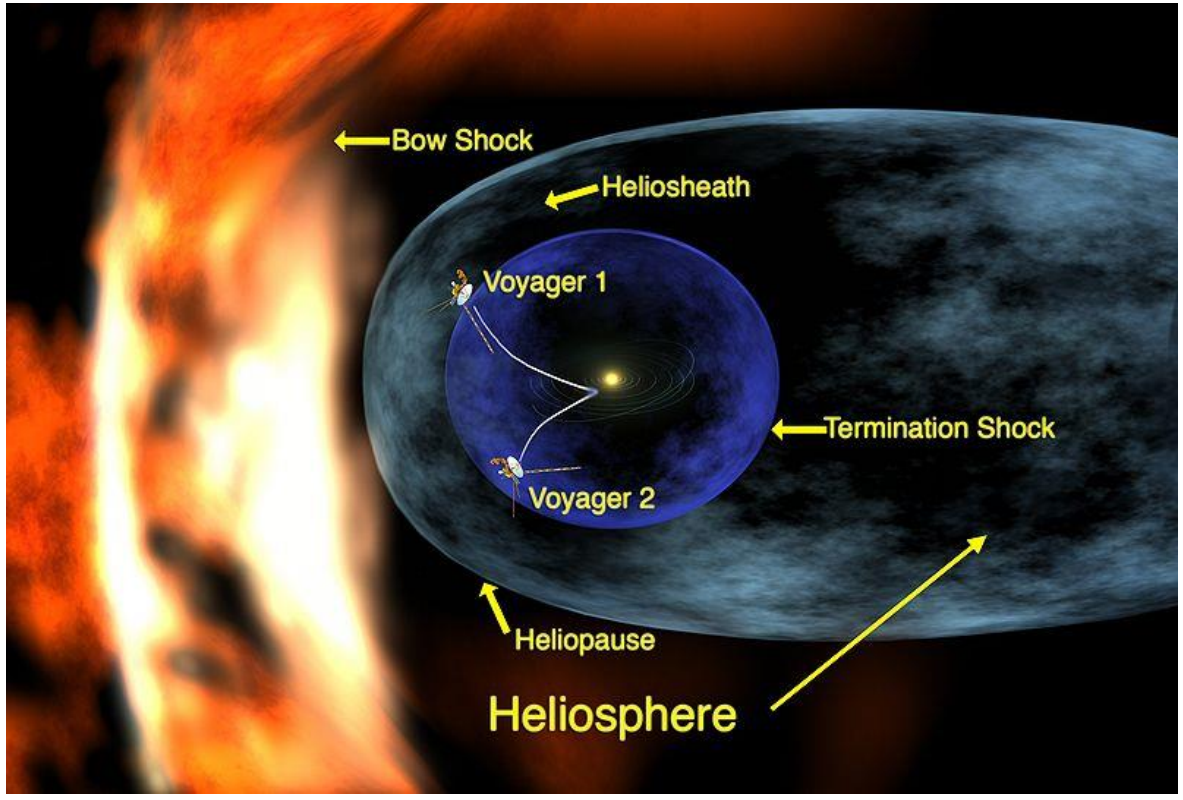
- The region dominated by solar wind particles is called the heliosphere.

- Termination shock: The solar wind (moving at supersonic speeds) is decelerated to subsonic speeds. In this process, the solar wind is heated and compressed. The magnetic field strength increases.



- The Voyager 1 spacecraft left the heliosphere (probably) in late 2012 and is the first human-made object that has reached interstellar space.

- Voyager 2 is expected to enter interstellar space within a few years of 2016.



Properties of the solar wind

- composition: protons and electrons (quasi-neutrality!), minor helium component (< 5%)

- solar wind near Earth's orbit (1 AU):

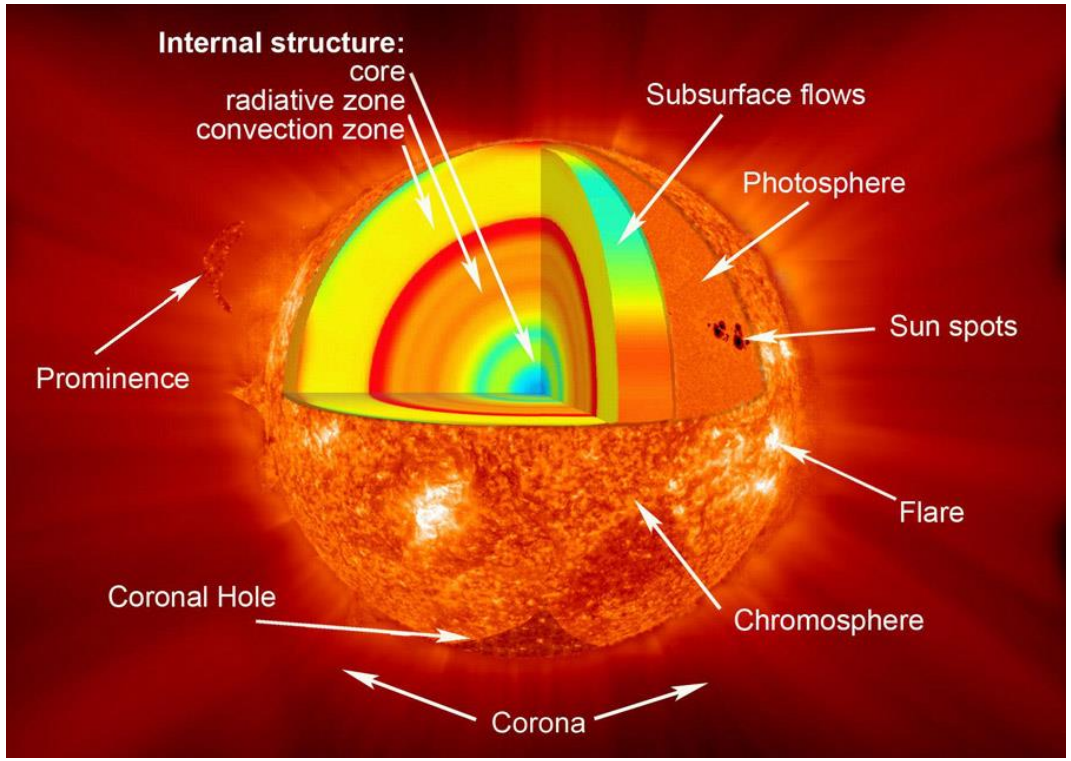
Quantity		Typical value
Magnetic field strength	B_0	5nT
Density	n_0	5cm^{-3}
Bulk velocity	u_0	400km/s
Electron temperature	T_e	10^5K
Ion temperature	T_i	$5 \cdot 10^4$K
		Derived value
Electron gyrofrequency	Ω_e	1040Hz
Electron gyroradius	r_e	380m
Electron plasma frequency	ω_{pe}	150kHz
Electron inertia length	c/ω_{pe}	2km
Debye length	λ_D	20m
Proton gyrofrequency	Ω_p	0.5Hz
Proton gyroradius	r_p	800km
Proton plasma frequency	ω_p	3.5kHz
Proton inertia length	c/ω_p	85km
Alfvén velocity	v_A	48km/s
Alfvénic Mach number	M_A	8
Electron plasma β	β_e	0.7
Ion plasma β	β_p	0.35
Sound velocity	c_s	35km/s
Sound Mach number	M_s	11

velocity of 400-500 km/s corresponds to a travel time of 4 days from the Sun to the orbit of Earth

Properties of the solar wind (cont'd)

- The solar wind emerges from the Sun's atmosphere (photosphere). The photosphere is "rather" cold: ~ 6000 K.

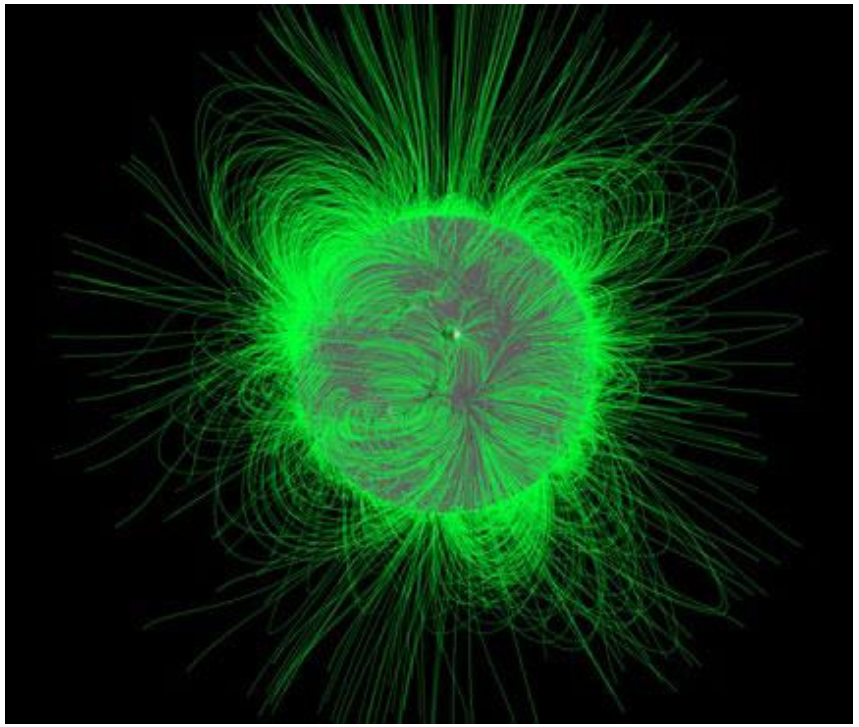
- In the solar corona, the solar wind is heated to its high temperature (temperature within the corona: 1.6 x 10^6 K).



Influence of the Sun's magnetic field

- "closed" magnetic field lines (both ends anchored at the Sun): solar wind cannot escape

- coronal holes: magnetic field lines are stretched into interplanetary space => solar wind can escape
  Coronal holes are the source regions of the solar wind.



The magnetic field of the solar wind

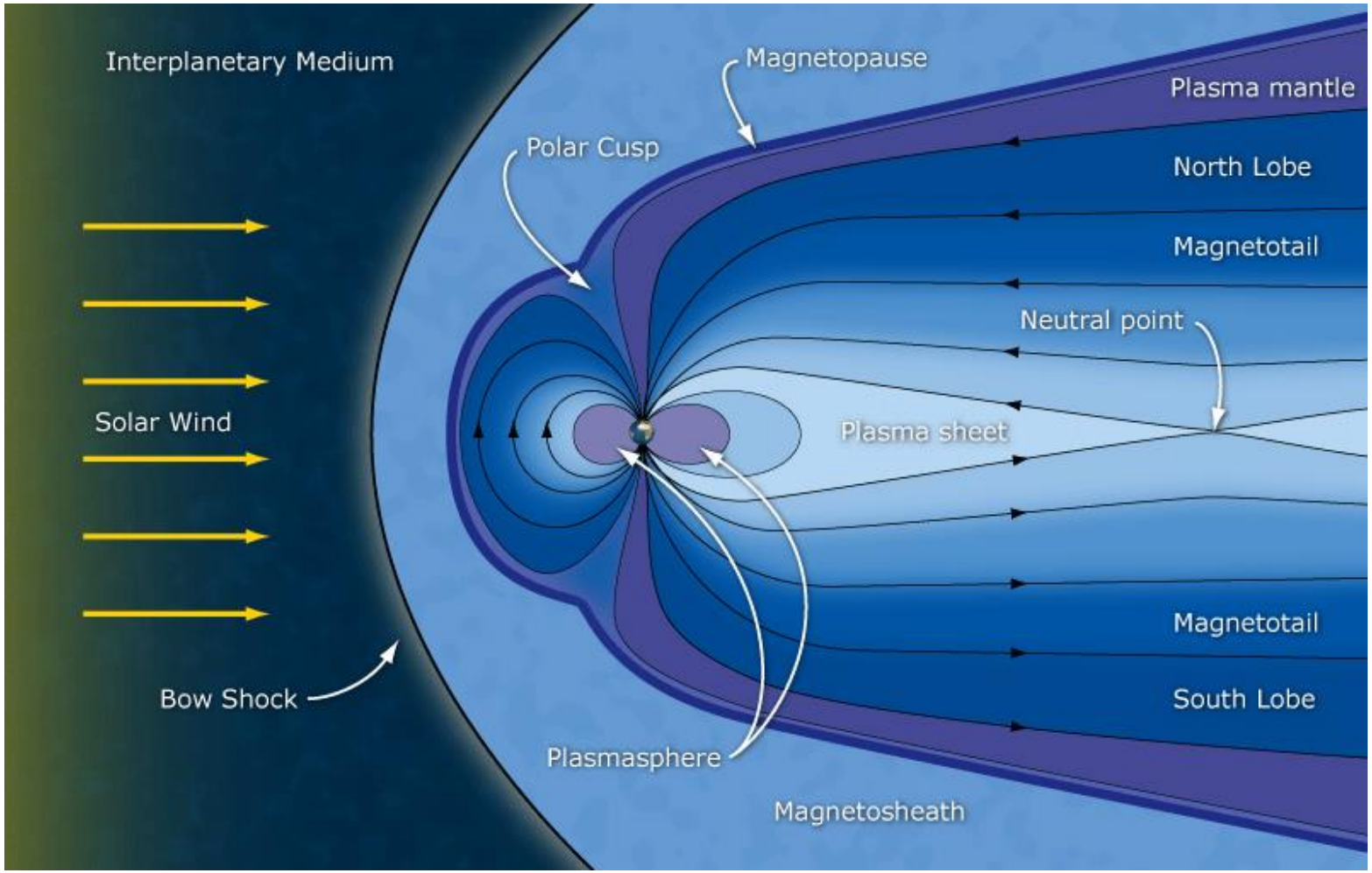
- The solar wind is a magnetized plasma.
- The strength of the interplanetary magnetic field (IMF) at 1 AU is about 5 nT.
- plasma beta: 1 – 30. Thus, the structure of the magnetic field is almost completely determined by the plasma flow.
- The solar magnetic field is transported into interplanetary space by the radial expansion of the solar wind (frozen-flux theorem).
- The foot points of the magnetic field lines remain anchored at the surface of the Sun.

The magnetic field of the solar wind (cont'd)

Magnetic field and plasma density		
Mercury:	39 nT	33 cm^{-3}
Earth:	5 nT	5 cm^{-3}
Jupiter:	1 nT	0.2 cm^{-3}
Saturn:	0.6 nT	0.06 cm^{-3}
Uranus:	0.3 nT	0.01 cm^{-3}
Neptune:	0.005 nT	0.005 cm^{-3}

Magnetospheres

Earth's magnetosphere is generated by the interaction between the planet's magnetic field and the solar wind



Earth's magnetic field

Earth is one of 8 bodies in the solar system that currently possess a dynamo magnetic field:

- Sun (22 year cycle)
- Mercury (weakest field in the solar system)
- Earth ("default" to compare with)
- (Mars) -> probably had an internal field in the past, now only remnant magnetization on its surface
- Jupiter (largest magnetic moment)
- Ganymede (only known moon with a magnetic field)
- Saturn (second-largest magnetic moment)
- Uranus (odd orientation)
- Neptune (odd orientation)

Causes of the magnetic field above the Earth's surface:

internal contributions:

- main contribution from the dynamo process in Earth's liquid core
- remanent magnetization of the crust
- induction in oceans and crust

external contributions:

- small (up to 5%) and strongly time-variable (months, days, hours, minutes) contributions from the ionosphere and the magnetosphere
- with increasing distance to the surface, the magnetospheric and ionospheric contributions become more and more important

Secular variations of Earth's magnetic field

- internal component of Earth's magnetic field changes very slowly on time scales of years to 1 million year

- polarity changes are irregular

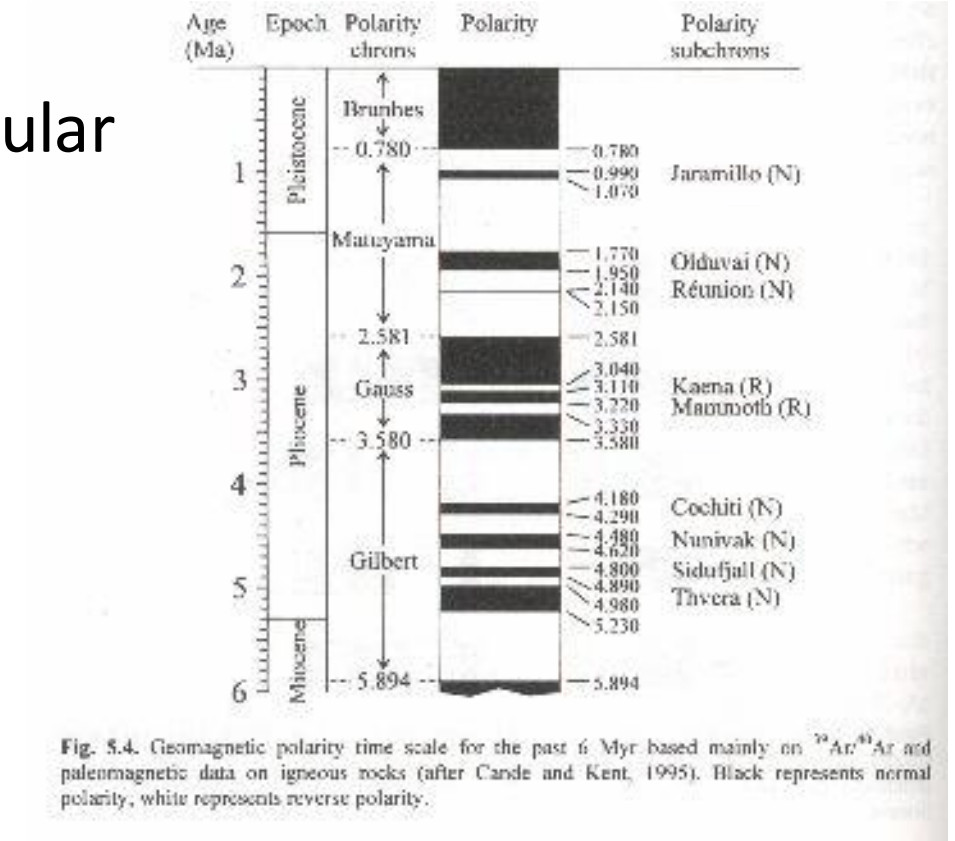
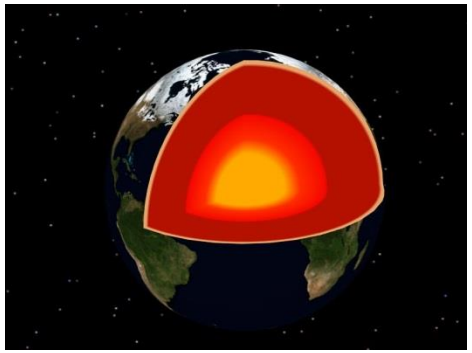


Fig. 5.4. Geomagnetic polarity time scale for the past 6 Myr based mainly on $^{39}Ar/^{40}Ar$ and paleomagnetic data on igneous rocks (after Cande and Kent, 1995). Black represents normal polarity, white represents reverse polarity.

Origin of Earth's internal magnetic field



- dynamo process in the liquid outer core
- the outer core consists of electrically conducting fluid
- through convection, a self-excited dynamo magnetic field is generated (some aspects are similar to the dynamos of electro-technics)

Question:

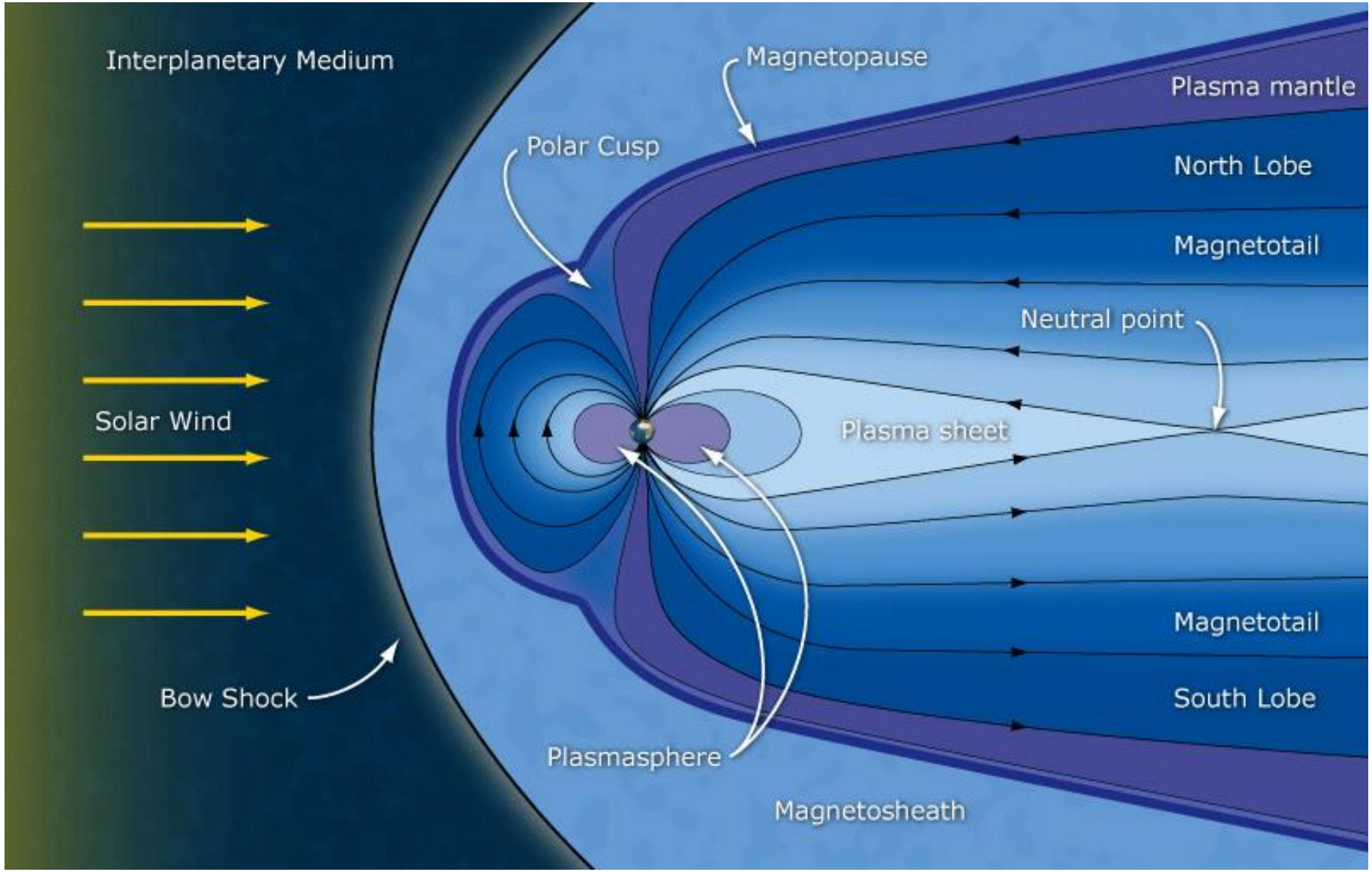
- **What are some energy sources for the internal dynamo process?**

Origin of the internal magnetic field (cont'd)

Energy sources for the dynamo:

- chemical convection (accumulation of light chemical elements in alloys), buoyancy of lighter alloys
- freezing of iron on the boundary to the inner core
- heat from the creation of the Earth

The magnetosphere of Earth

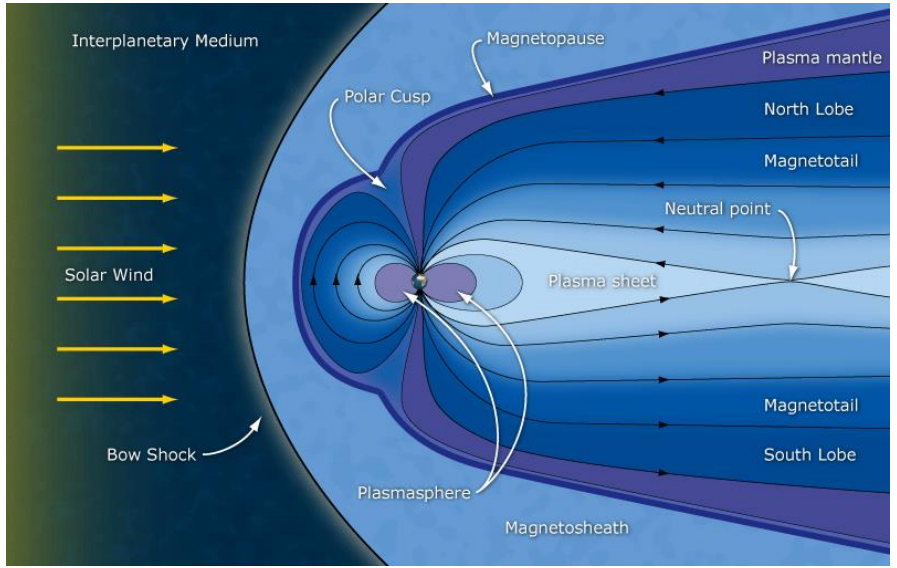


The magnetosphere of Earth

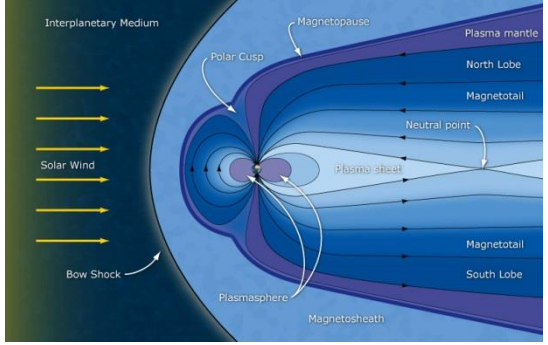
What is a magnetosphere?

- A magnetosphere in its wider sense is the interaction region between the solar wind and a planetary body.

- A magnetosphere in its classical sense is the region bounded by the magnetopause (outer boundary) and the planet's ionosphere (inner boundary).



Overview: Structure of the magnetosphere



Bow Shock:

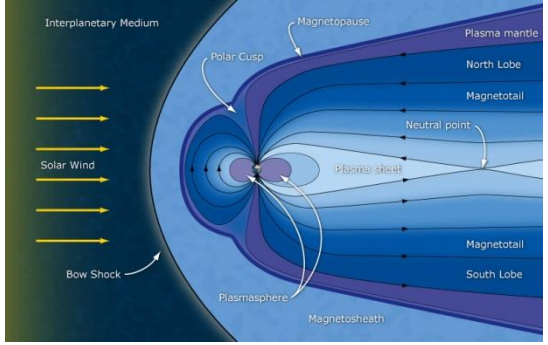
- solar wind hits Earth's magnetic field at velocity faster than the (magneto) sound speed
  => information on the obstacle cannot be "communicated" towards upstream

- shock wave: bow shock is generated

- in the bow shock, the solar wind is slowed down to subsonic velocities and is being heated
  => irreversible conversion of ram energy of the flow into thermal energy

- the decelerated solar wind is deflected around the obstacle

Overview: Structure of the magnetosphere

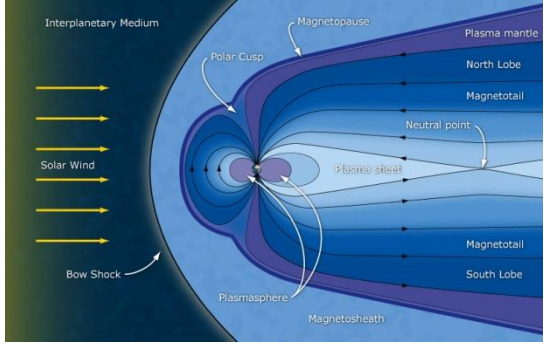


Magnetosheath:

- The region downstream of the bow shock is called magnetosheath.

- The plasma in the magnetosheath **(usually)** does not enter Earth's magnetic field, but it streams around the magnetosphere.

Overview: Structure of the magnetosphere



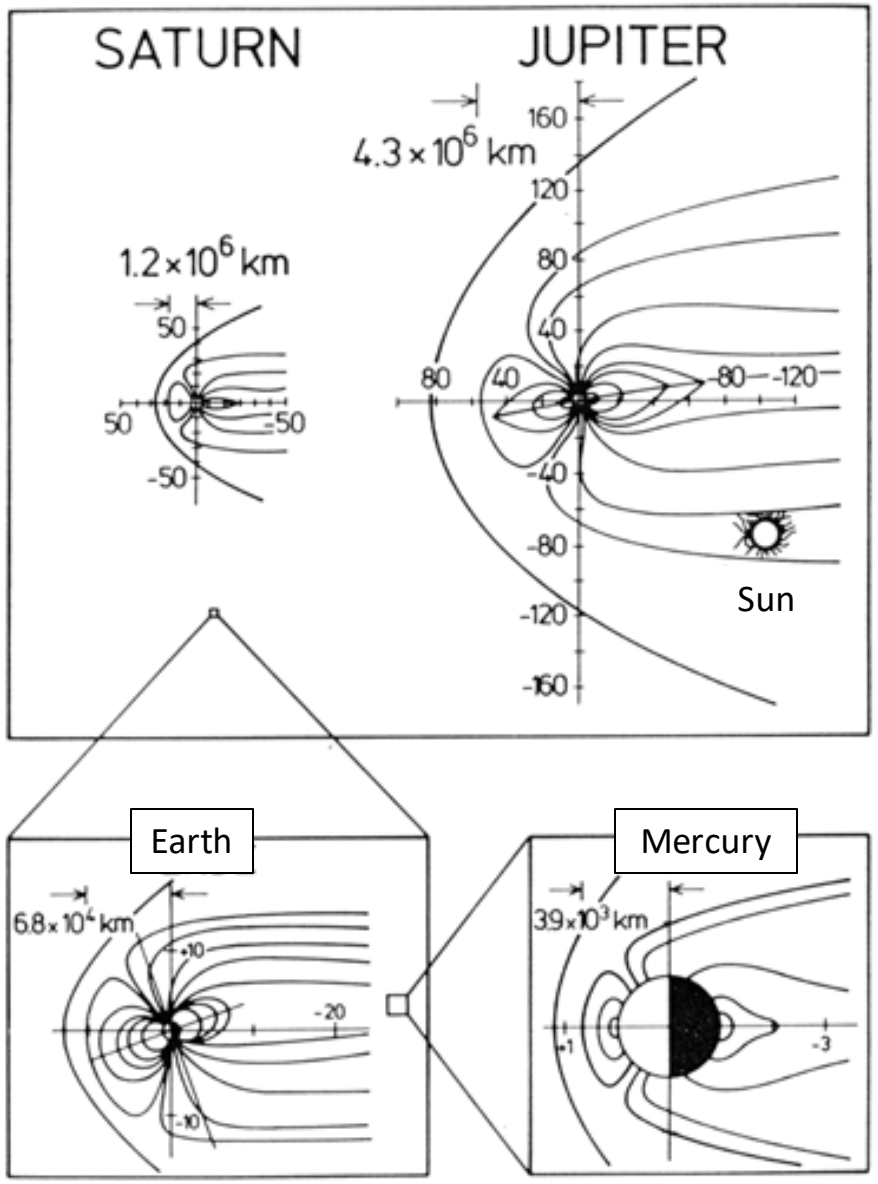
Magnetopause (MP):

- the boundary between the magnetosheath and the magnetosphere is called magnetopause (MP)

- the MP separates regions which are controlled by the solar wind plasma/magnetic field from regions controlled by Earth's magnetic field

- location of MP is determined by the balance between the ram pressure of the solar wind and the magnetic pressure of the Earth's magnetic field

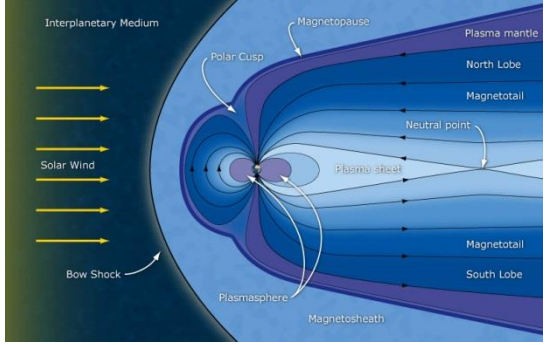
Various sizes of the magnetospheres in the solar system



Jupiter‘s magnetosphere is the largest object in the solar system.

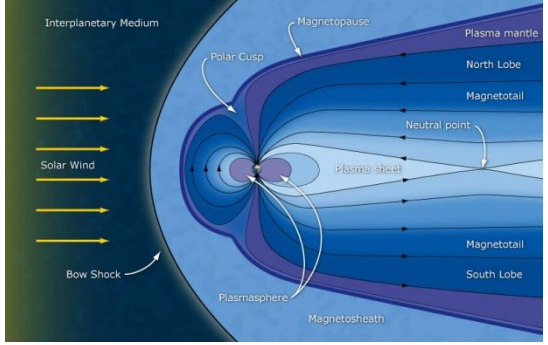
The Sun (radius 700,000 km) fits well within Jupiter‘s magnetosphere.

Magnetospheric magnetic field:



- the solar wind compresses the magnetosphere on the upstream side (dayside)
- magnetopause on dayside at approximately 10 Earth radii
- on the nightside, the magnetosphere is stretched and possesses an extended magnetospheric tail ("magnetotail")
- the Earth's magnetotail extends way beyond the orbit of the moon (i.e., 60 Earth radii)

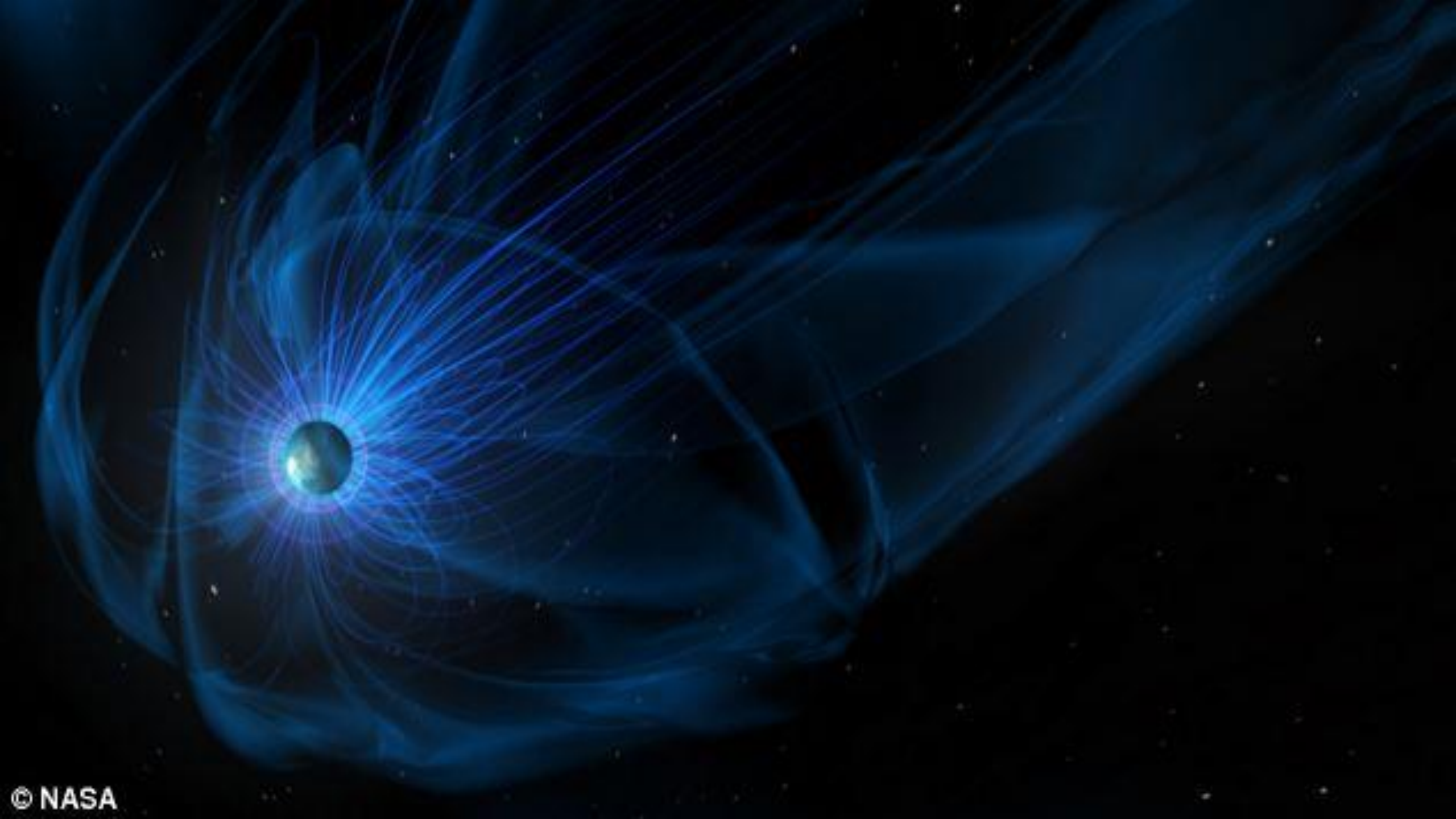
Magnetospheric plasma parameters:



- plasma in Earth‘s magnetosphere consists primarily of protons and electrons
- additional contributions: He^{+},O^{+},He^{++}
- sources of plasma: solar wind and Earth‘s ionosphere
- density and temperature of plasma in the magnetosphere are spatially very inhomogeneous

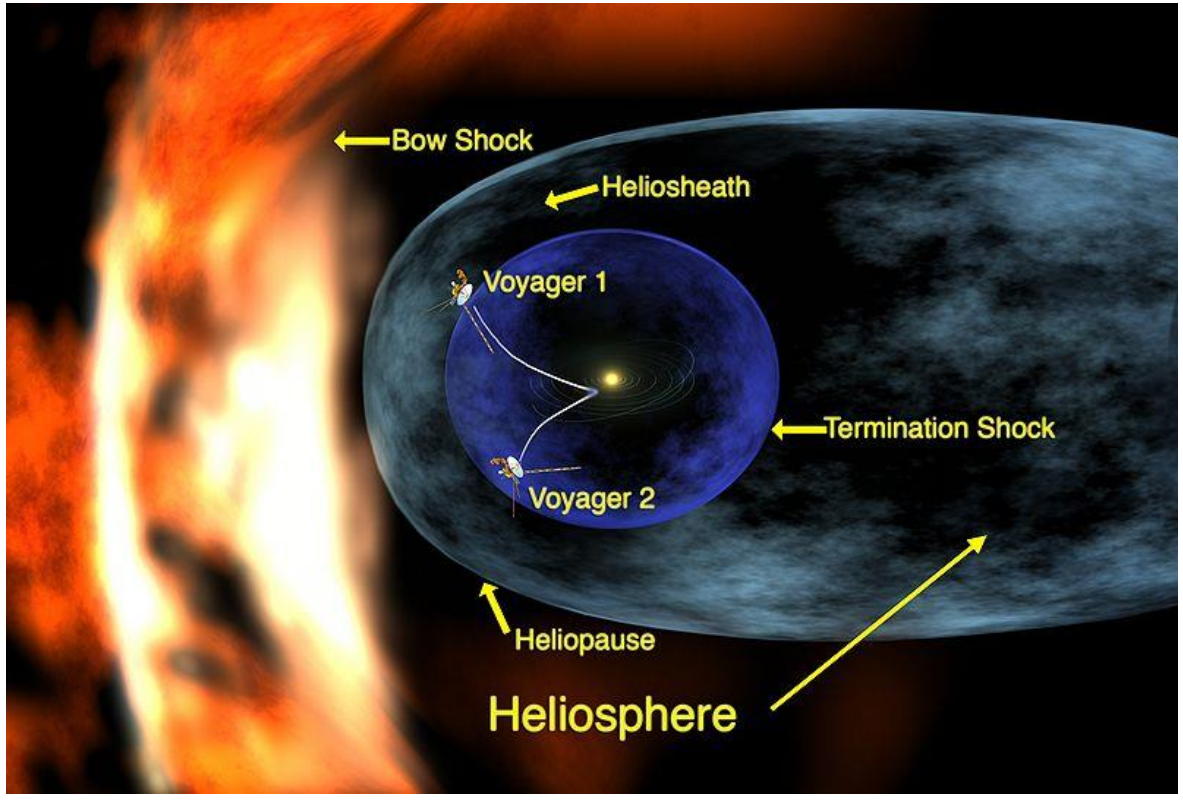
Question:

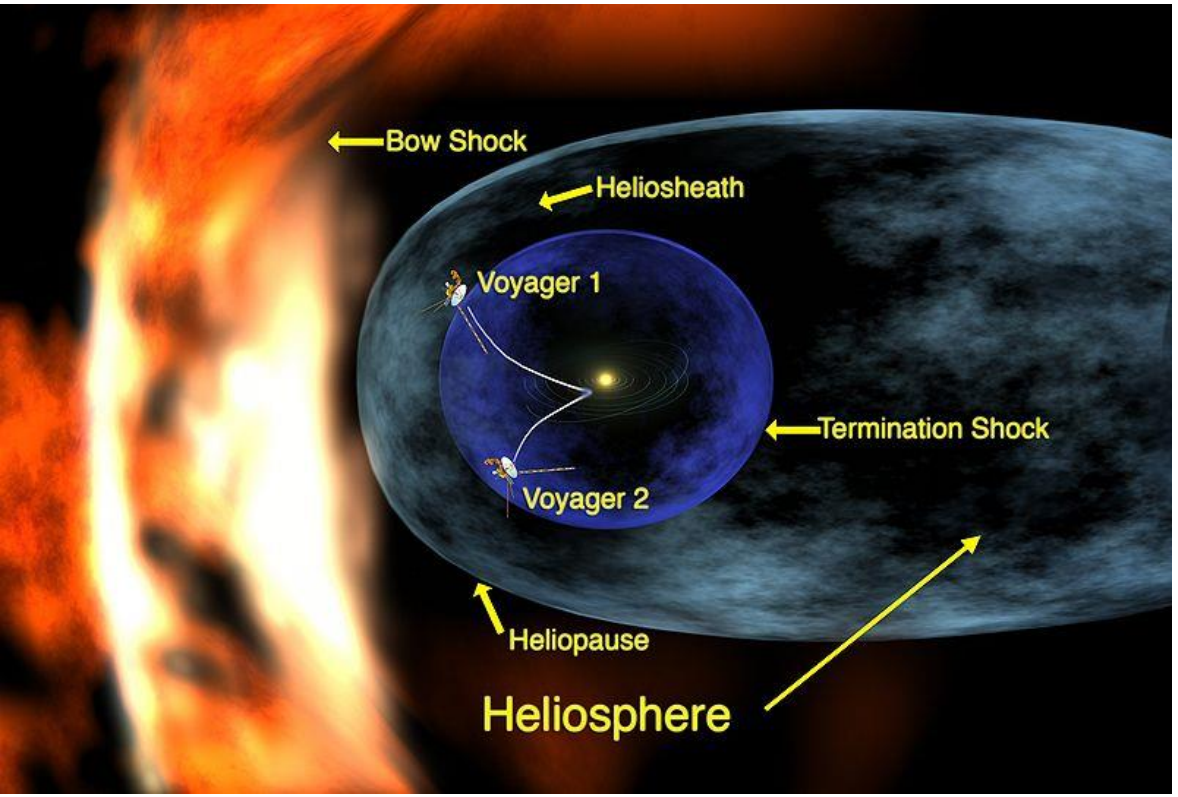
- **What were the main points of today's lecture?**
- **Are there any questions that you still have?**

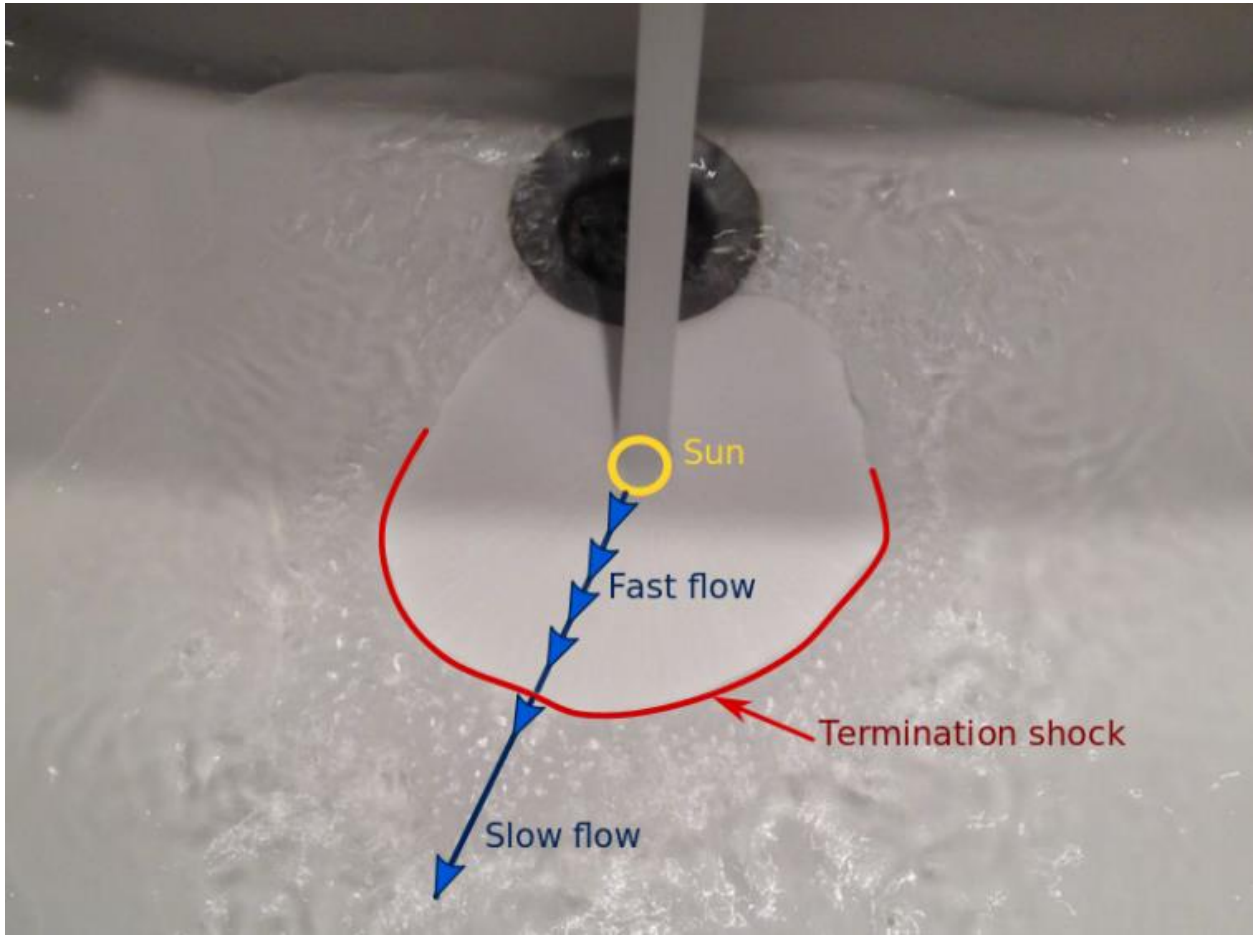

© NASA

- The region dominated by solar wind particles is called the heliosphere.

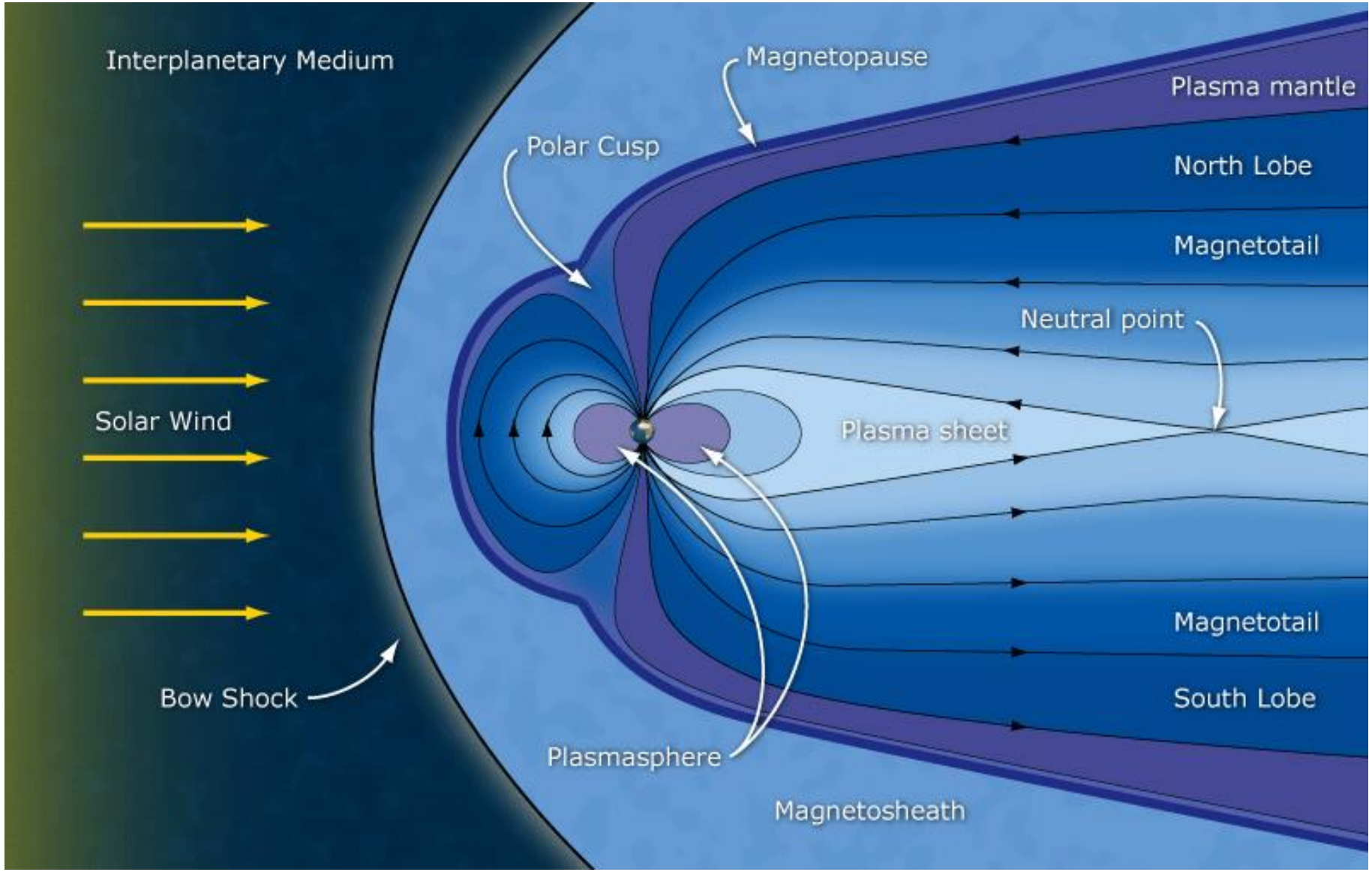
- Termination shock: The solar wind (moving at supersonic speeds) is decelerated to subsonic speeds. In this process, the solar wind is heated and compressed. The magnetic field strength increases.




Bow Shock
Heliosheath
Voyager 1
Termination Shock
Voyager 2
Heliopause
Heliosphere


Sun
Fast flow
Termination shock
Slow flow

The magnetosphere of Earth



Magnetospheres of the Planets

Magnetospheres of other solar system bodies

Magnetic fields of the planets

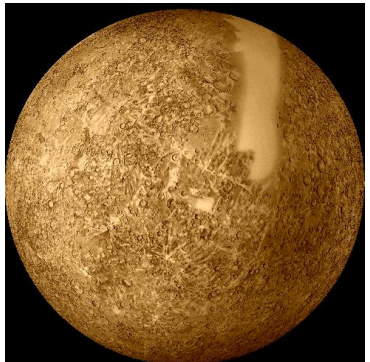
Table 2. *Summary of planetary magnetic fields, solar wind Sunward stagnation point and rotation periods of the planets*

(Note: 1 G $cm^3 = 10^{-3}$ A m^2; 1nT $= 10^{-5}$ G $= 10^{-9}$ T.)

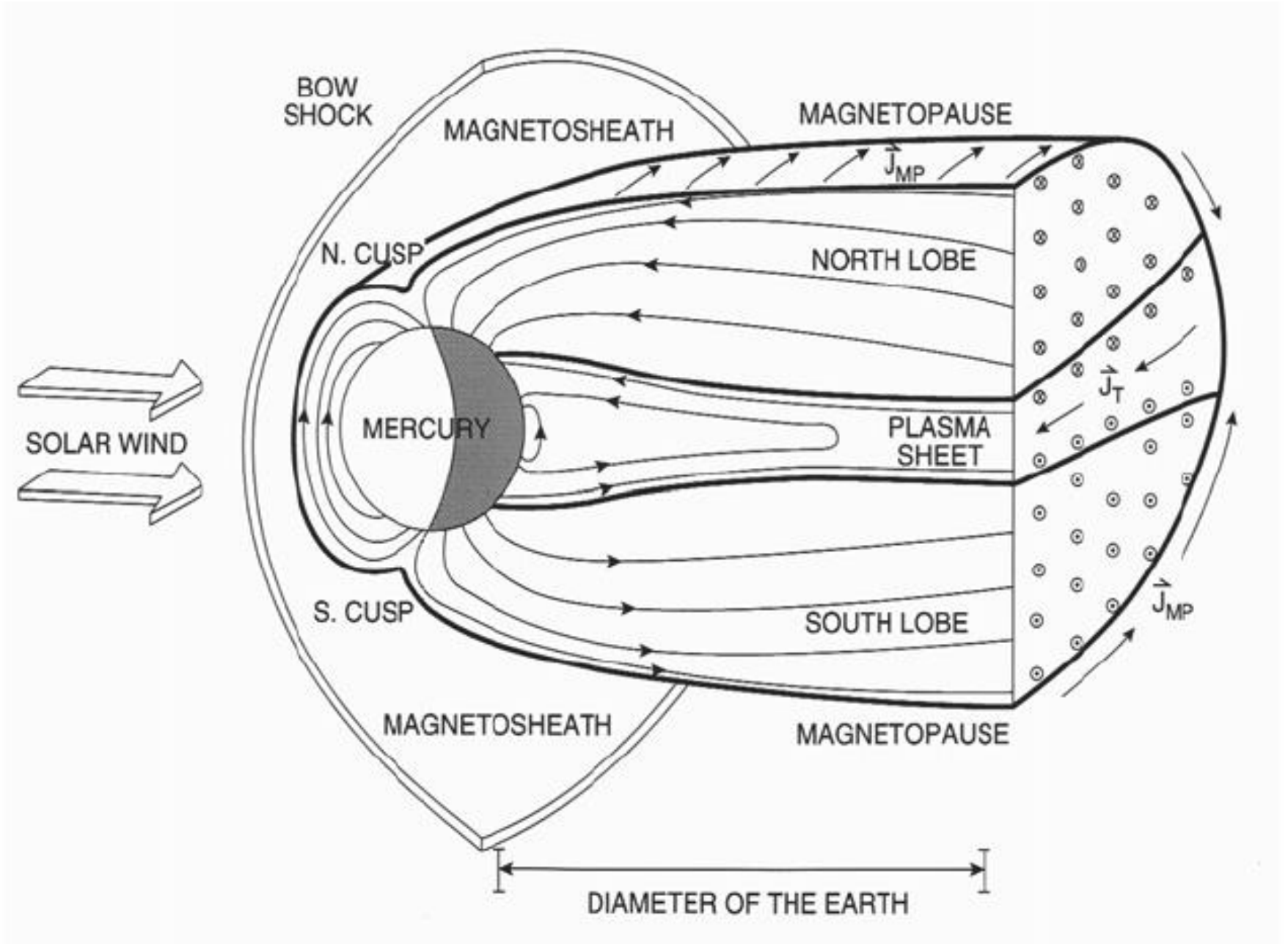
planet	dipole moment (G cm^3)	tilt and sense	dipole equal. field (nT)	stagnation point distance	rotation period (R_p)
Mercury	5×10^{22}	$+14°$	330	1.4	58.7^d
Venus	$< 4 \times 10^{21}$	–	< 2	1.0+	-243^d
Earth	8.0×10^{25}	$+11.7°$	31 000	10.4	23.9^h
Moon	$< 1 \times 10^{19}$	–	< 0.2	none	
Mars	$< 2 \times 10^{22}$	–	< 60	1.2	24.6^h
Jupiter	1.6×10^{30}	$-9.6°$	428 000	65±15	9.92^h
Saturn	4.7×10^{28}	$-0.0°$	21 200	20±3	10.66^h
Uranus	3.8×10^{27}	$-58.6°$	23 000	20	17.24^h
Neptune	2.0×10^{27}	$-46.8°$	14 000	26	16.1^h

Mercury

- smallest of the Terrestrial planets: radius = 2440 km
- smallest known body with a presently active dynamo
- weak magnetic field: Surface dipole magnetic field ~ 300 nT.
- no higher order moments are known
- magnetic moment points southward as at Earth (dipole tilt: 169°)
- magnetic field on surface 1% of Earth's magnetic field
- solar wind pressure is about 7 times larger than at Earth, therefore the magnetosphere is much smaller

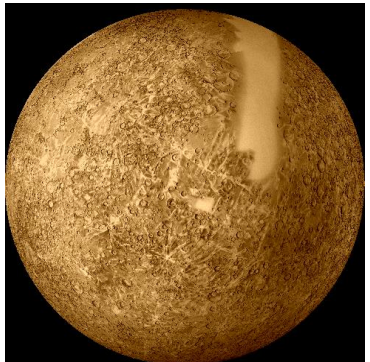


Mercury


BOW SHOCK
MAGNETOSHEATH
MAGNETOPAUSE
$\vec{J}_{MP}$
N. CUSP
NORTH LOBE
SOLAR WIND
MERCURY
PLASMA SHEET
$\vec{J}_T$
S. CUSP
SOUTH LOBE
$\vec{J}_{MP}$
MAGNETOSHEATH
MAGNETOPAUSE
DIAMETER OF THE EARTH

Mercury

- standoff distance of magnetopause: 1.3 - 1.6 planetary radii
- because of negligible atmosphere, there is no ionosphere
- interesting question: How does the magnetosphere couple to the planet? (maybe through Mercury's conducting core)
- Mercury's magnetosphere appears very dynamic from Mariner 10 observations, which is in accordance with a strong solar wind control.
- NASA's Messenger spacecraft was launched in 2004 and is in orbit since 2011
- ESA's BepiColombo orbiter will probably be launched in 2016



Venus

- no known intrinsic magnetic field

- embedded in an induced magnetosphere (similar to Mars)

Question:

- **What factors could cause differences between the planets' magnetospheres?**

Mars

- existence of remanent surface magnetic fields with strengths of 1500 nT above 100 km altitude

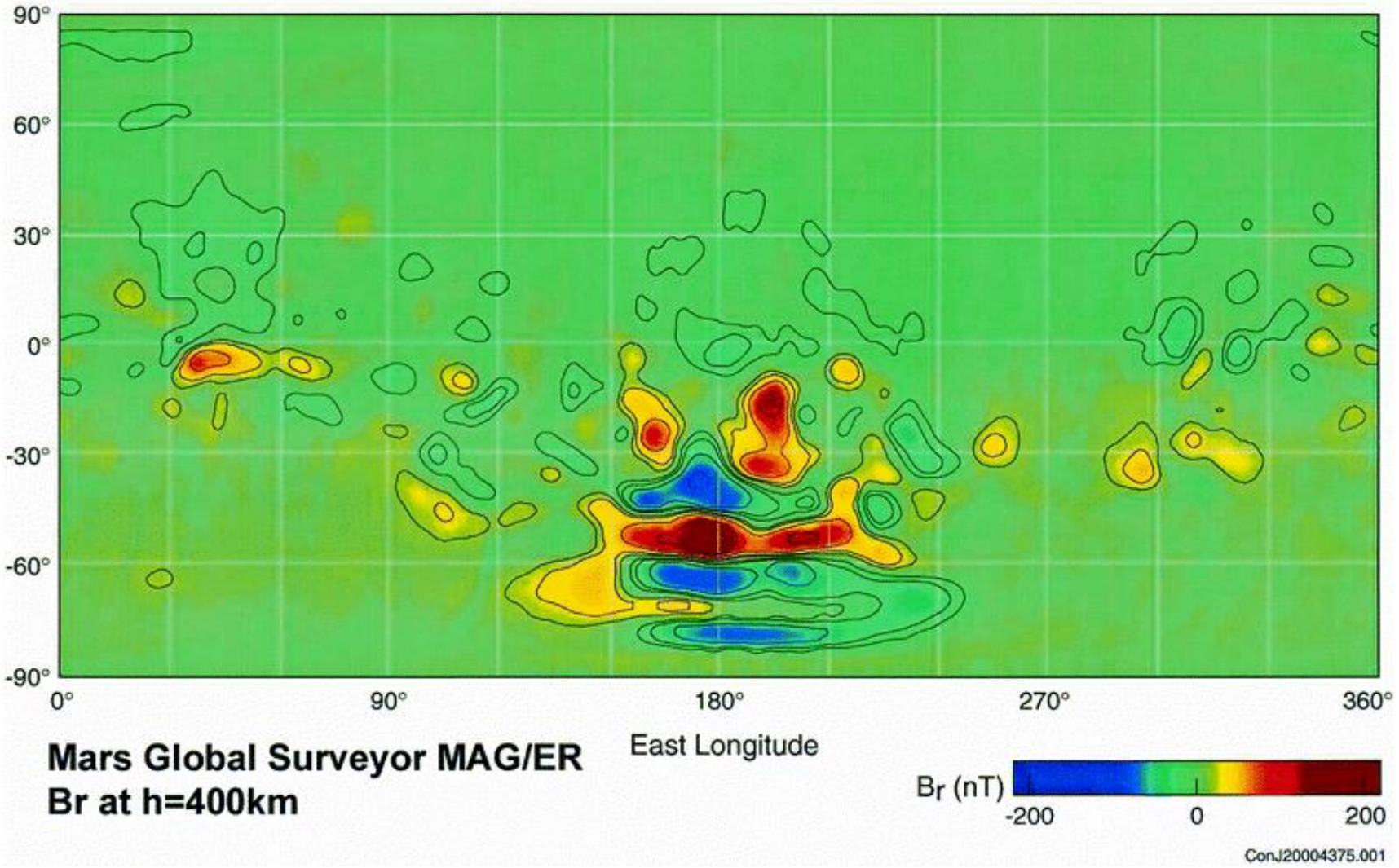
- Most of these magnetic anomalies lie south of the dichotomy boundary on the ancient densely cratered terrain of the highlands and extend 60° south of this boundary.

- no magnetosphere in the usual sense

- remanent magnetic fields have only very weak influence on the solar wind

Mars

- crustal surface magnetic fields



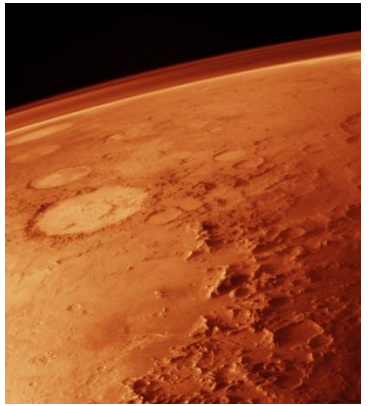
Mars

- Mars possesses an induced magnetosphere, arising from direct interaction between the solar wind and its ionosphere.

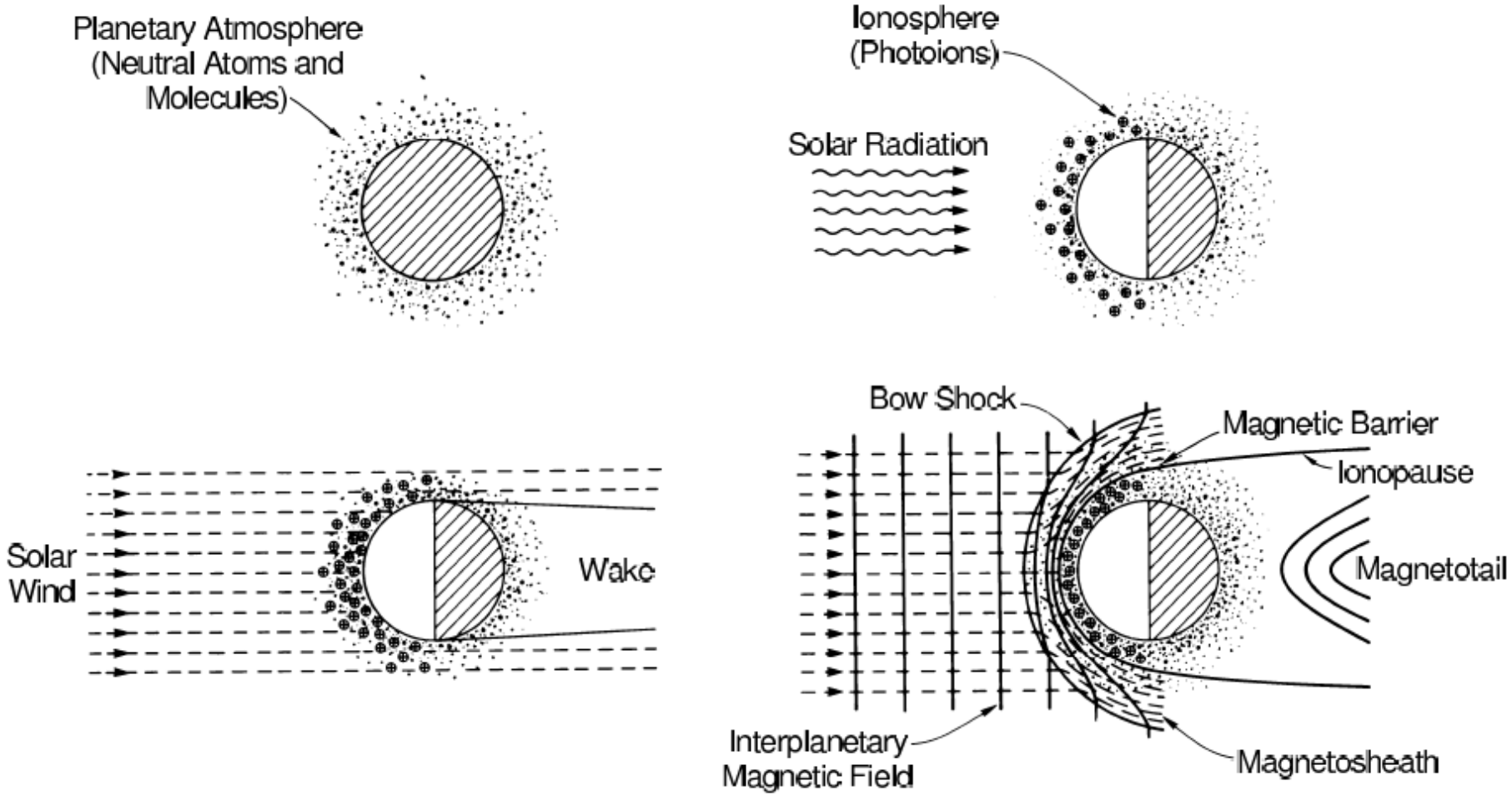
- Mars: extended neutral atmosphere, consisting mainly of CO_2

- upper atmosphere partially ionized by SUV radiation

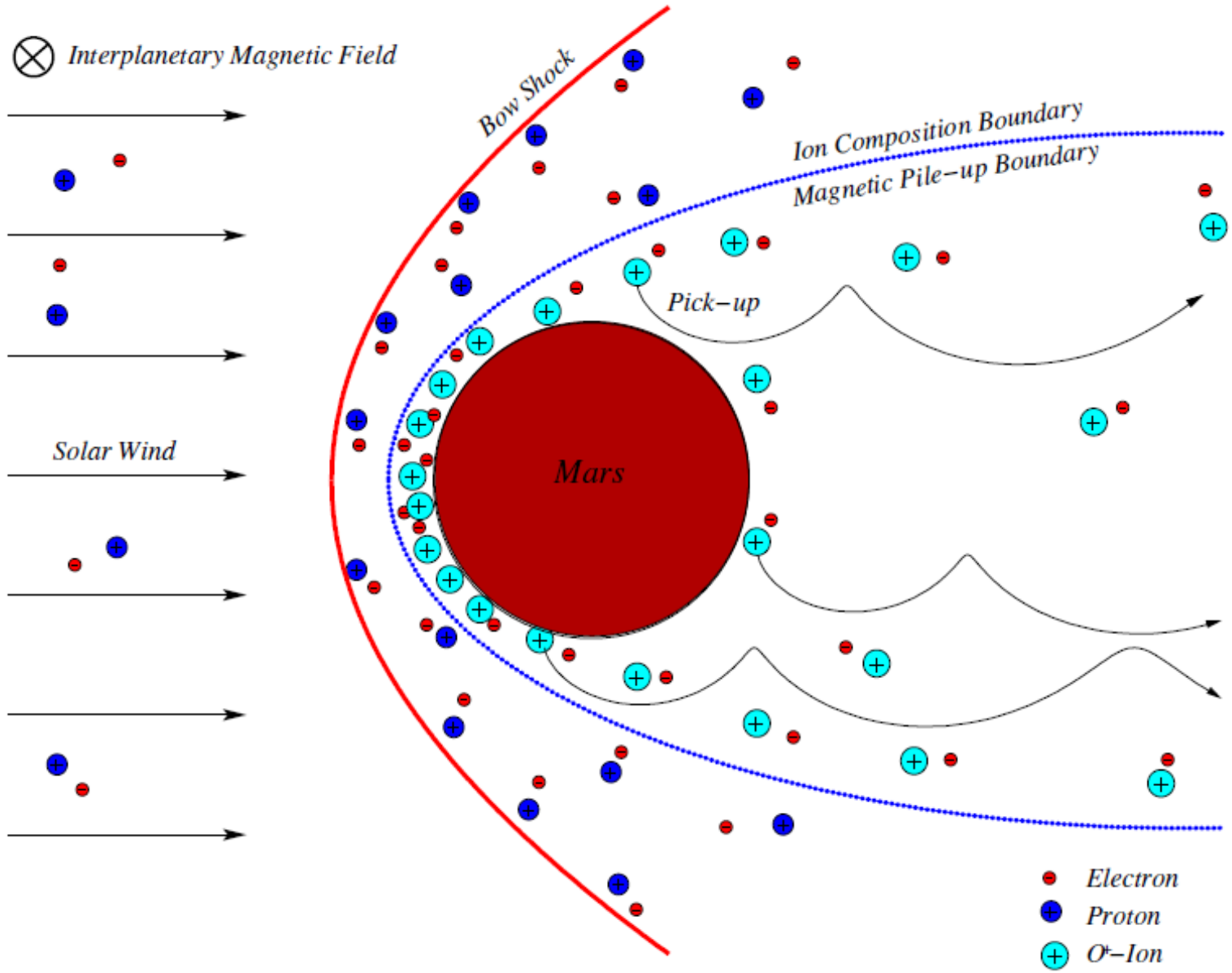
- pick-up process: ions are being swept out of the ionosphere by the solar wind electromagnetic fields
  => erosion of the atmosphere



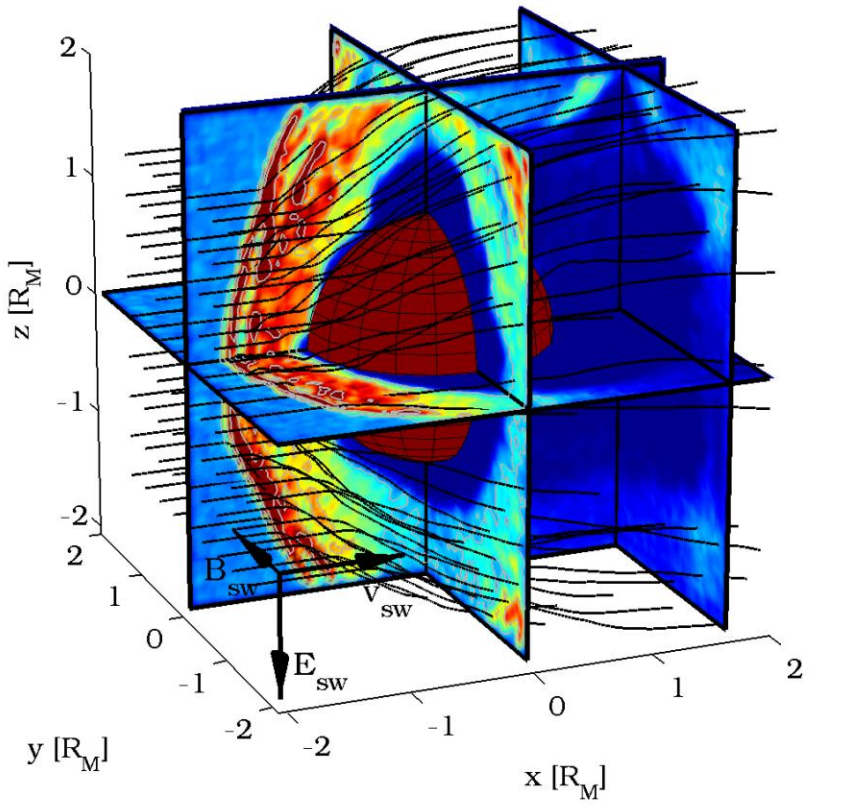
Mars: induced magnetosphere



Mars: induced magnetosphere



Mars: induced magnetosphere

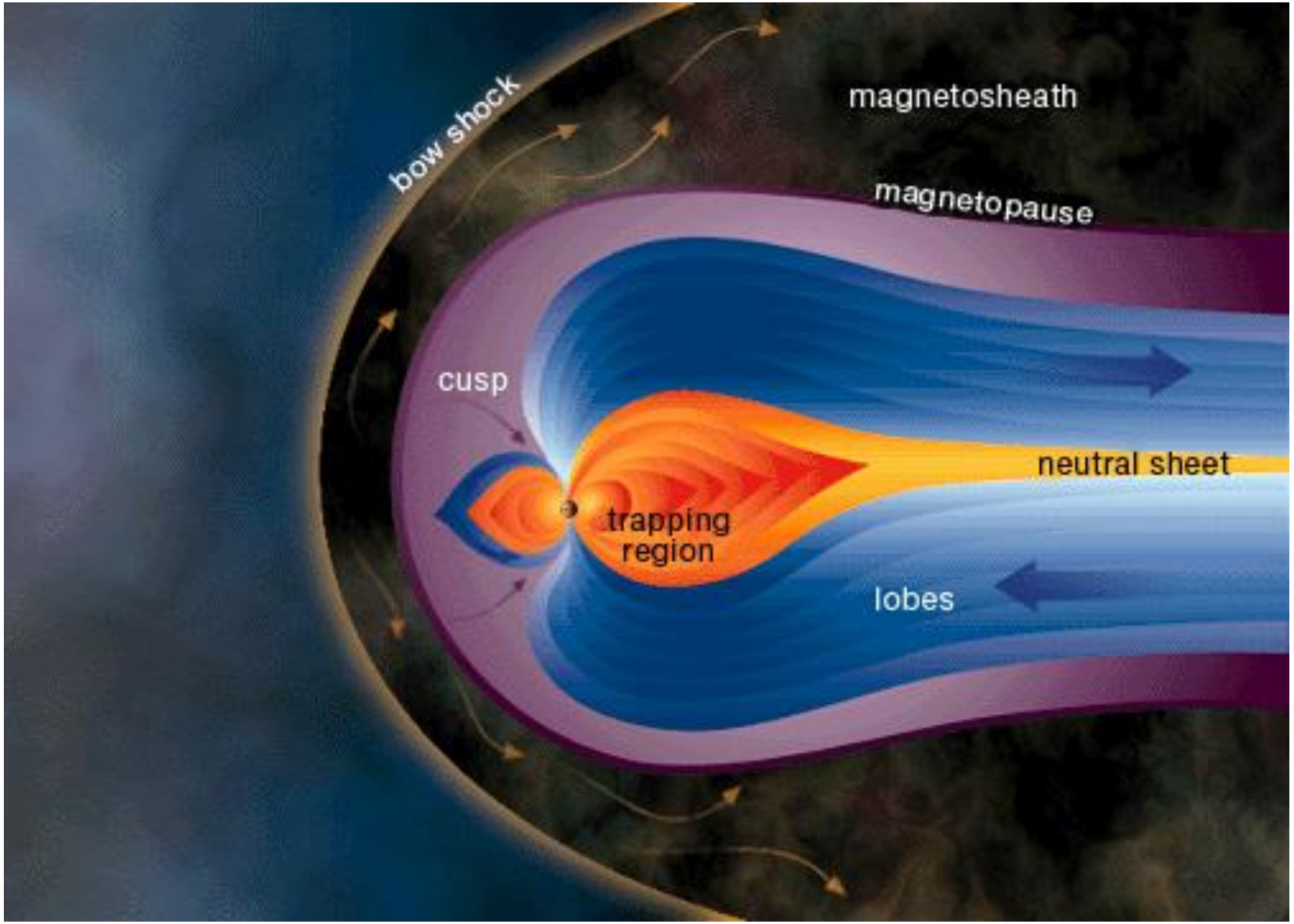


solar wind number density & stream lines

Jupiter

- planet with strongest magnetic field in our solar system
- rotation period: 9.93 h
- dipole tilt: 9.6°
- standoff distance of magnetopause: 50-100 Jupiter radii
- Jupiter's magnetosphere is the largest object in the solar system.

Jupiter's magnetosphere

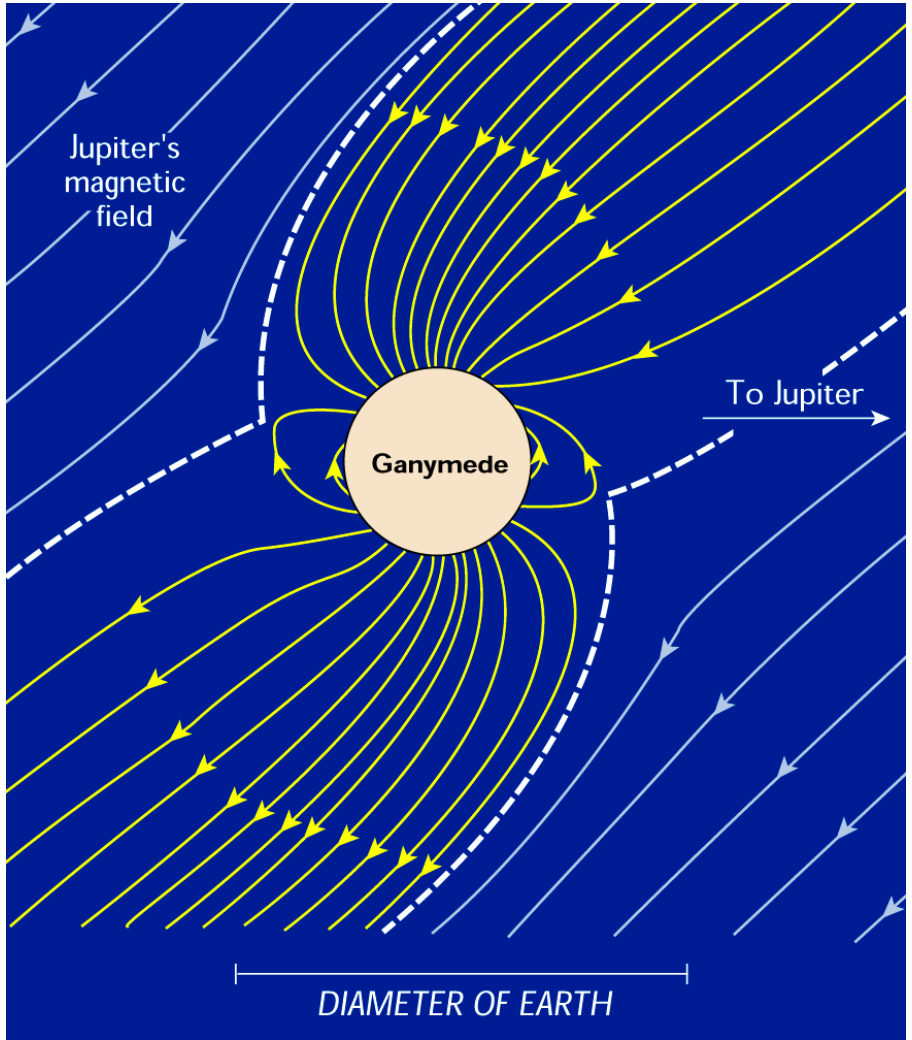


Ganymede, satellite of Jupiter

- only known moon with a dynamo magnetic field
- orbital period (= rotation period): 7.2 days
- dipole tilt: <10°
- interaction between Ganymede's magnetic field and the plasma in Jupiter's magnetosphere generates a mini-magnetosphere around the moon

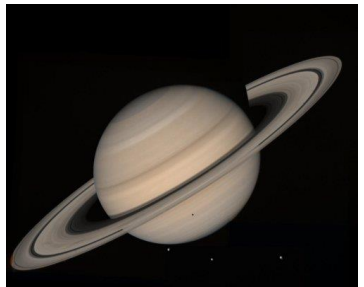
Ganymede, satellite of Jupiter

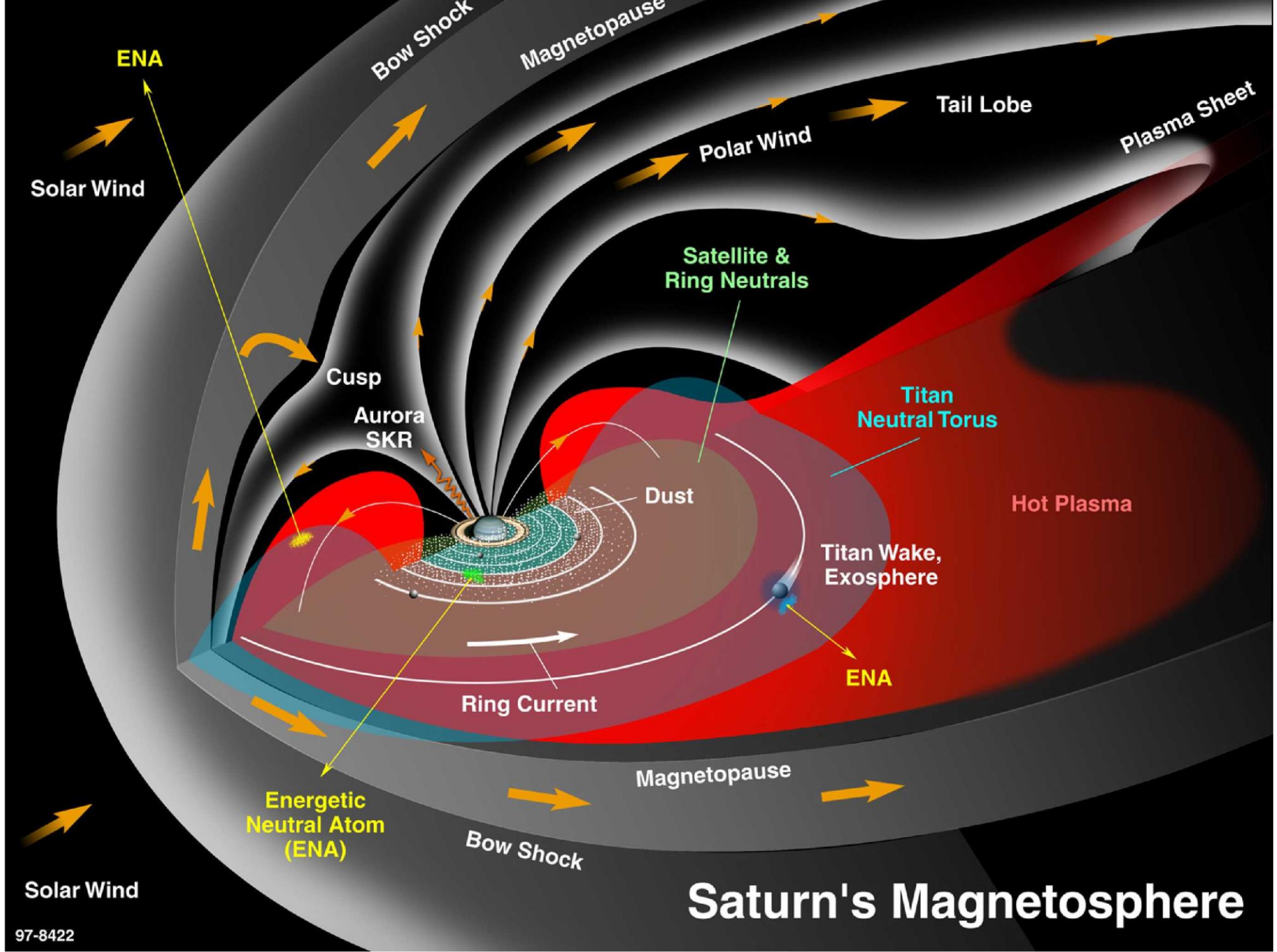
- Ganymede possesses a mini-magnetosphere within the magnetosphere of Jupiter



Saturn

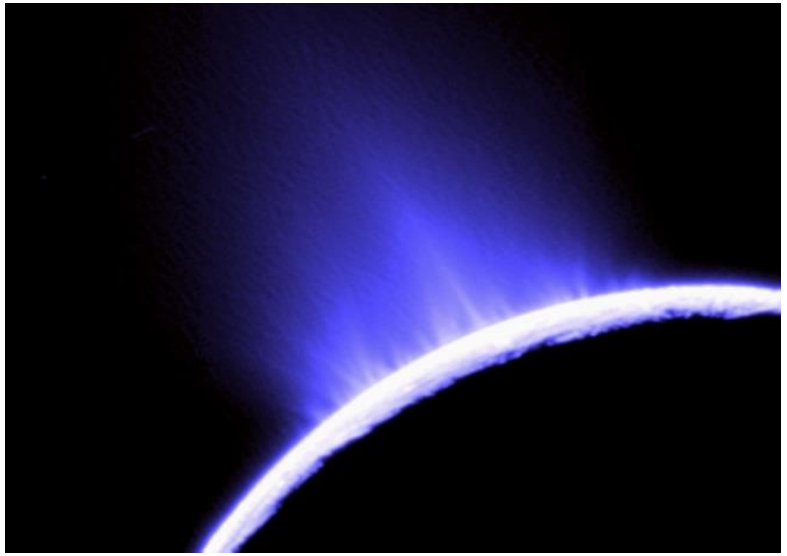
- Saturn's surface magnetic field is comparable to Earth's field
- No measured tilt of the magnetic field with respect to Saturn's spin axis!
- rotation period: 10 h 39 min? (appears to vary as a function of time, huge currently unresolved puzzle)
  - Maybe even different rotation periods in the different hemispheres?
- standoff distance of magnetopause: 17-24 planetary radii

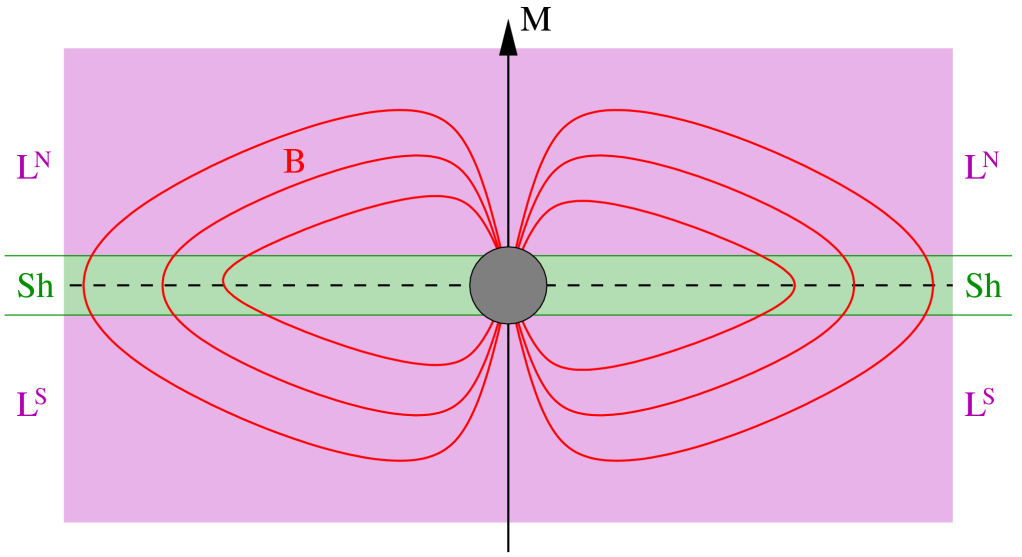



ENA
Bow Shock
Magnetopause
Solar Wind
Polar Wind
Tail Lobe
Plasma Sheet
Satellite &
Ring Neutrals
Cusp
Aurora
SKR
Titan
Neutral Torus
Dust
Hot Plasma
Titan Wake,
Exosphere
ENA
Ring Current
Magnetopause
Energetic
Neutral Atom
(ENA)
Bow Shock
Solar Wind
97-8422
Saturn's Magnetosphere

Saturn

- due to strong internal plasma sources (Enceladus' plumes), Saturn's magnetosphere possesses a magnetodisk configuration
  => field lines are stretched radially away from the rotation axis

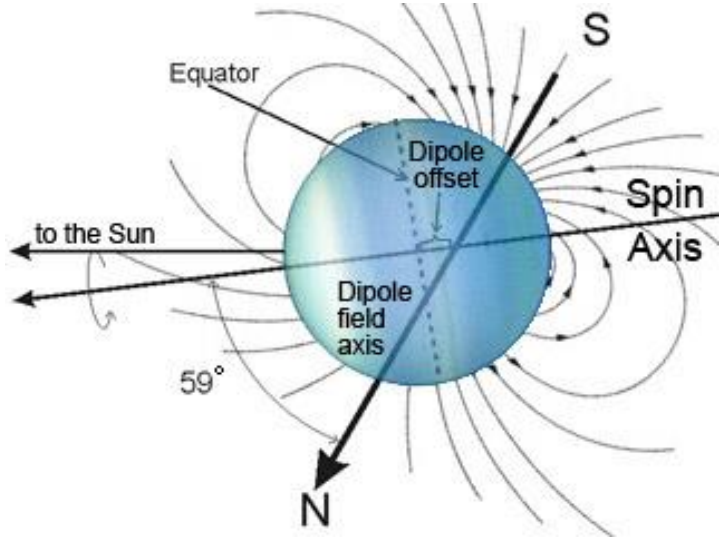




Uranus

- equatorial surface magnetic field a bit weaker than on Earth (23,000 nT)

- **specialty:** dipole tilt with respect to spin axis: 58.6°

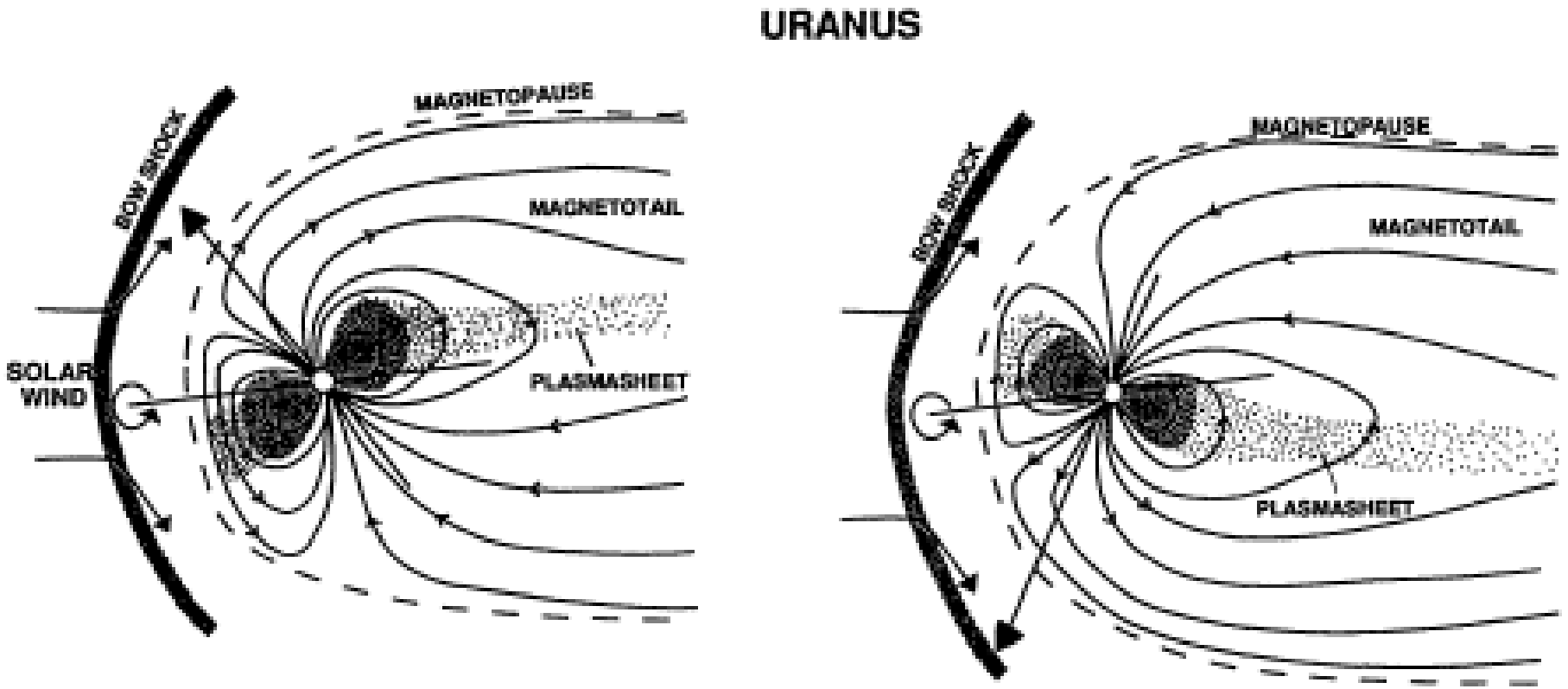


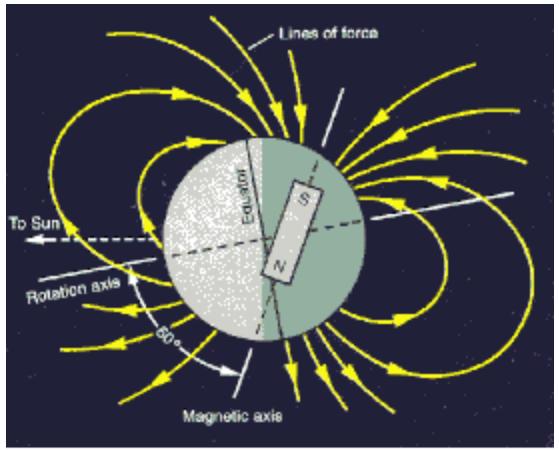
- tilt of spin axis: 97.8°

- rotation period: 17 h 14 min

- standoff distance of m'pause: 18-19 planetary radii

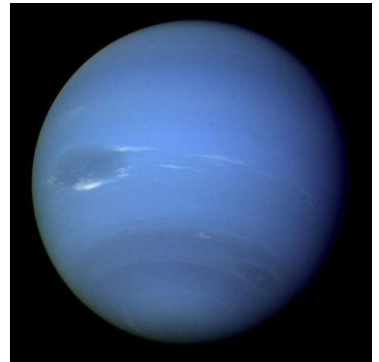
Uranus


URANUS
BOW SHOCK
MAGNETOPAUSE
MAGNETOTAIL
SOLAR WIND
PLASMASHEET
BOW SHOCK
MAGNETOPAUSE
MAGNETOTAIL
PLASMASHEET

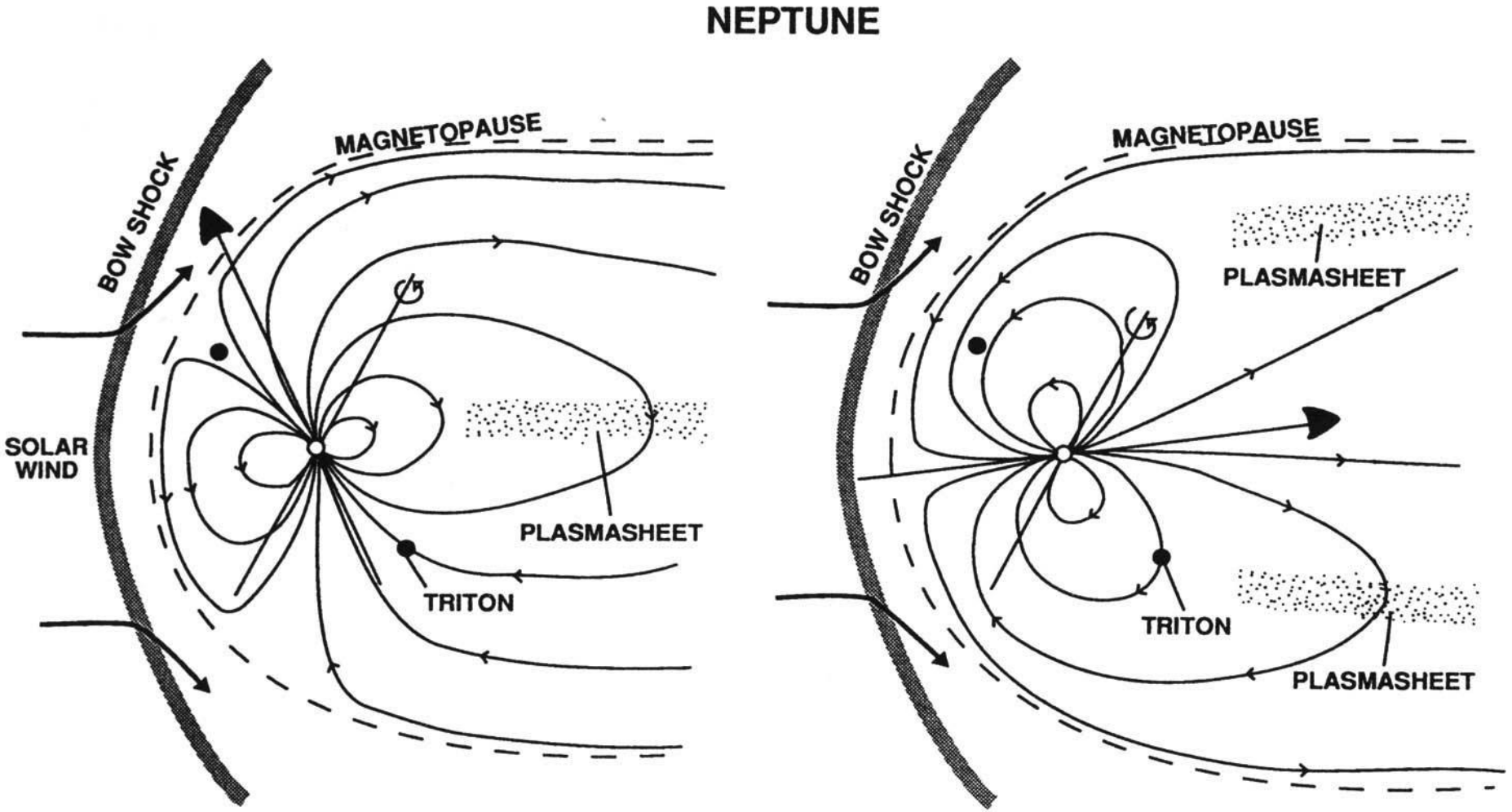

Lines of force
Equator
S
N
To Sun
Rotation axis
30°
Magnetic axis

Neptune

- equatorial surface magnetic field weaker than at Earth (14,000 nT)
- dipole tilt with respect to spin axis: 46.9°
- tilt of spin axis: 28.3°
- standoff distance of magnetopause: 23 -27 planetary radii
- rotation period: 16 h 6 min



Neptune


NEPTUNE
BOW SHOCK
MAGNETOPAUSE
SOLAR WIND
PLASMASHEET
TRITON
BOW SHOCK
MAGNETOPAUSE
PLASMASHEET
TRITON
PLASMASHEET