Last lecture (6)

- Drift motion

- Ionospheric conductivities

- Particle motion in the magnetosphere

Today's lecture (7)

- Particle motion in the magnetosphere

- Other magnetospheres

- Aurora

Drift motion

$$\mathbf{u}_{drift} = \frac{\mathbf{F} \times \mathbf{B}}{qB^2}$$
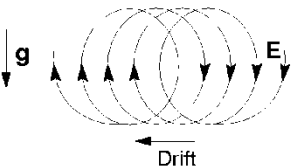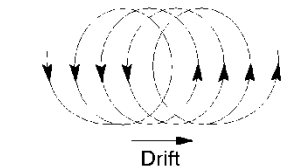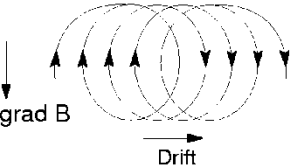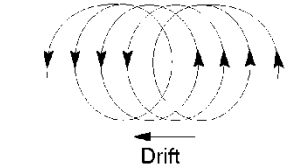
	Positive particles	Negative particles
Homogeneous magnetic field No disturbing force $\mathbf{F} = 0$	⊙ B	⊙ B
Homogeneous magnetic field Homogeneous electric field $\mathbf{F} = q\mathbf{E}$	⊙ B E Drift	⊙ B Drift
Homogeneous magnetic field Gravitation $\mathbf{F} = m\mathbf{g}$	⊙ B g E Drift	⊙ B Drift
Inhomogeneous magnetic field $\mathbf{F} = -\mu \text{ grad } B$	⊙ B grad B Drift	⊙ B Drift

ExB-drift

E ⊙ **B**

Without collisions

With collisions

i⁺

e⁻

i⁺

e⁻
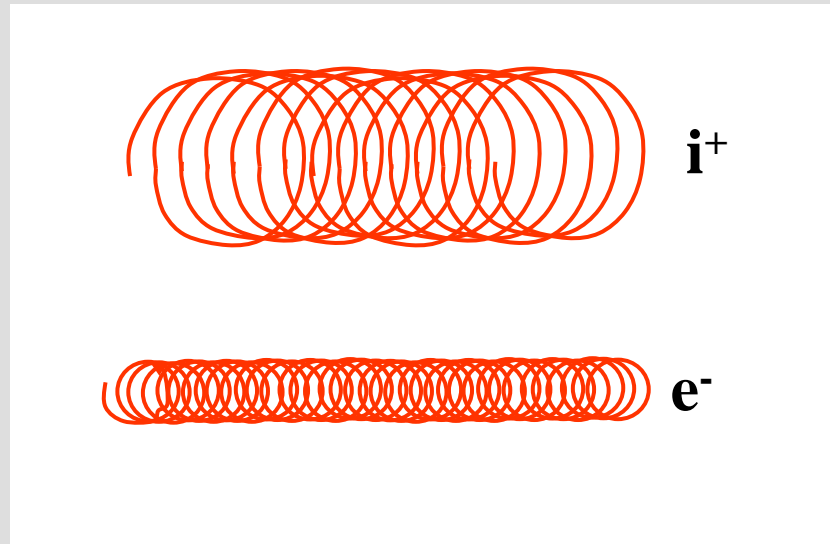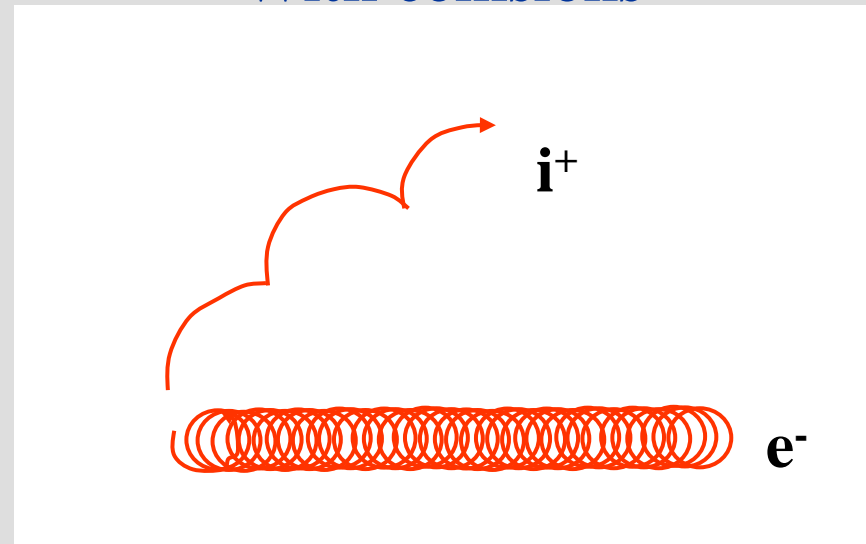
Electric conductivity in a magnetized plasma
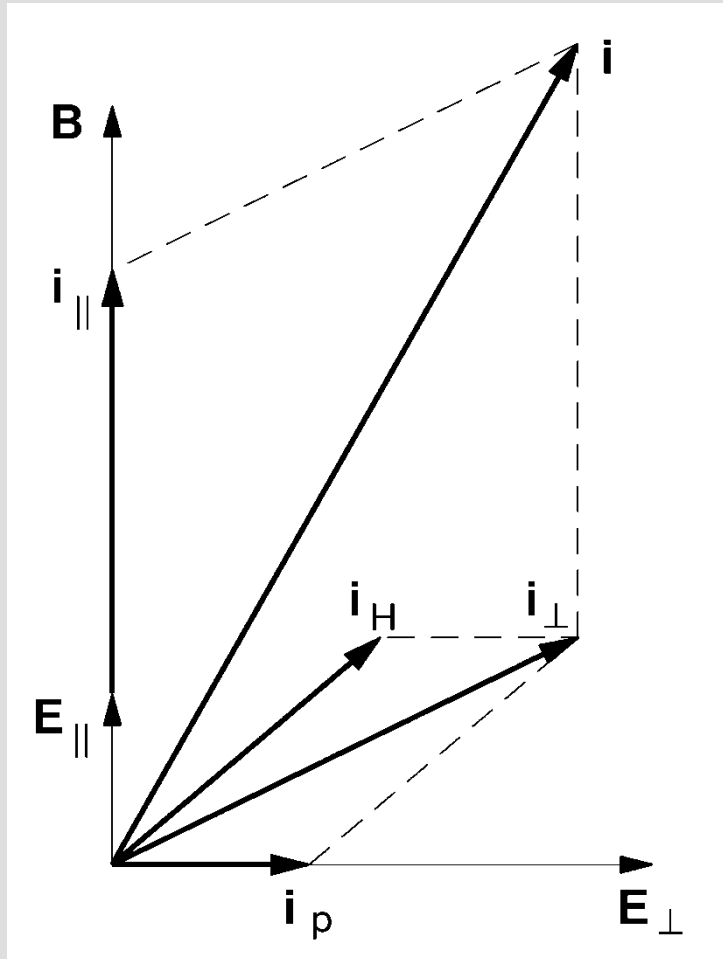
- $i_{//} =$ parallel current
- $i_P =$ Pedersen current
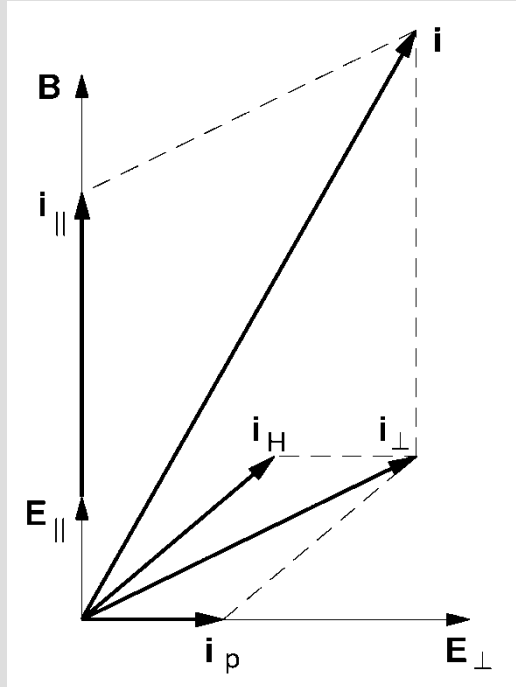- $i_H =$ Hall current

Electric conductivity in a magnetized plasma II

$$\sigma_P = \sigma_e \frac{1}{1 + \omega_{ge}^2 \tau_e^2} + \sigma_i \frac{1}{1 + \omega_{gi}^2 \tau_i^2}$$

$$\sigma_H = \sigma_e \frac{\omega_{ge} \tau_e}{1 + \omega_{ge}^2 \tau_e^2} - \sigma_i \frac{\omega_{gi} \tau_i}{1 + \omega_{gi}^2 \tau_i^2}$$

$$\sigma_{/\!/} = \sigma_e + \sigma_i$$

$$\sigma_e = e^2 n \tau_e / m_e \qquad \sigma_i = e^2 n \tau_i / m_i$$

$$i_{/\!/} = \sigma_{/\!/} E_{/\!/}$$

$$\left. \begin{array}{l} i_P = \sigma_P E_\perp \\ i_H = \sigma_H E_\perp \end{array} \right\} \quad \text{or} \quad \mathbf{i}_\perp = \sigma_P \mathbf{E}_\perp + \sigma_H \frac{\mathbf{B} \times \mathbf{E}_\perp}{B}$$
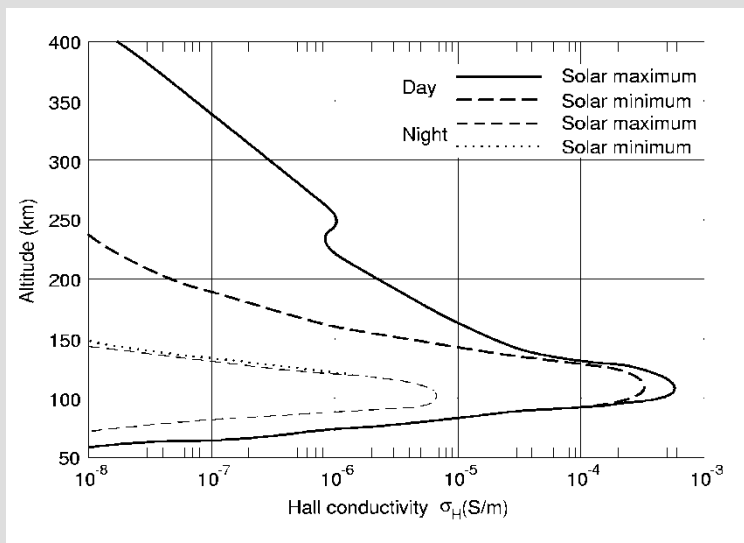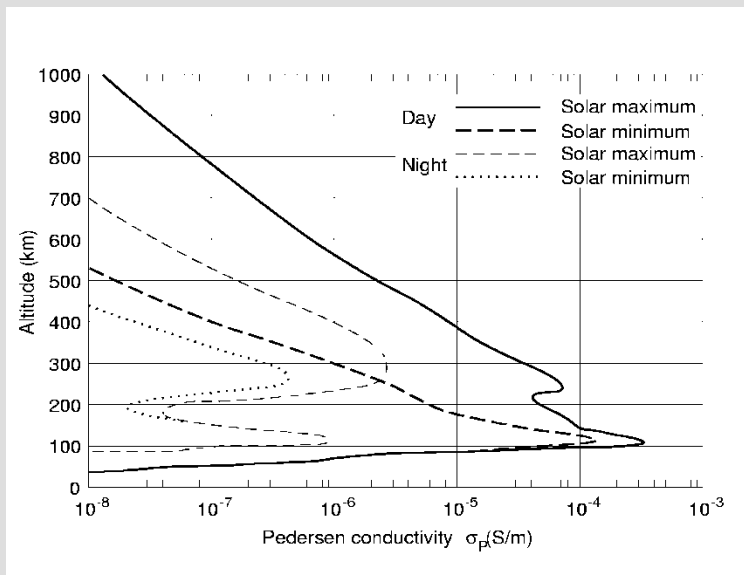
Ionospheric conductivities
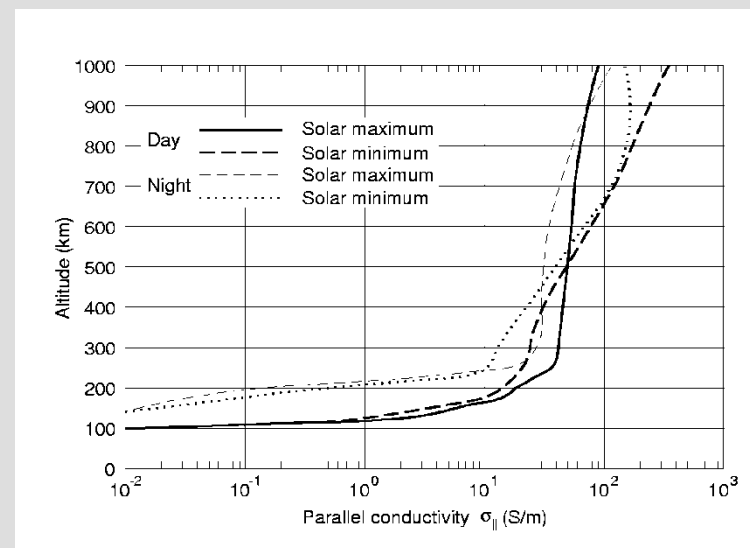
Geomagnetic field

Approximated by a
dipole close to Earth.

$$B_r = B_p (\frac{R_E}{r})^3 \cos\theta$$

$$B_\theta = \frac{B_p}{2}(\frac{R_E}{r})^3 \sin\theta$$

$$a = \frac{2\pi R_E^3 B_p}{\mu_0}$$

magnetic dipole moment

Magnetic field at the
"north pole"

$B_r\hat{r}$

B

$B_\theta\hat{\theta}$

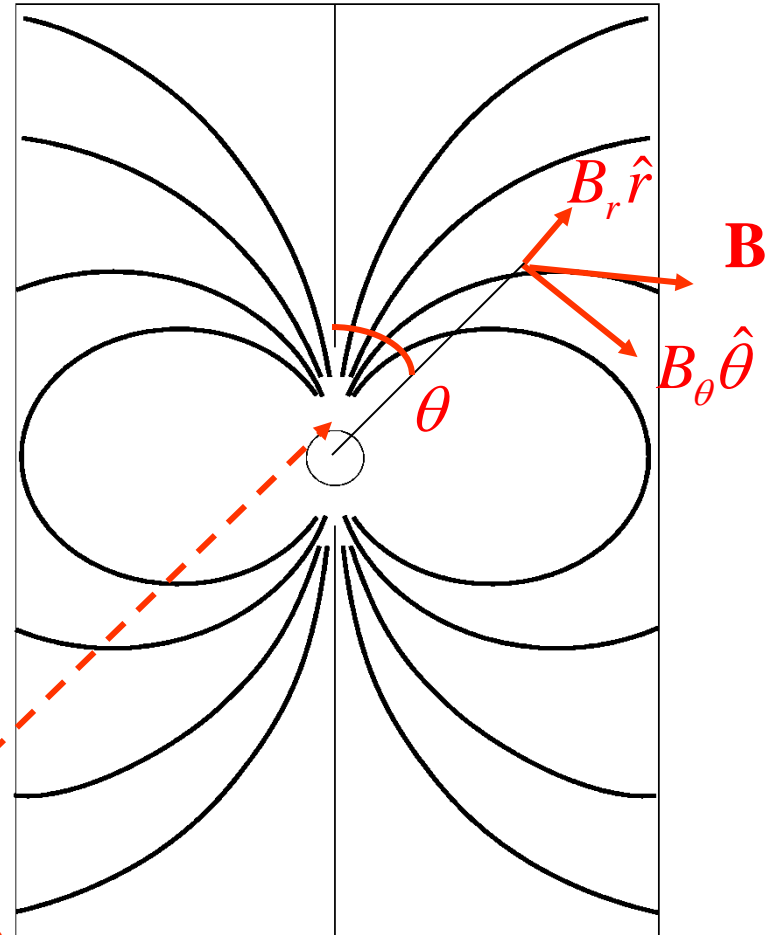θ

Geomagnetic field

Alternative formulation of dipole field

$$B_r = B_p \left(\frac{R_E}{r}\right)^3 \cos\theta$$

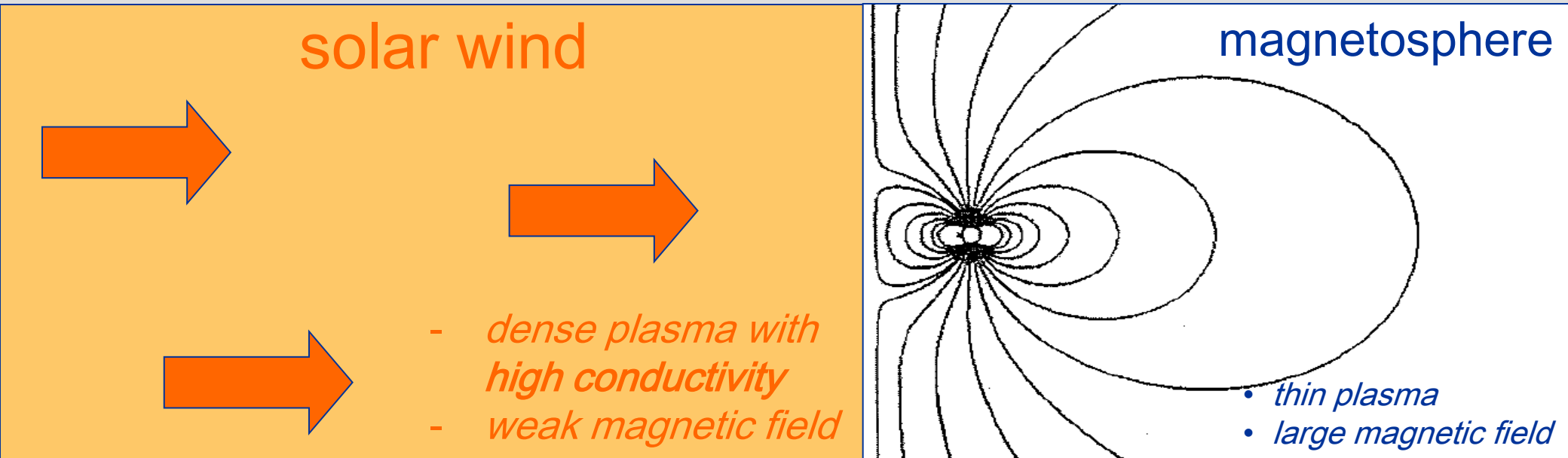$$B_\theta = \frac{B_p}{2}\left(\frac{R_E}{r}\right)^3 \sin\theta$$

$$B_r = \frac{\mu_0 a}{2\pi}\frac{1}{r^3}\cos\theta$$

$$B_\theta = \frac{\mu_0 a}{2\pi}\cdot\frac{1}{2}\cdot\frac{1}{r^3}\sin\theta$$

$$a = \frac{2\pi R_E^3 B_p}{\mu_0}$$

magnetic dipole moment

Stand-off distance from pressure balance
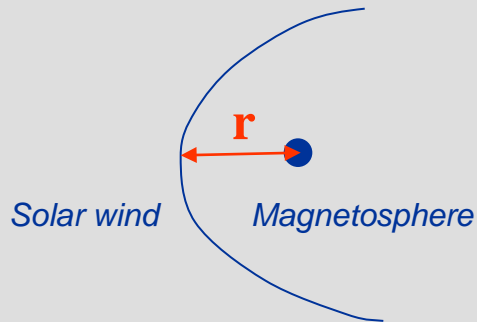
solar wind

magnetosphere

- dense plasma with *high conductivity*
- weak magnetic field

- thin plasma
- large magnetic field

Dynamic pressure:

$$p_d = \rho_{SW} v_{SW}^2$$

Magnetic pressure:

$$p_B = \frac{B^2}{2\mu_0}$$

Magnetopause "stand-off distance"

Dynamic pressure: $\quad p_d = \rho_{SW} v_{SW}^2$

Magnetic pressure: $\quad p_B = \dfrac{1}{2\mu_0} B^2$

Solar wind   Magnetosphere

Dipole field strength
(in equatorial plane): $\quad B = \dfrac{\mu_0 a}{4\pi} \dfrac{1}{r^3}$
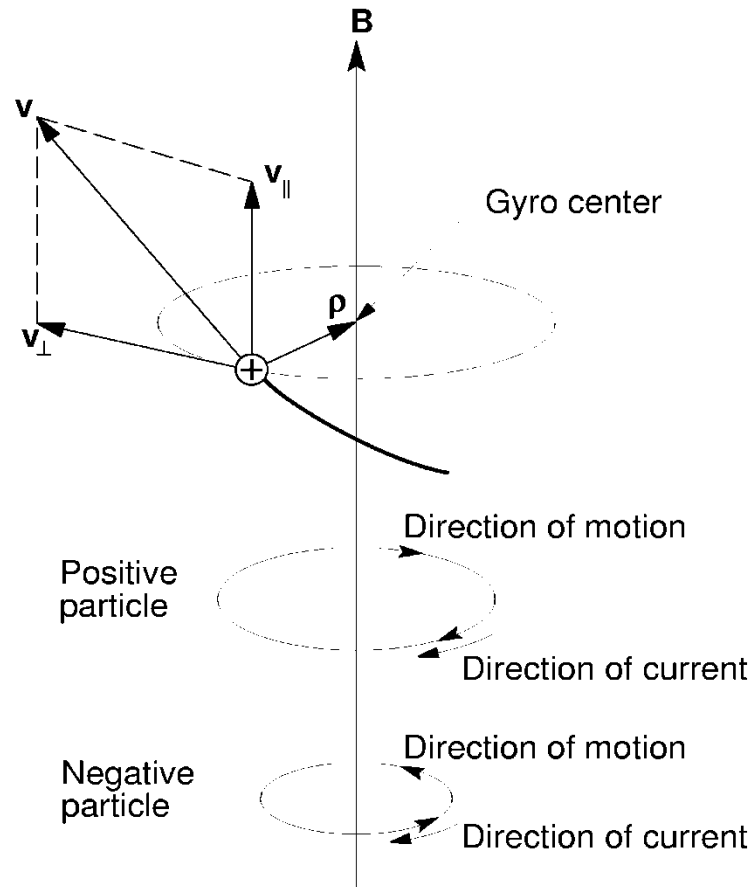
$$p_d = p_B \quad \Rightarrow \qquad \rho_{SW} v_{SW}^2 = \left[\dfrac{\mu_0 a}{4\pi} \dfrac{1}{r^3} \right]^2 / 2\mu_0 \quad \Rightarrow$$

$$r = \left(\dfrac{\mu_0 a}{4\pi} \right)^{1/3} \left(2\mu_0 \rho_{SW} v_{SW}^2 \right)^{-1/6}$$

$a = 8 \times 10^{22} \ Am^2, \qquad v = 500 \ km/s, \qquad \rho_{SW} = 10^7 \times 1.7 \times 10^{-27} \ kg/m^3$:

r = 7 R$_e$ $\qquad$ (1 R$_e$ = 6378 km)

Particle motion in magnetic field

gyro radius

$$\rho = \frac{mv_{\perp}}{qB}$$

gyro frequency

$$\omega_g = \frac{qB}{m}$$

magnetic moment

$$\mu = IA = q\, f_g \pi\, \rho^2 = mv_{\perp}^2/2B$$

Adiabatic invariant

DEFINITION:

An **adiabatic invariant** is a property of a physical system which stays constant when changes are made slowly.

By 'slowly' in the context of charged particle motion in magnetic fields, we mean much slower than the gyroperiod.
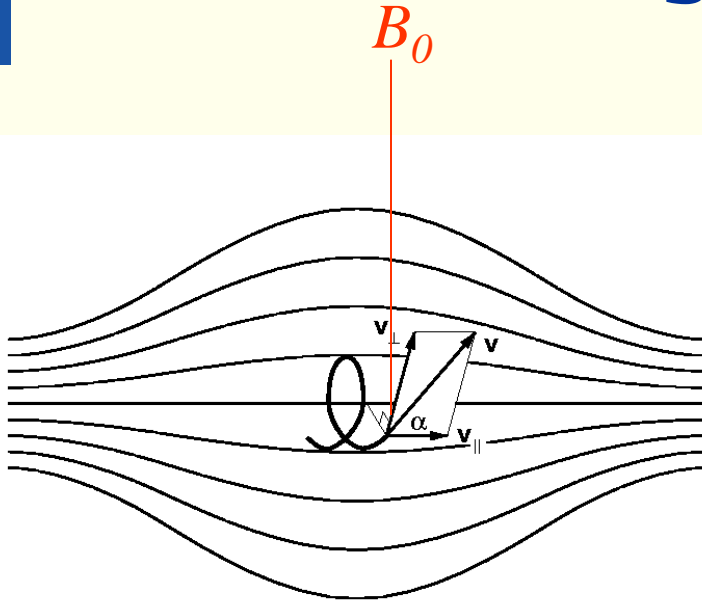
'First adiabatic invariant' of particle drift:

$$\mu = \frac{mv_\perp^2}{2B}$$

Magnetic mirror

B_0

mv²/2 constant (energy conservation) ⟹

$$\frac{\sin^2 \alpha}{B} = konst$$

What happens with α as the particle moves into the stronger magnetic field?

The magnetic moment μ is an **adiabatic invariant**.

$$\mu = \frac{mv_\perp^2}{2B} = \frac{mv^2 \sin^2 \alpha}{2B}$$

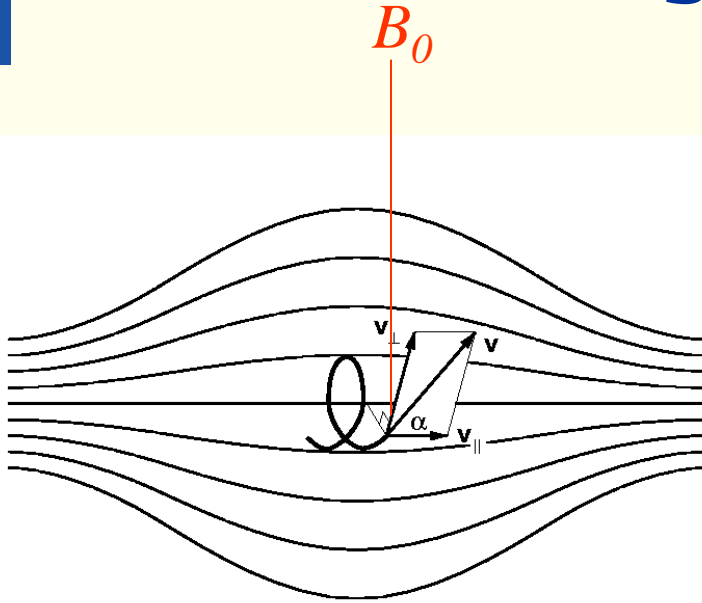| Red	Yellow
α increases	α decreases

Magnetic mirror

B_0

mv²/2 constant (energy conservation) ➡

$$\frac{\sin^2 \alpha}{B} = konst$$
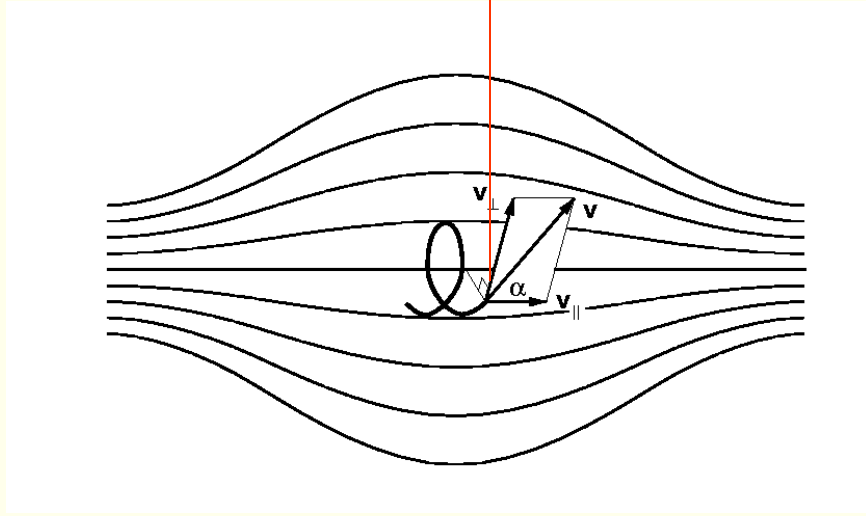
What happens with α as the particle moves into the stronger magnetic field?

$$\sin \alpha = \sqrt{B \cdot konst}$$

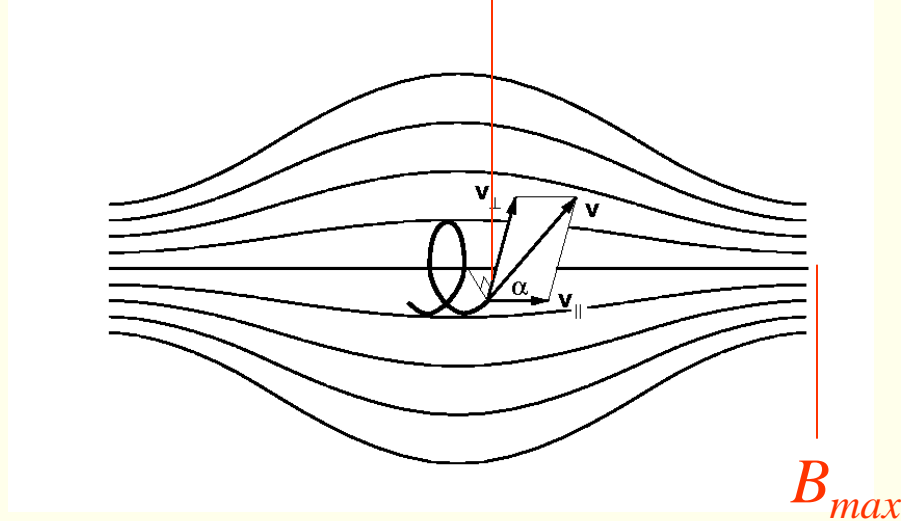<div style="background:red;color:white">Red</div>

α increases

The magnetic moment μ is an *adiabatic invariant*.

$$\mu = \frac{mv_\perp^2}{2B} = \frac{mv^2 \sin^2 \alpha}{2B}$$

Magnetic mirror

B_0

mv²/2 constant (energy conservation) ➡

$$\frac{\sin^2 \alpha}{B} = konst$$

particle turns when $\alpha = 90°$ ➡

$$\frac{B_{turn}}{\sin^2 90°} = \frac{B_0}{\sin^2 \alpha}$$ ➡

The magnetic moment μ is an *adiabatic invariant*.

$$B_{turn} = \frac{B_0}{\sin^2 \alpha}$$

$$\mu = \frac{mv_{\perp}^2}{2B} = \frac{mv^2 \sin^2 \alpha}{2B}$$

Magnetic mirror

Magnetic mirror

B_0

B_{max}

mv²/2 constant (energy conservation) ➡

$$\frac{\sin^2 \alpha}{B} = konst$$

particle turns when $\alpha = 90°$ ➡

$$B_{turn} = B_0 / \sin^2 \alpha$$

If maximal *B*-field is B_{max} a particle with pitch angle α can only be turned around if

The magnetic moment μ is an *adiabatic invariant*.

$$B_{turn} = B_0 / \sin^2 \alpha \leq B_{max}$$ ➡

$$\alpha > \alpha_{lc} = \arcsin \sqrt{B_0 / B_{max}}$$

$$\mu = \frac{mv_\perp^2}{2B} = \frac{mv^2 \sin^2 \alpha}{2B}$$

Particles in *loss cone* :

$$\alpha < \alpha_{lc}$$

What will happen to the particle?

$B_0 = 25\ \mu T$

$\alpha = 45°$

$B_{max} = 40\ \mu T$
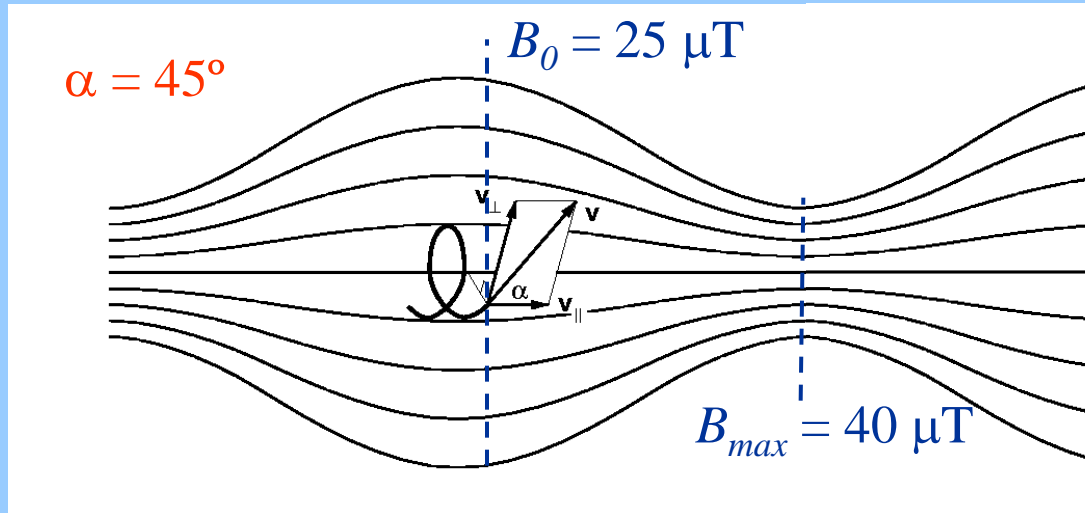
$$\alpha_{lc} = \arcsin \sqrt{B_0 / B_{max}}$$

Blue   It will mirror
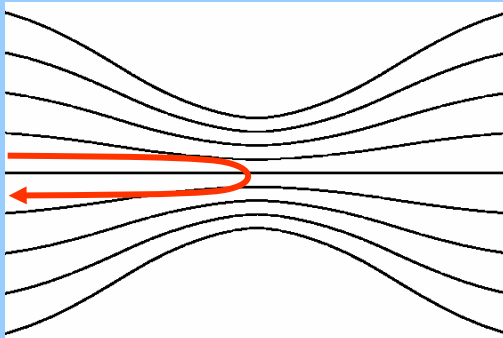
Yellow   It will escape

What will happen to the particle?

$B_0 = 25\ \mu\text{T}$

$\alpha = 45°$

$B_{max} = 40\ \mu\text{T}$
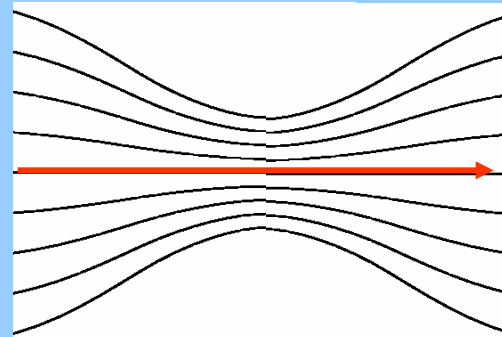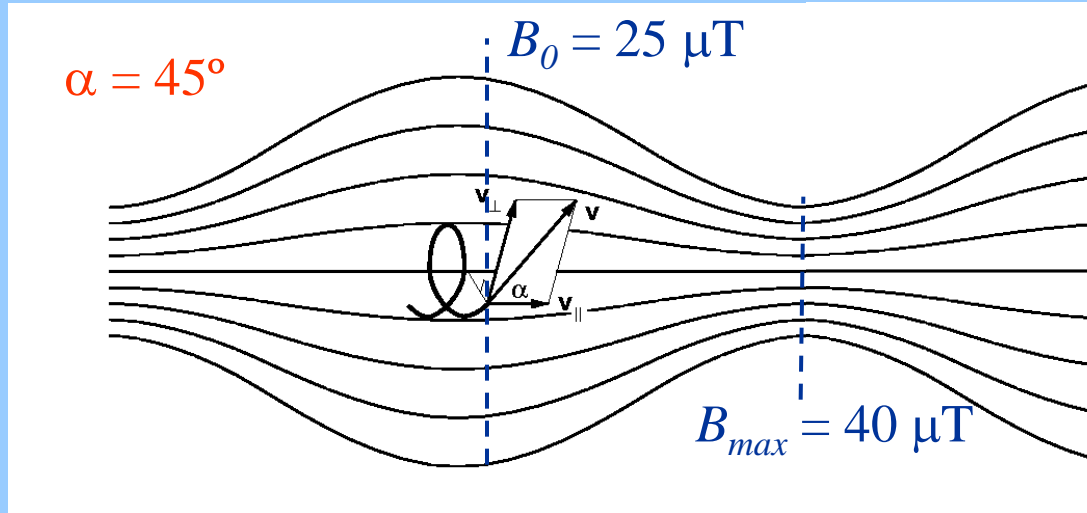
$$\alpha_{lc} = \arcsin \sqrt{B_0 / B_{max}} =$$

$$\arcsin \sqrt{25 / 40} = 52°$$

Yellow It will escape
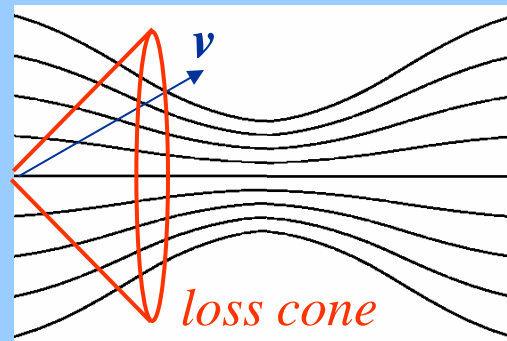
loss cone

Particle motion in geomagnetic field

gyration **longitudinal oscillation** **azimuthal drift**
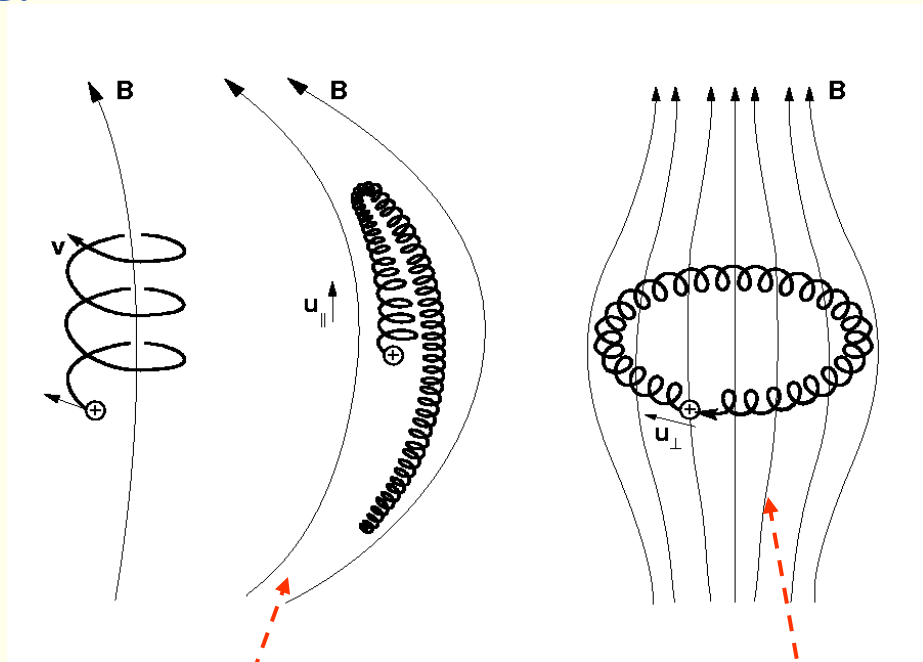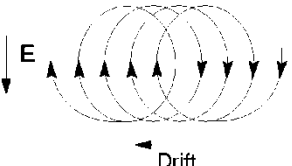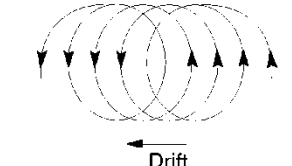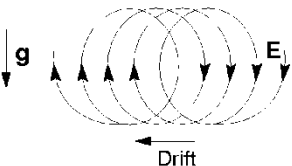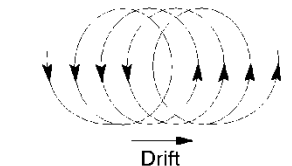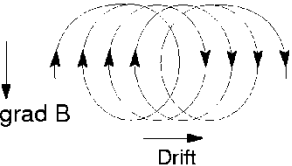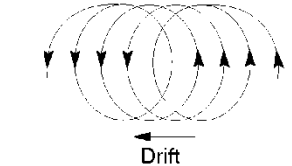

Magnetic mirror
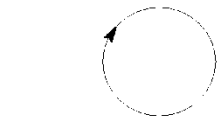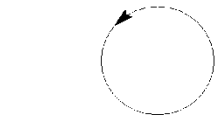
grad B drift
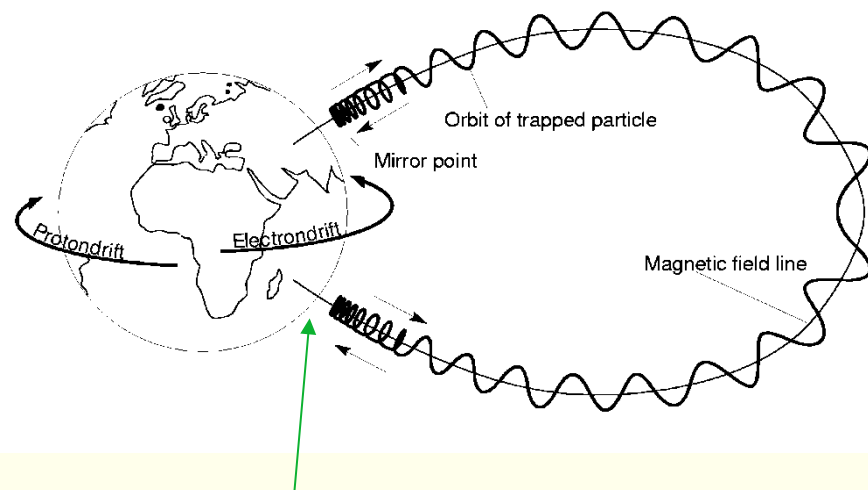
Particles in the loss cone create the aurora!

Drift motion

$$\mathbf{u} = \frac{\mathbf{F} \times \mathbf{B}}{qB^2}$$

	Positive particles	Negative particles
Homogeneous magnetic field No disturbing force $\mathbf{F} = 0$	⊙ B	⊙ B
Homogeneous magnetic field Homogeneous electric field $\mathbf{F} = q\mathbf{E}$	⊙ B E Drift	⊙ B Drift
Homogeneous magnetic field Gravitation $\mathbf{F} = m\mathbf{g}$	⊙ B g E Drift	⊙ B Drift
Inhomogeneous magnetic field $\mathbf{F} = -\mu \text{ grad } B$	⊙ B grad B Drift	⊙ B Drift

Force on magnetic dipole
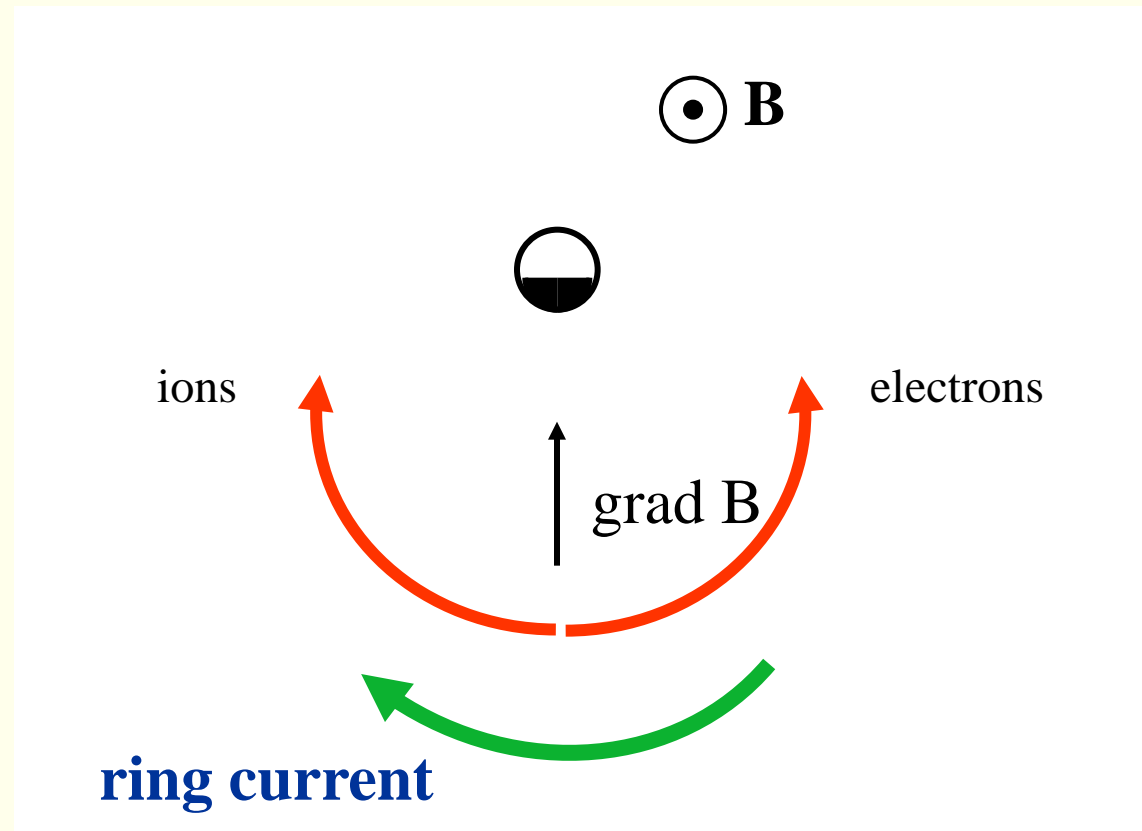
$$\boldsymbol{\mu} \sim -\mathbf{B} \quad \Rightarrow \quad \boldsymbol{\mu} = -\mu \frac{\mathbf{B}}{B}$$

$$\mathbf{F} = \nabla(\boldsymbol{\mu} \cdot \mathbf{B}) = -\mu \nabla \left(\frac{\mathbf{B}}{B} \cdot \mathbf{B} \right) =$$

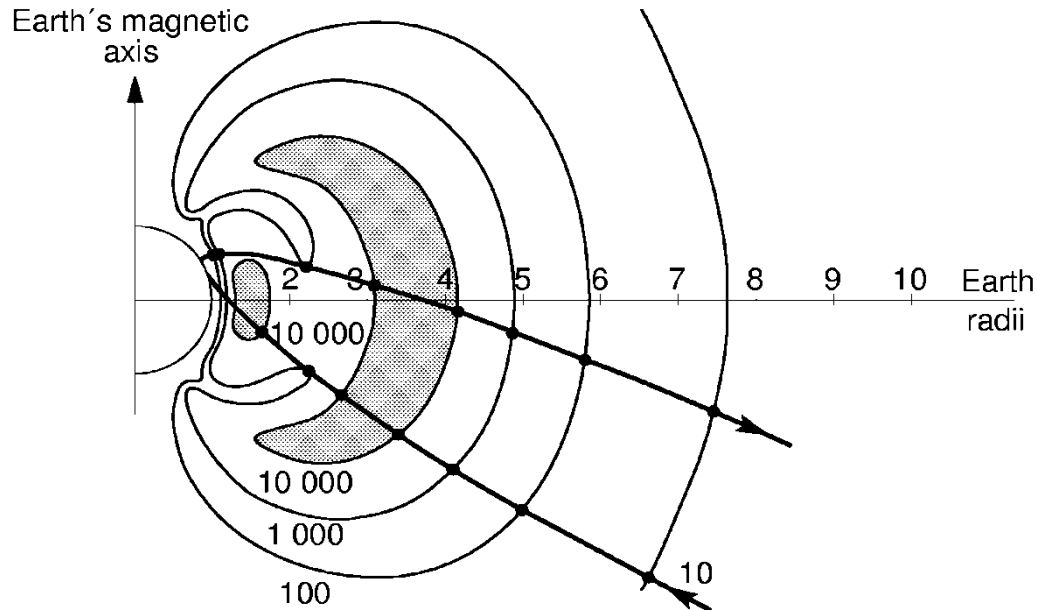$$= -\mu \nabla \left(\frac{B^2}{B} \right) = -\mu \nabla B$$
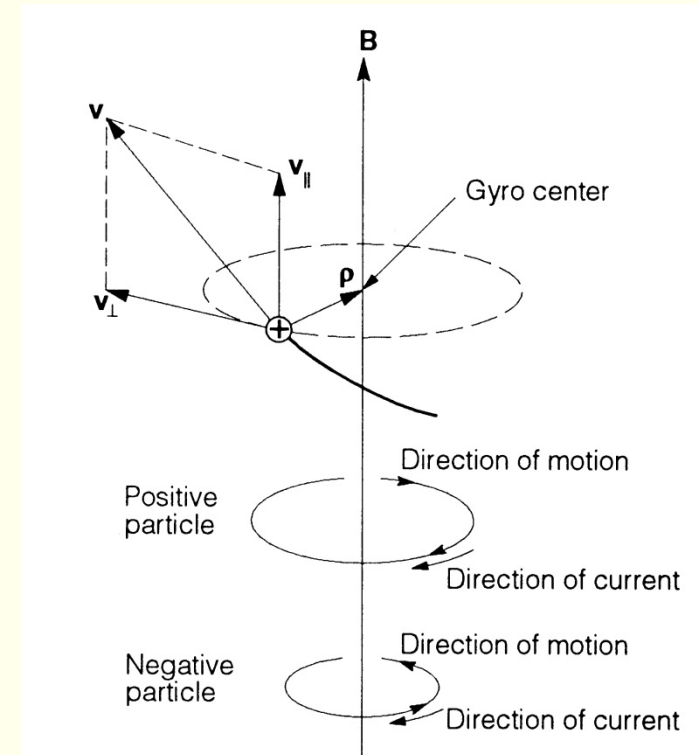
Ring current and particle motion

$$\mathbf{u} = -\frac{\mu \nabla B \times \mathbf{B}}{qB^2}$$

$$\mu = \frac{mv_\perp^2}{2B}$$

⊙ **B**

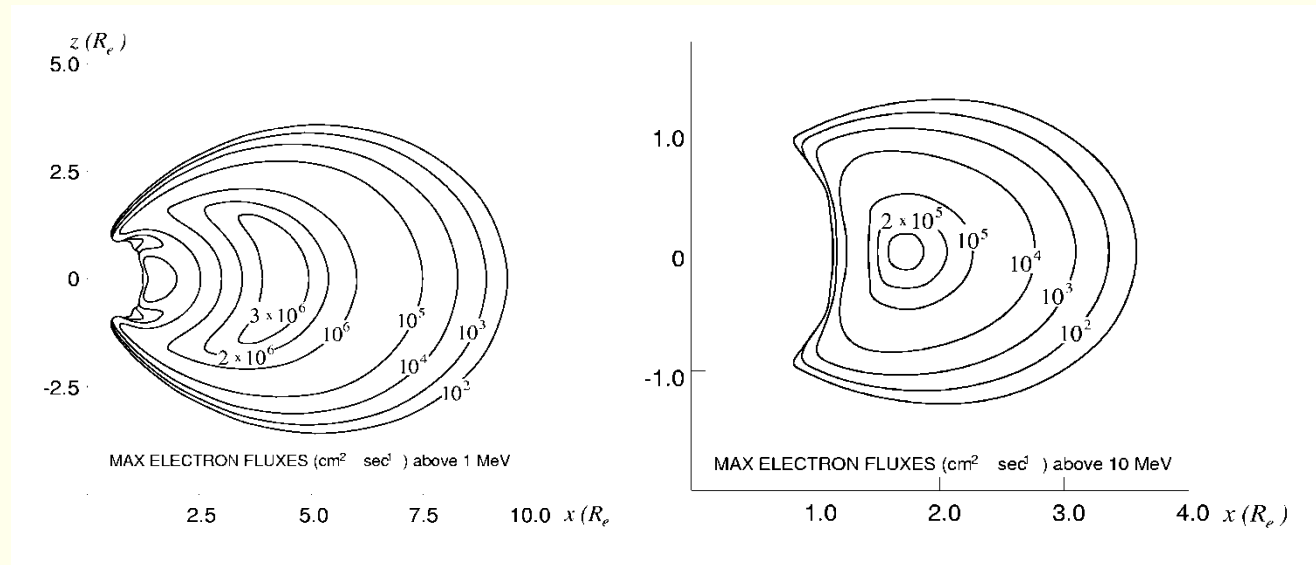ions

electrons

grad B

ring current

Radiation belts

I. Van Allen belts

- Discovered in the 50s , Explorer 1

- Inner belt contains protons with energies of ~30 MeV

- Outer belt (Explorer IV, Pioneer III): electrons, $W > 1.5$ MeV

Radiation belts

MAX ELECTRON FLUXES (cm² sec¹) above 1 MeV

MAX ELECTRON FLUXES (cm² sec¹) above 10 MeV

- At lower energies there is a more or less continous population of energetic particles in the inner magnetosphere. (Inner part of *plasma sheet*)

- source: **CRAND** (Cosmic Ray Albedo Neutron Decay).
- a danger for satellites and astronauts.
- associated with a current (*ring current*) which distorts the inner part of the geomagnetic field.

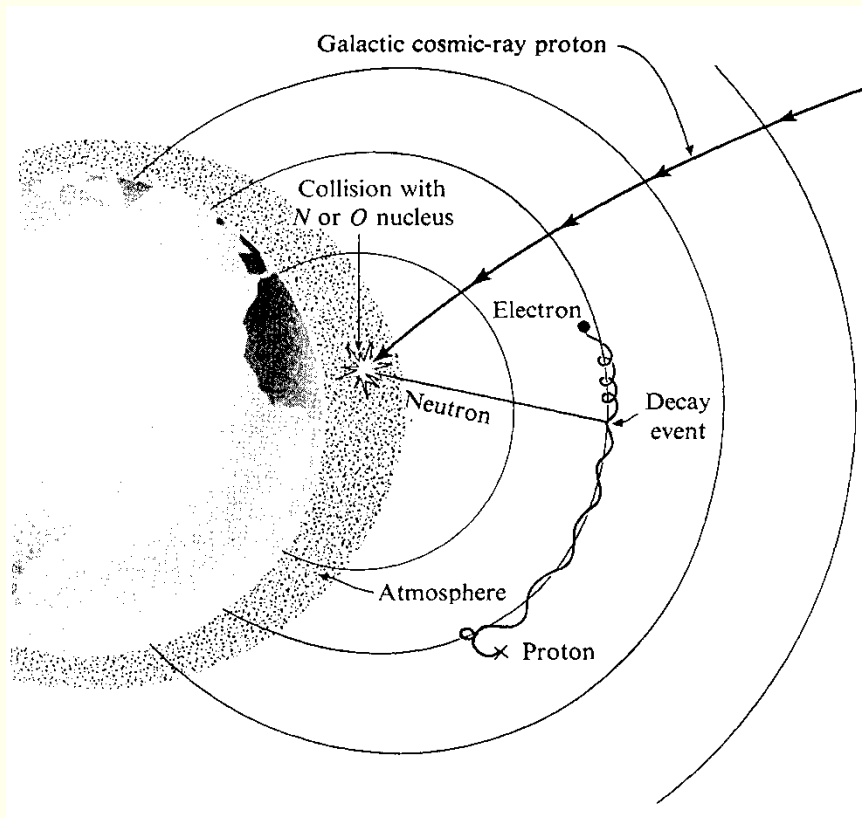# CRAND (Cosmic Ray Albedo Neutron Decay

Figure 8. An illustration of the CRAND process for populating the inner radiation belts [Hess, 1968].

Collisions between cosmic ray particles and the Earth create new particles. Among these are neutrons, that are not affected by the magnetic field. They decay, soom eof them when they happen to be in the radiation belts. The resulting protons and electrons are trapped in the radiation belts.

This contribution to the radiation belts are called the **neutron albedo**.
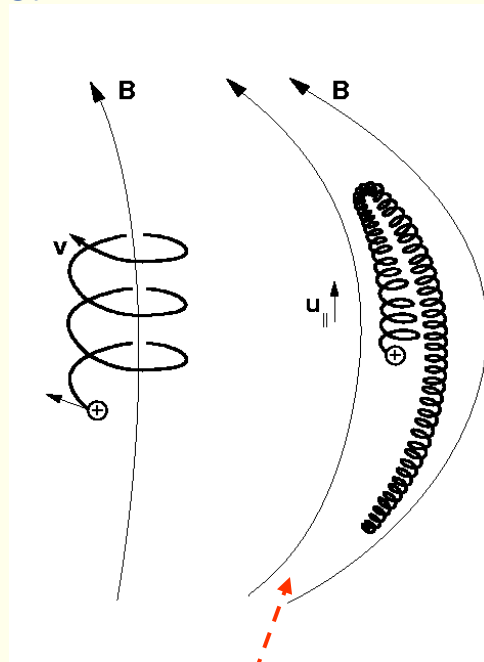
Radiation belts
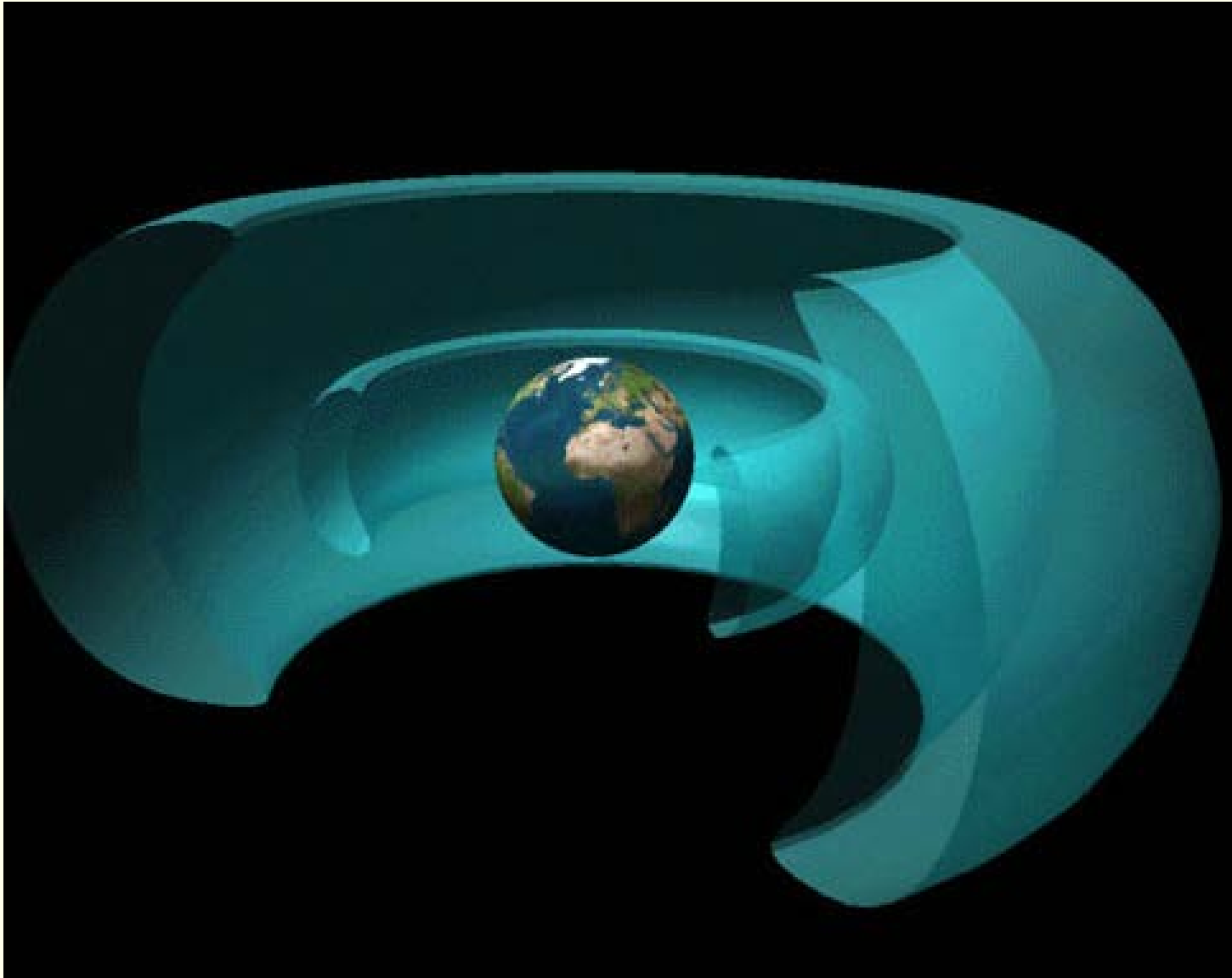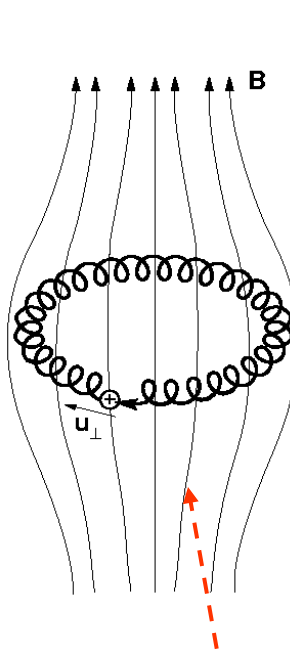
Radiation belts
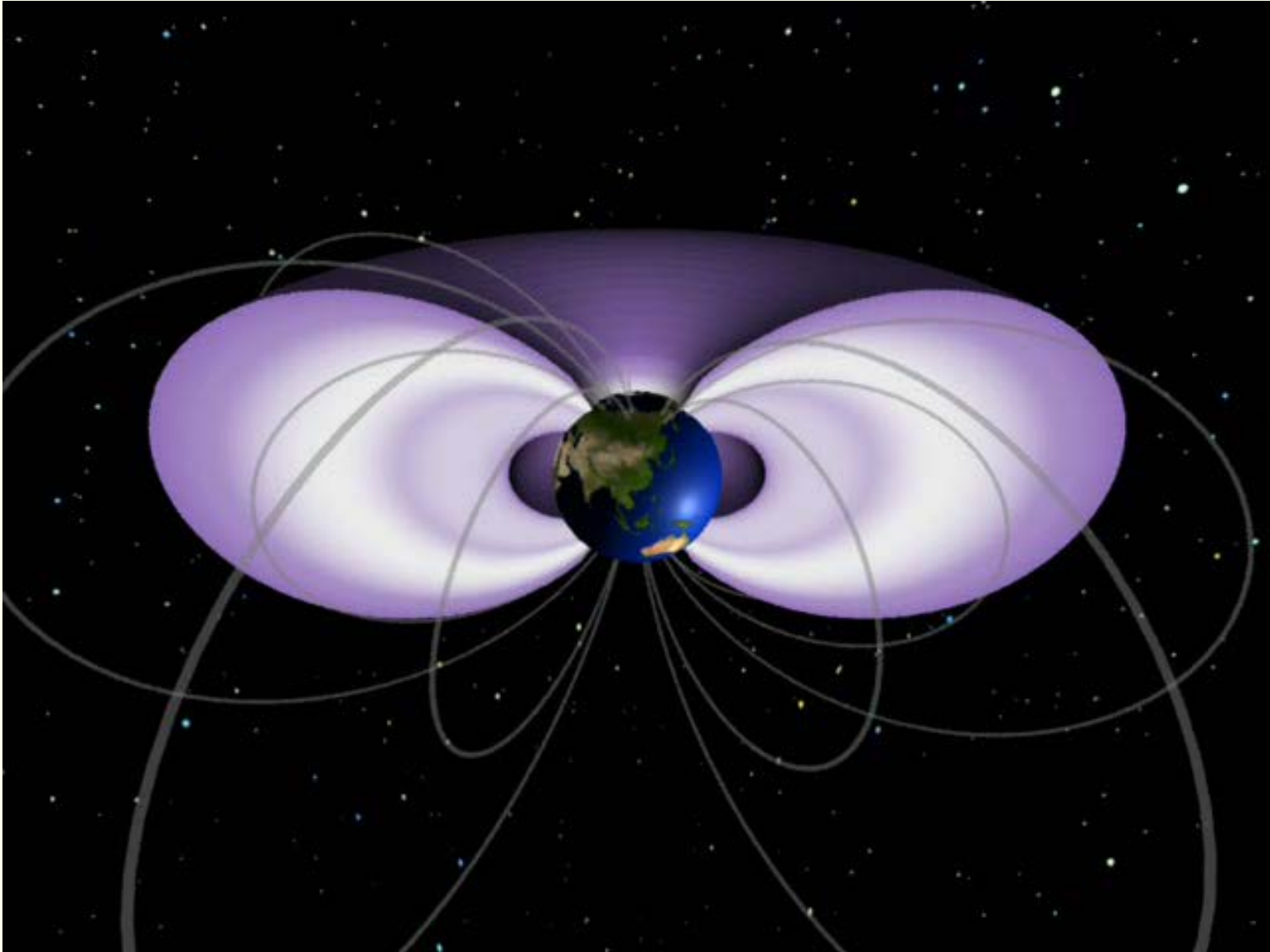
Particle motion in geomagnetic field
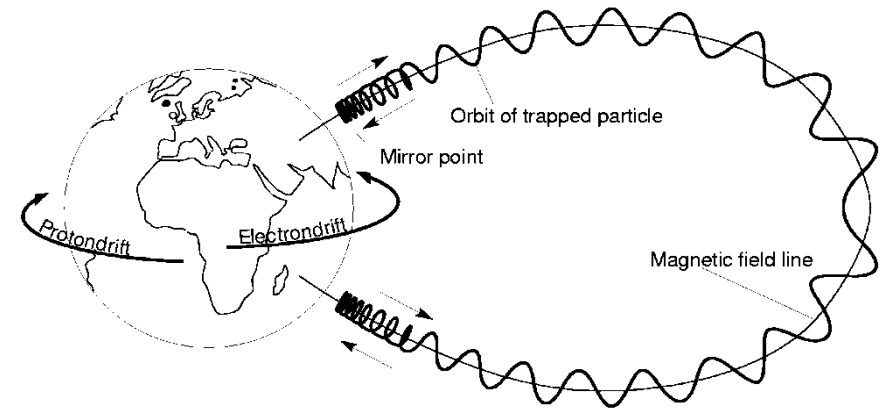
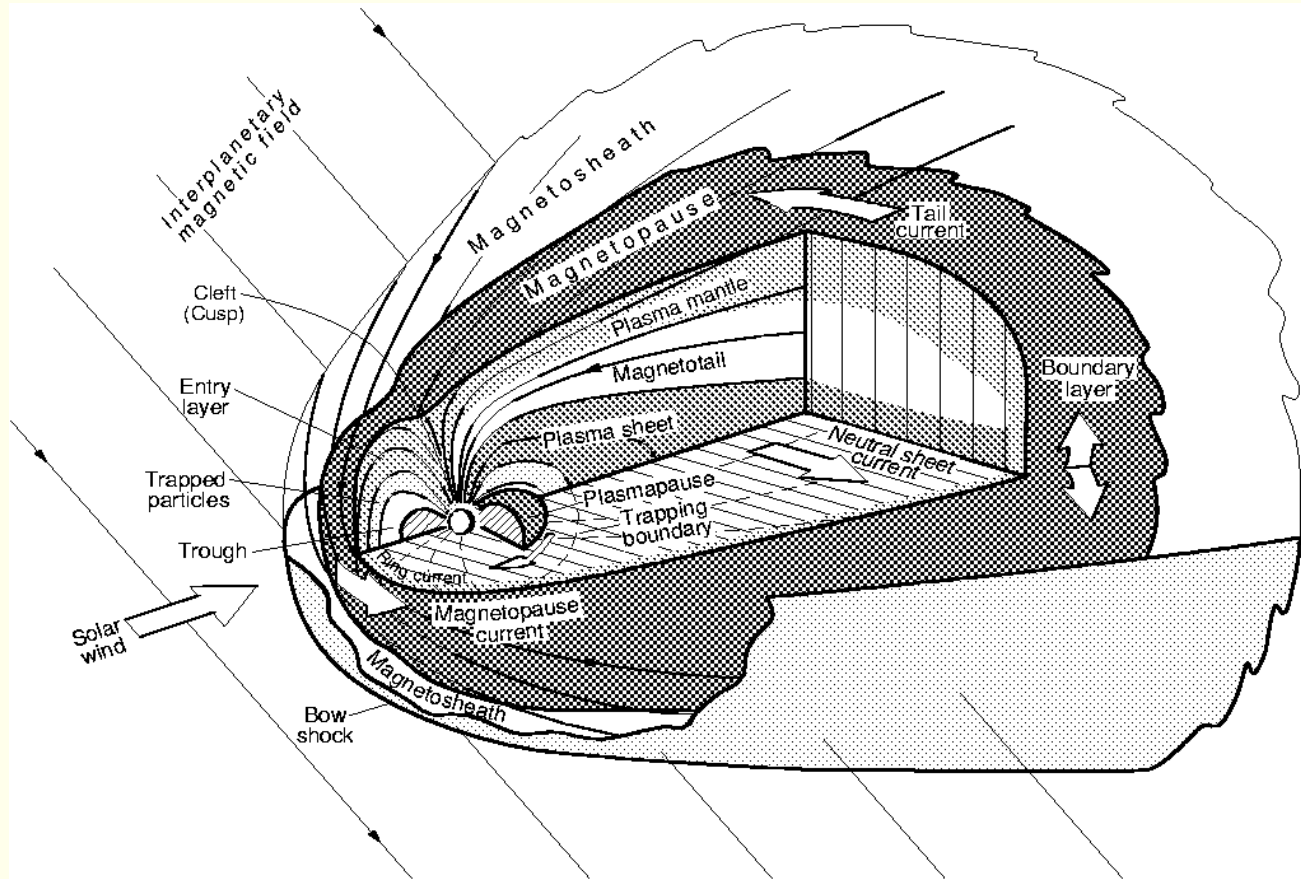longitudinal oscillation

gyration

azimuthal drift

Magnetic mirror
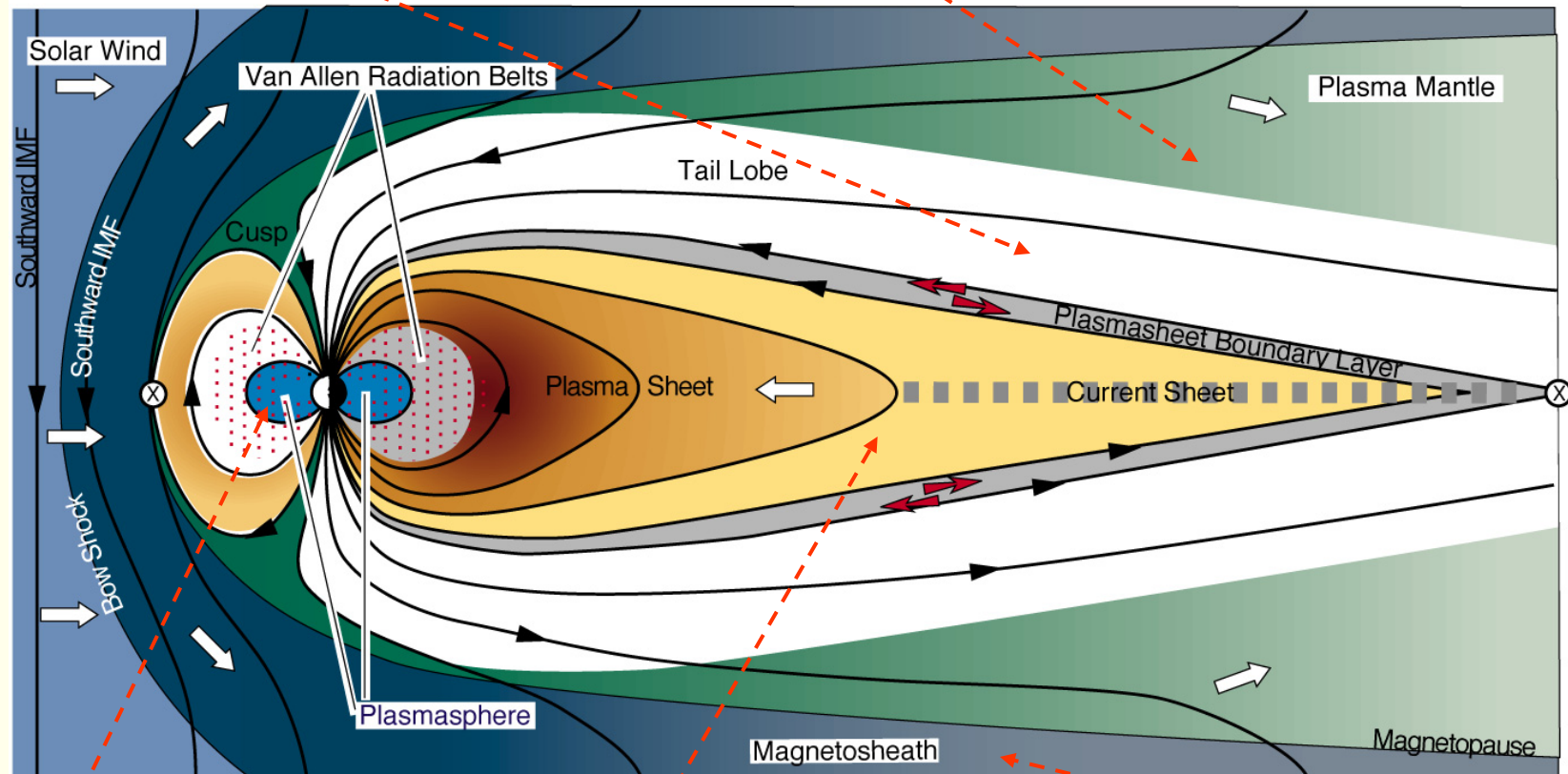
grad B drift

Structure of magnetosphere

- The plasma in the is made up of approximately equal parts of H^+ and O^+.

- Plasma populations organized by geomagnetic field.

- Particles will mirror between northern and southern hemispheres on closed field lines

Magnetospheric structure

polar plumes = tail lobe
$n_e \sim 0{,}01$ cm^{-3}, $T_e \sim 10^6$ K

plasma mantle
$n_e \sim 0{,}1$-1 cm^{-3}, $T_e \sim 10^6$ K

Solar Wind

Van Allen Radiation Belts

Plasma Mantle

Southward IMF

Southward IMF

Cusp

Tail Lobe

Bow Shock

Plasma Sheet

Plasmasheet Boundary Layer

Current Sheet

X

X

Plasmasphere

Magnetosheath

Magnetopause

plasmasphere:
$n_e \sim 10$-100 cm^{-3}, $T_e \sim 1000$ K
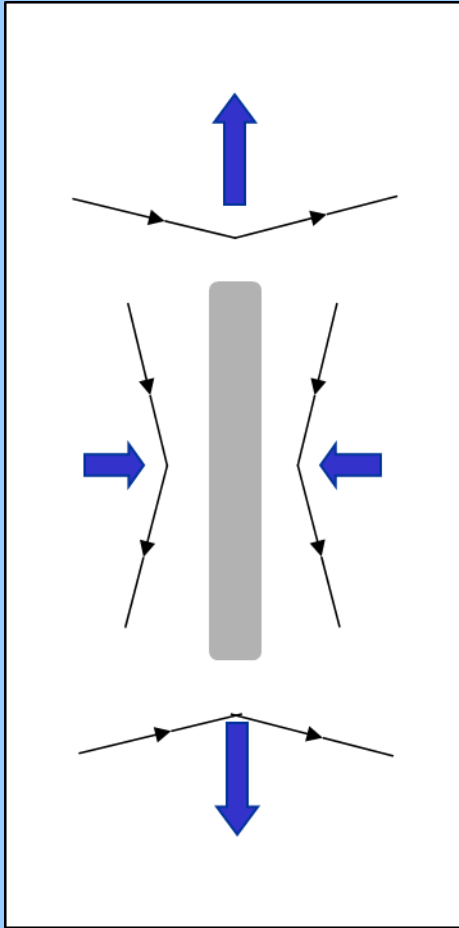
plasma sheet:
$n_e \sim 1$ cm^{-3}, $T_e \sim 10^7$ K

magnetosheath:
$n_e \sim 5$ cm^{-3}, $T_e \sim 10^6$ K
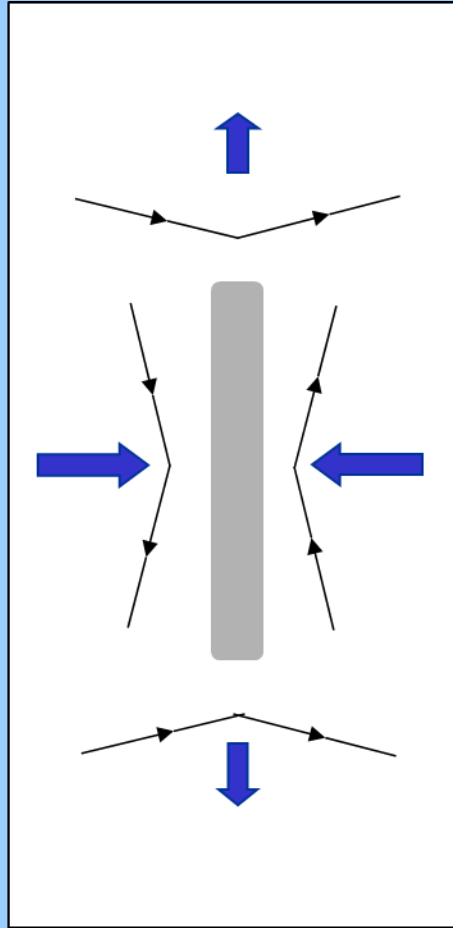
Outflow from the ionosphere
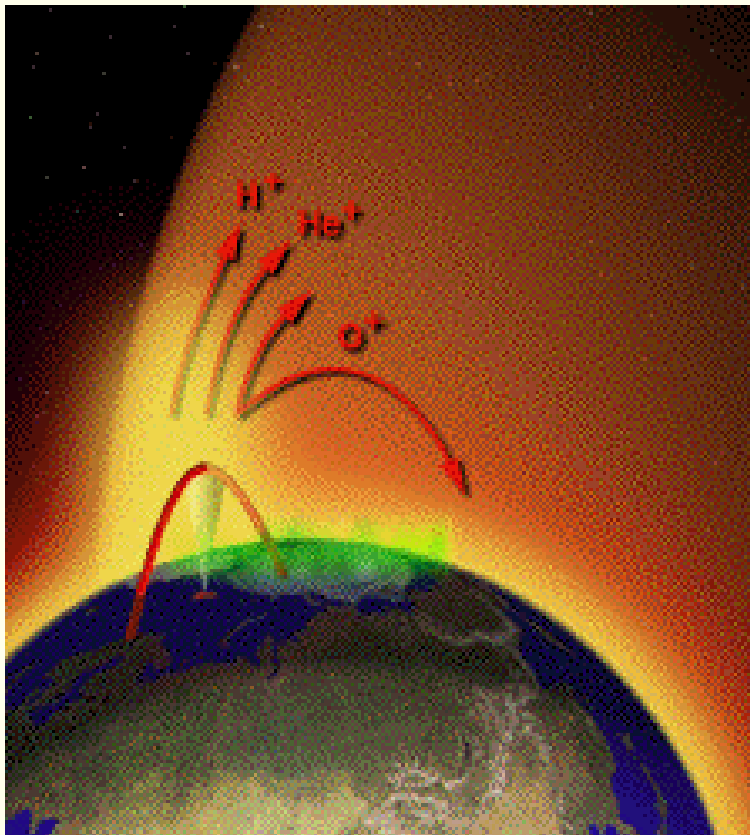
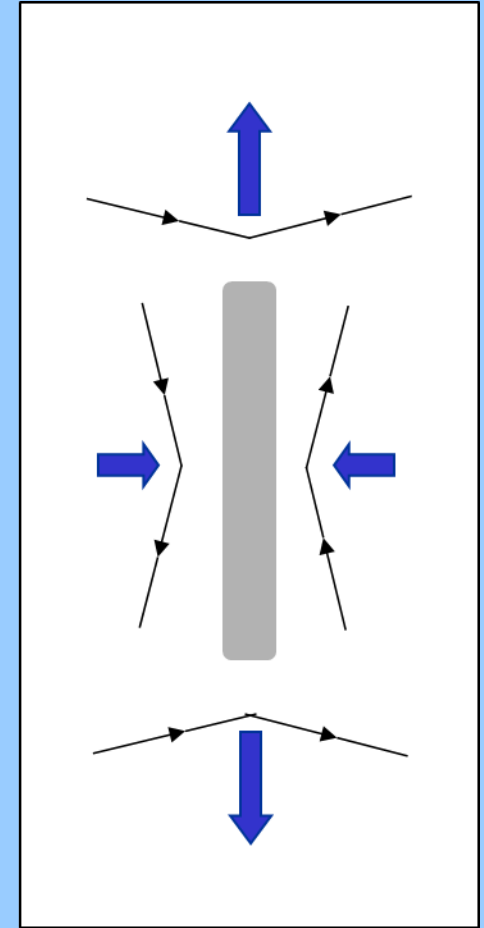An important source for the magnetospheric plasma. Research is ongoing.
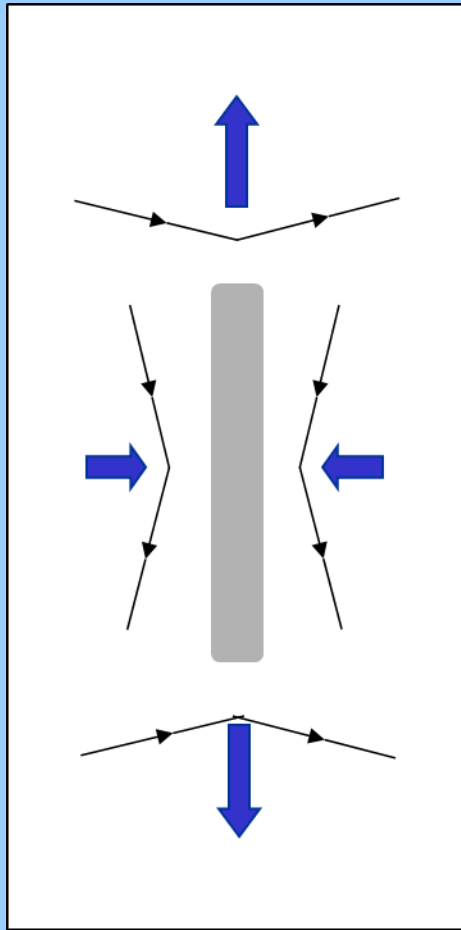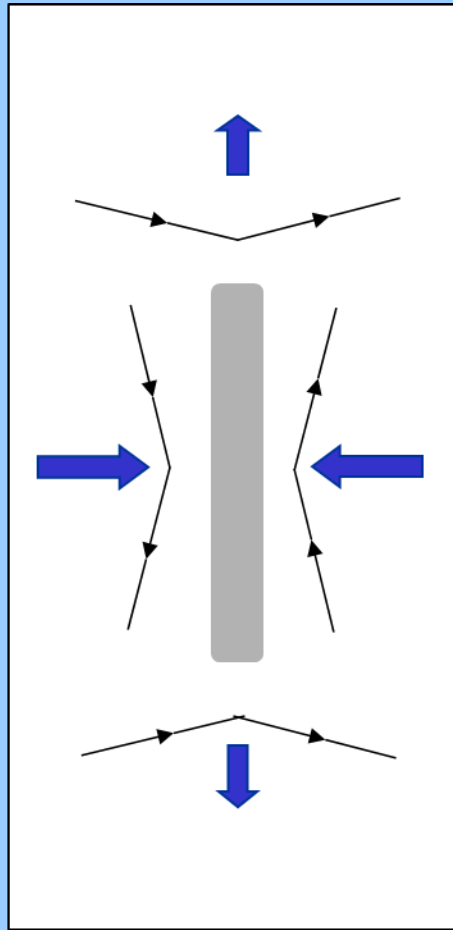
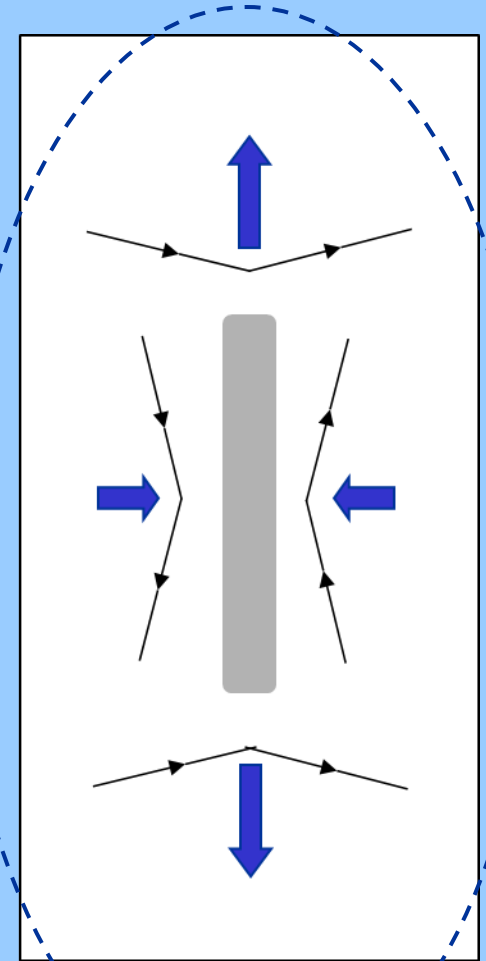# Magnetic reconnection

Green

Yellow

Red

Magnetic reconnection

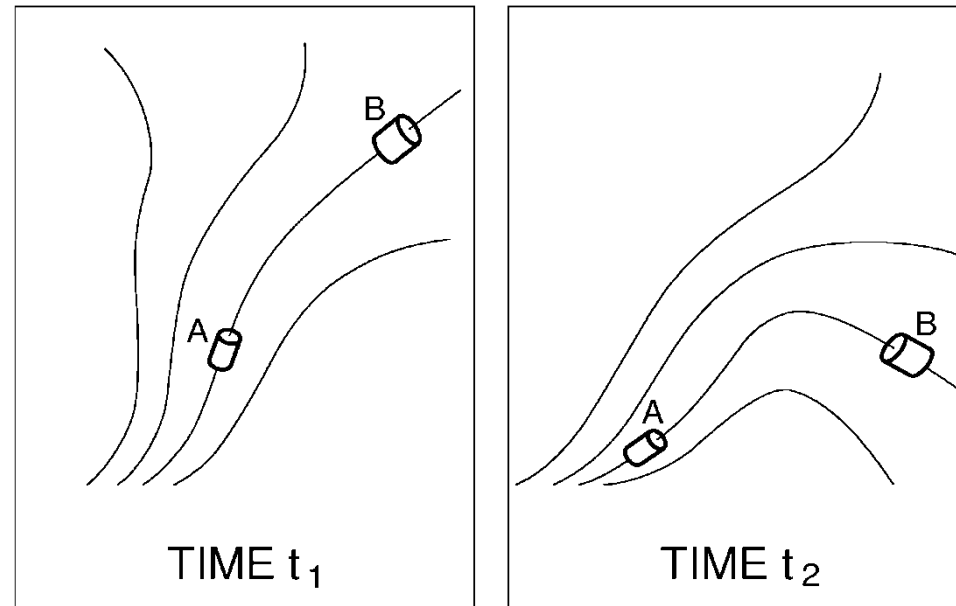

Green

Yellow

Red

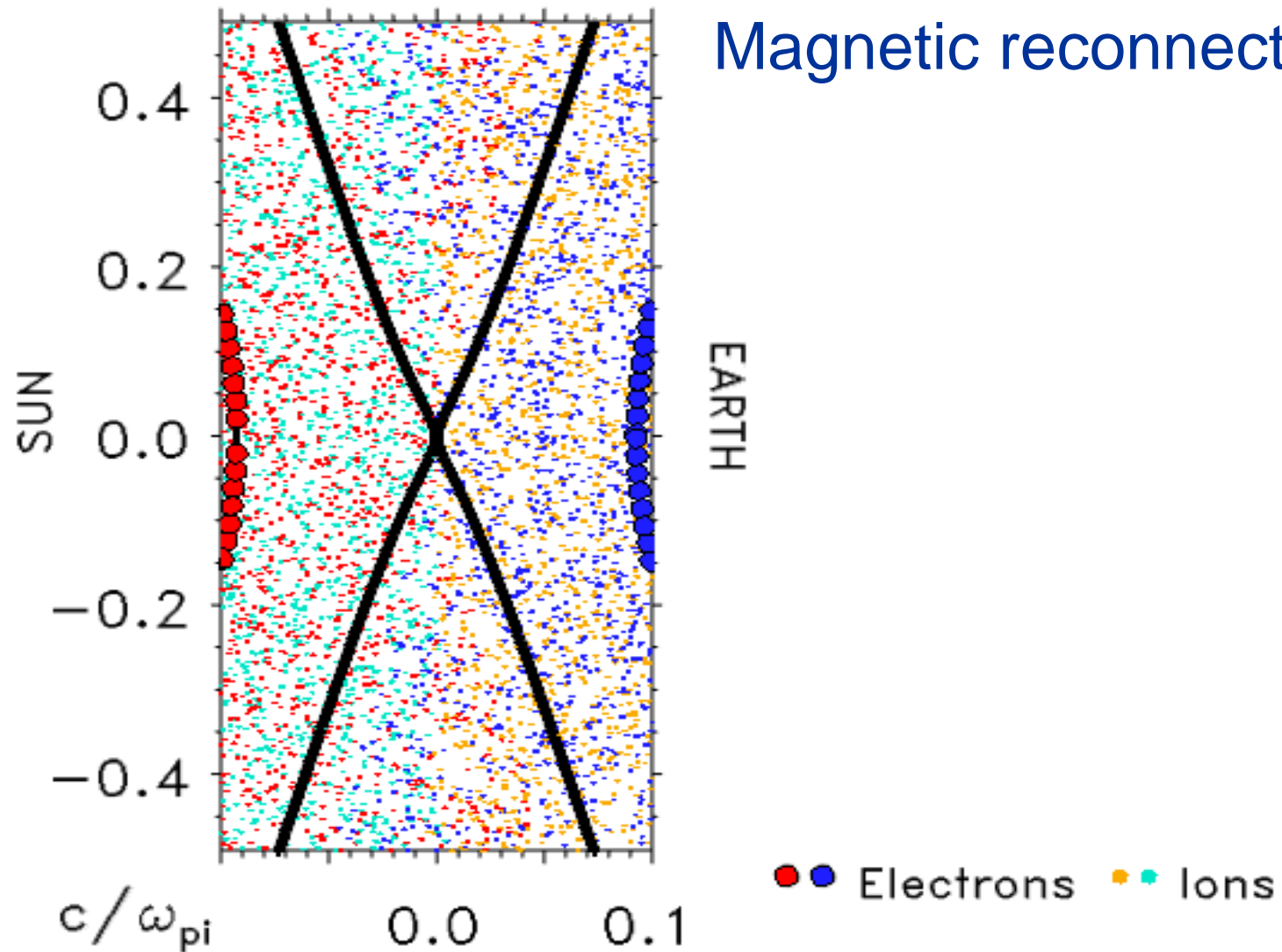# Frozen in magnetic field lines

TIME t_1 TIME t_2

In fluid description of plasma two plasma elements that are connected by a common magnetic field line at time t_1 will be so at any other time t_2.

This applies if the magnetic Reynolds number is large:

$$R_m = \mu_0 \sigma l_c v_c >> 1$$

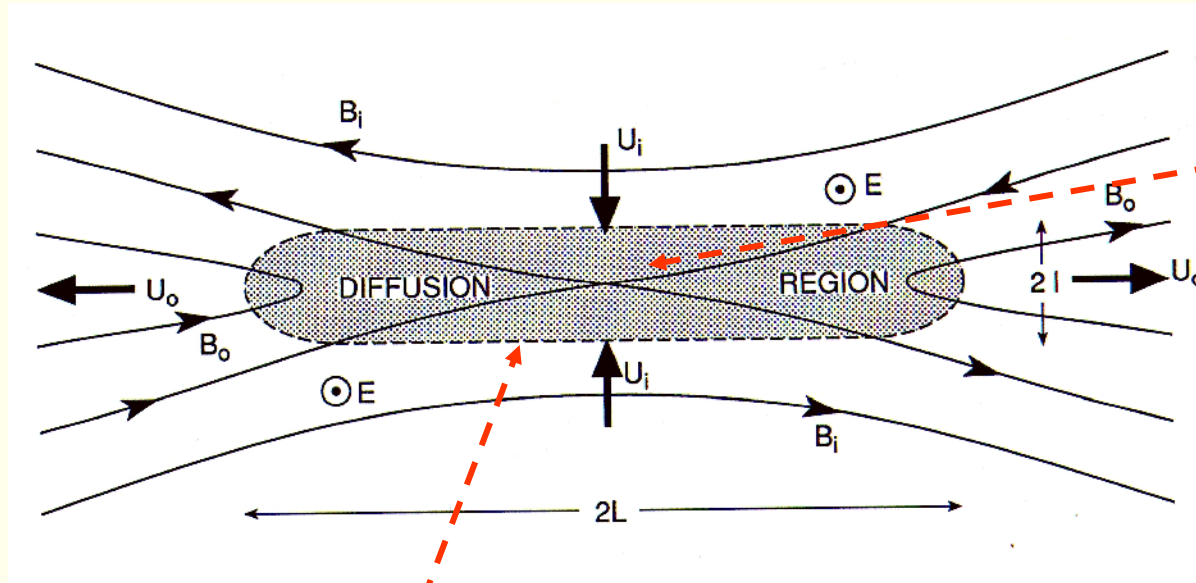*An example of the collective behaviour of plasmas.*

Magnetic reconnection

Reconnection

In 'diffusion region':

$$R_m = \mu_0 \sigma l v \sim 1$$
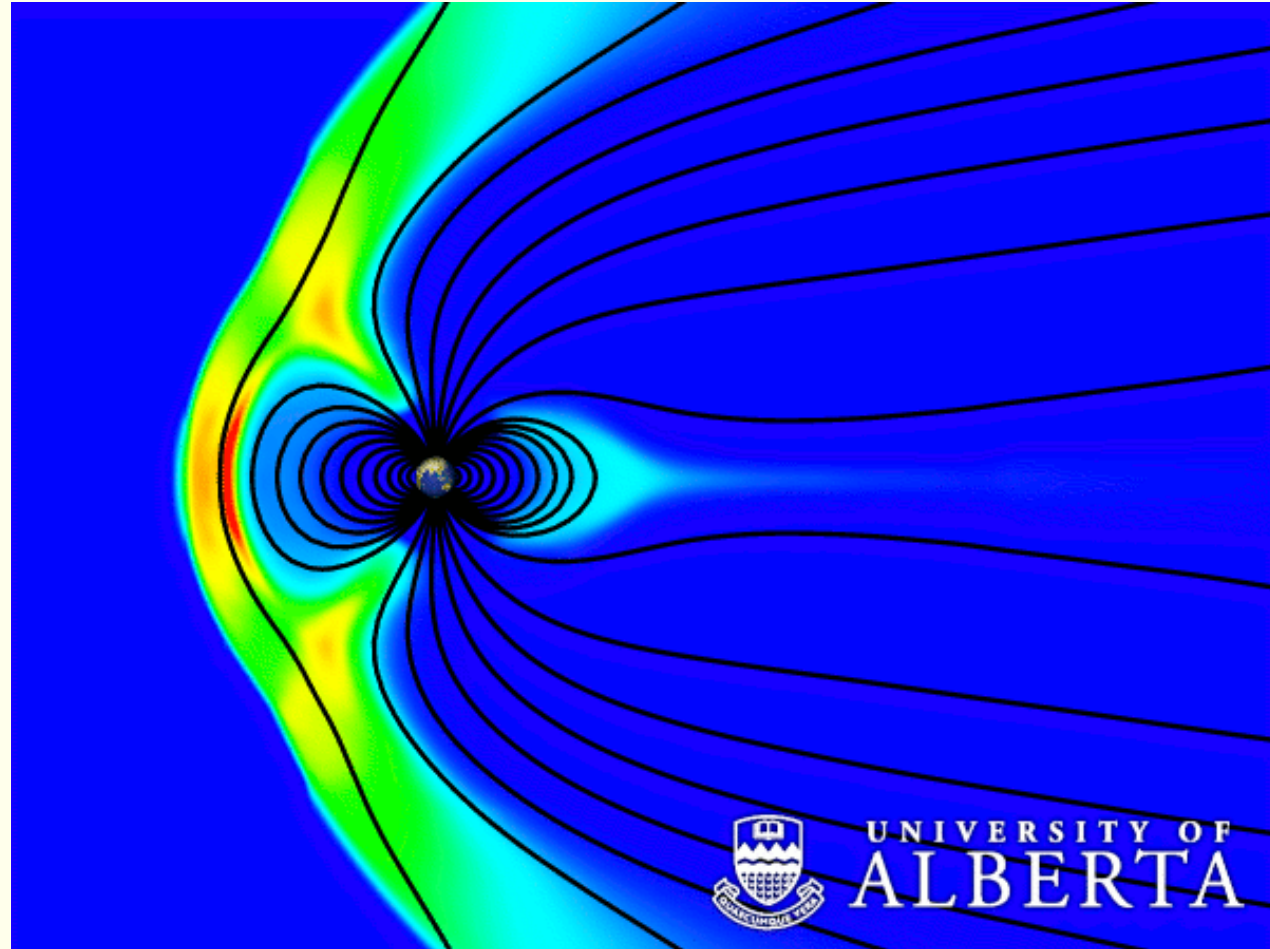
Thus: condition for frozen-in magnetic field breaks down.

A second condition is that there are two regions of magnetic field pointing in *opposite* direction:

- Field lines are "cut" and can be re-connected to other field lines

- **Magnetic energy is transformed into kinetic energy $(U_o \gg U_i)$**

- **Plasma from different field lines can mix**

# Reconnection and plasma convection

Solar wind

Reconnection och plasma convection

- Reconnection on the dayside "re-connects" the solar wind magnetic field and the geomagnetic field

- In this way the plasma convection in the outer magnetosphere is driven

- In the night side a second reconnection region drives the convection in the inner magnetosphere.
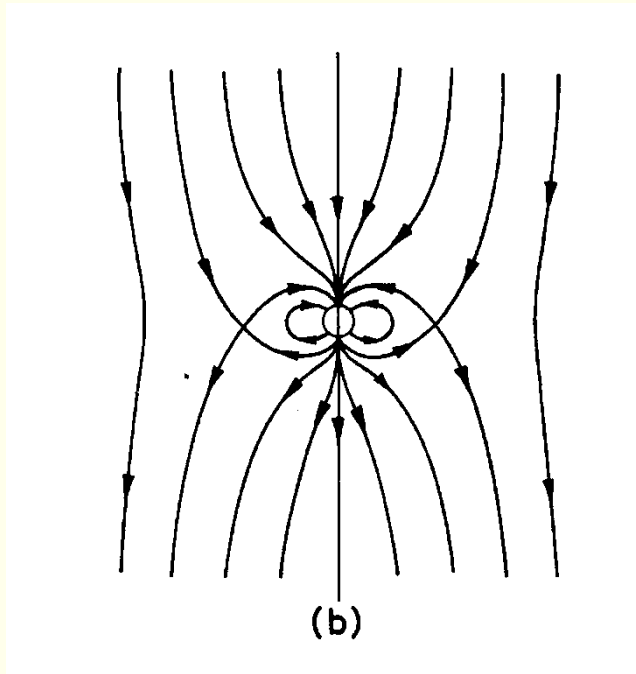The reconnection also heats the plasmasheet plasma.
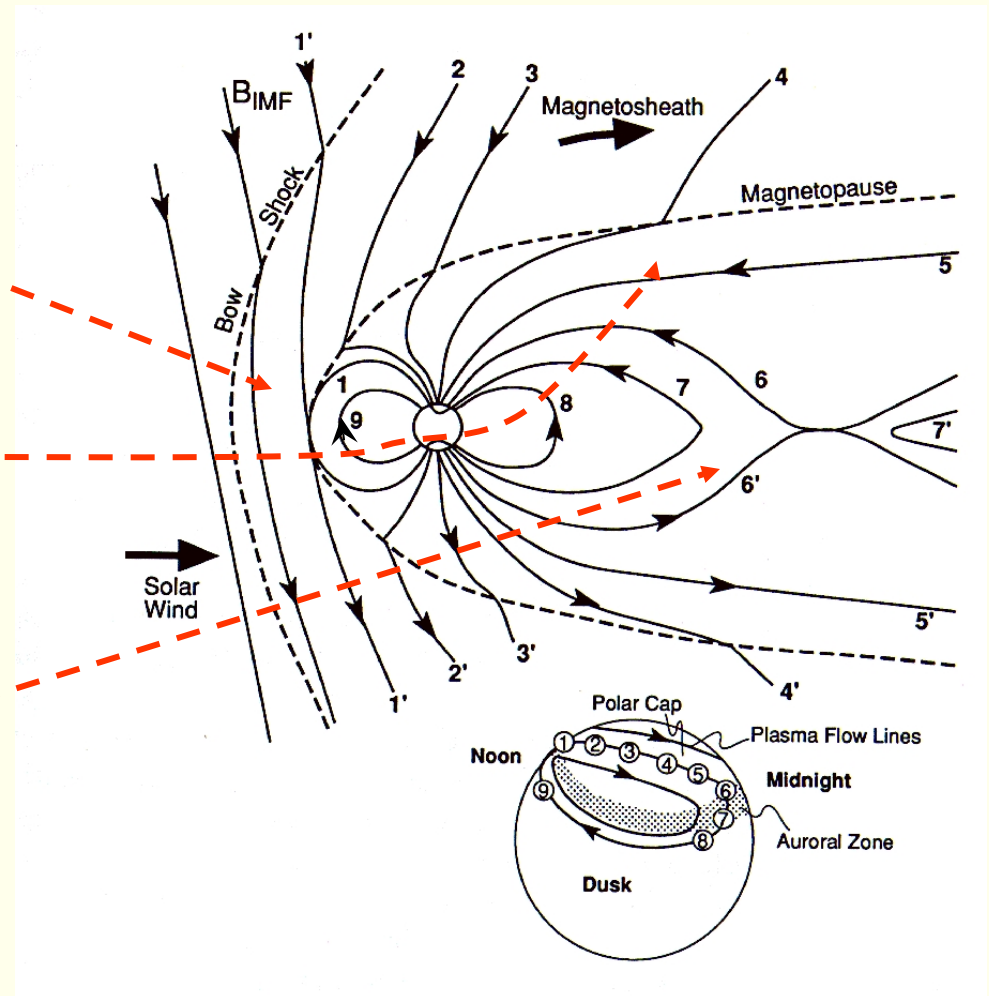
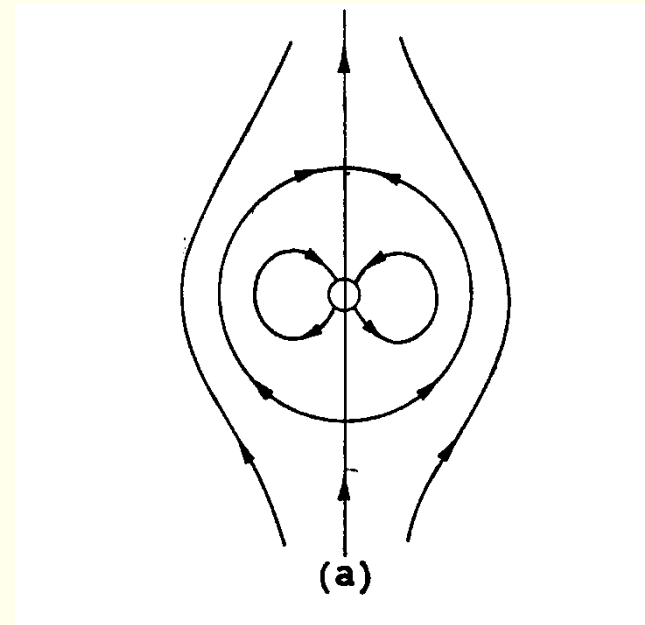# What happens if IMF is northward instead?
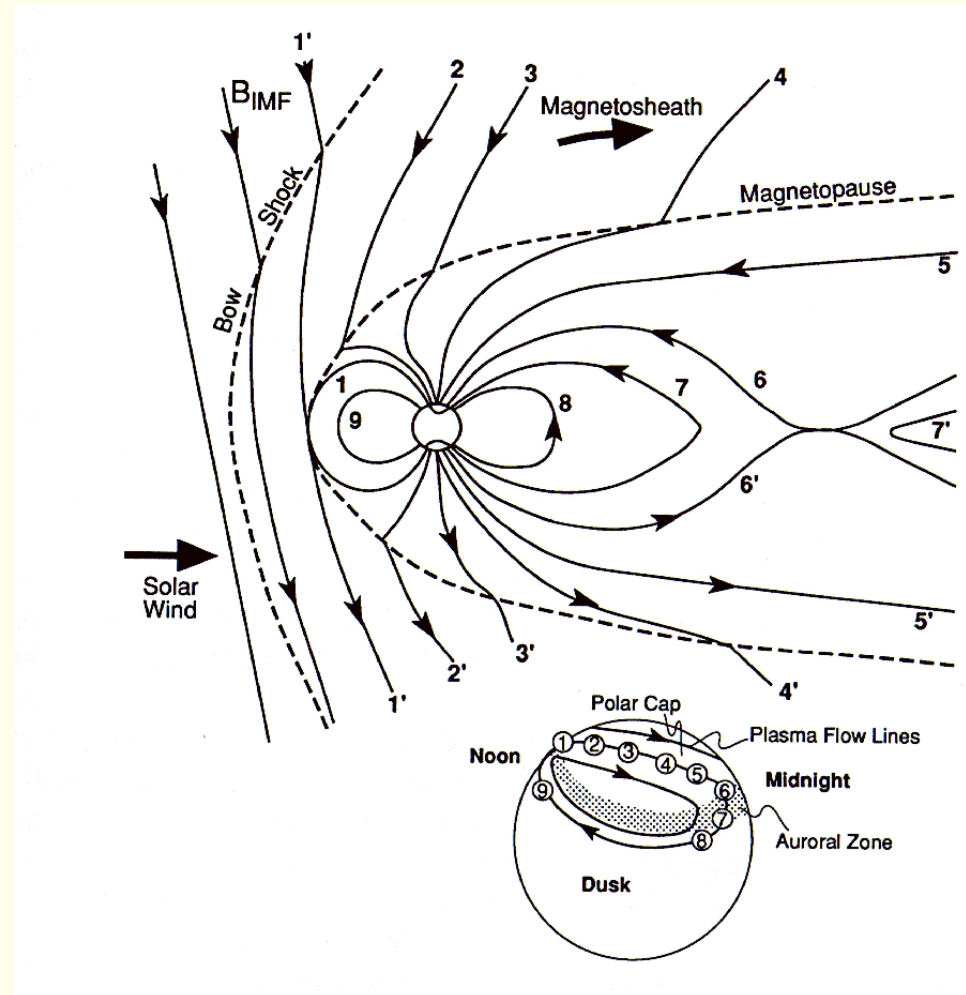
Magnetospheric dynamics

open magnetosphere

closed magnetosphere

southward ⬇ **Interplanetary magnetic field (IMF)** ⬆ **northward**

What do the magnetospheres of the other planets look like?
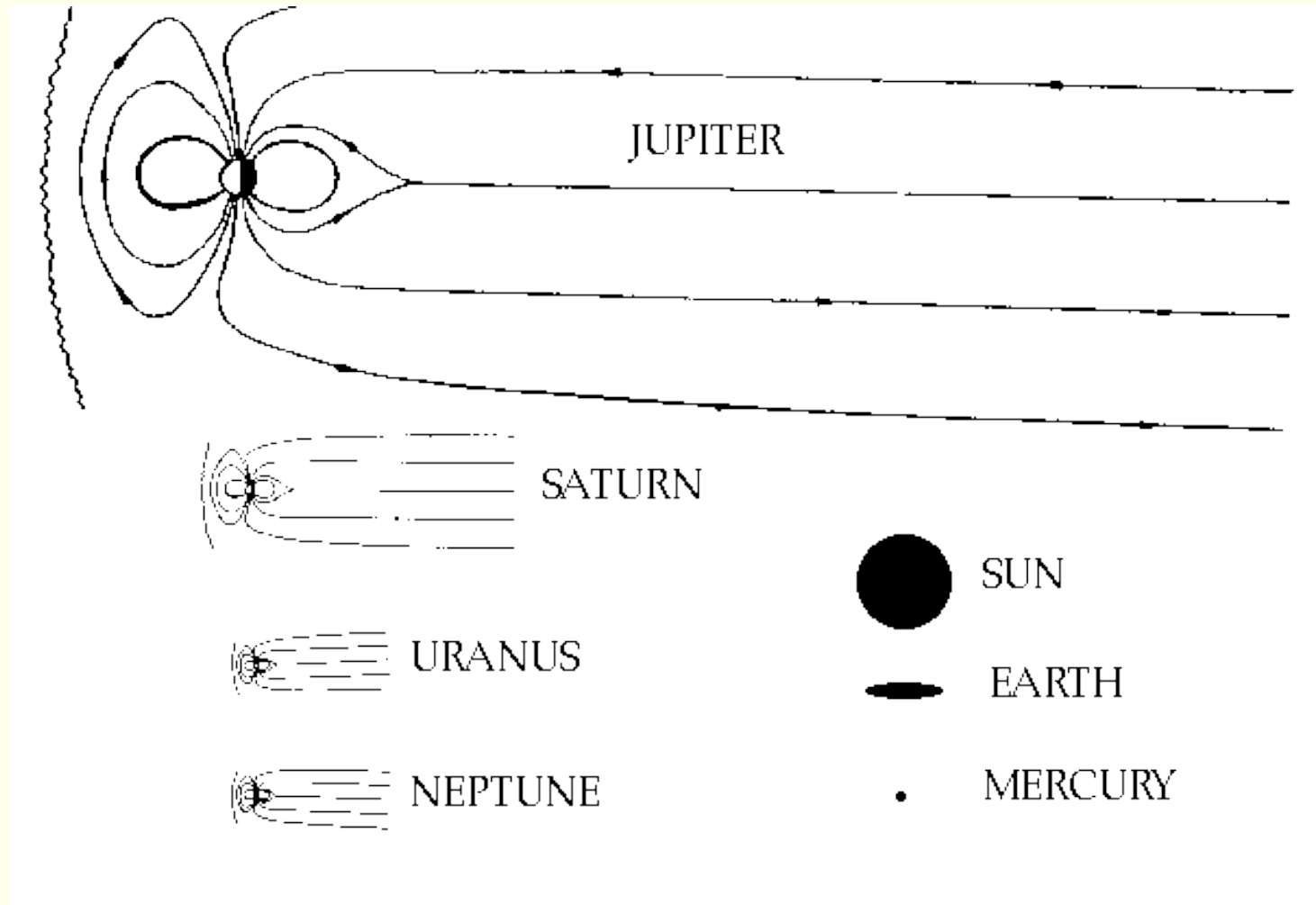
Planetary magnetospheres

	Radius Earth radii	Spin period (days)	Equatorial field strength (μT)	Magnetic axis direction relative to spin axis	Polarity relative to Earth´s	Typical magneto-pause distance (planetary radii)
Mercury	0.38	58.6	0.35	10°	Same	1.1
Venus	0.95	243	< 0.03	-	-	1.1
Earth	1.0	1	31	11.5°	Same	10
Mars	0.53	1.02	0.065	-	Opposite	?
Jupiter	11.18	0.41	410	10°	Opposite	60-100
Saturn	9.42	0.44	40	<1°	Opposite	20-25
Uranus	3.84	0.72	23	60°	Opposite	18-25
Neptune	3.93	0.74	20-150 [*]	47°	Opposite	26 [**]

[*] The magnetic field differs greatly from a dipole field. The numbers represent maximum and minimum strength at the planetary surface

[**] Based on single passage

Very weak magnetic fields

Relative size of the magnetospheres

Comparative magnetospheres

In situ observations

Space probe	Planets	Observations
Mariner 10	Mercury	*1974 – 1975*
Messenger *	Mercury	*2008 –*
Pioneer 10,11	Jupiter, Saturn	*1973 – 1979*
Voyager 1,2	Jupiter, Saturn, Uranus, Neptune	*1977 – 1989*
Ulysses	Jupiter	*1992*
Galileo*	Jupiter	*1995 – 2003*
Cassini*	Jupiter, Saturn	*2004 –*
New Horizons	Jupiter	*2007*

* Orbiters

Galileo

New Horizons

Messenger

Mariner 10

Ulysses

Pioneer 10
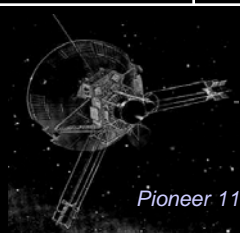
Pioneer 11

Voyager 1 and 2
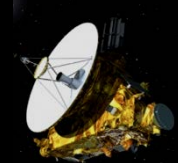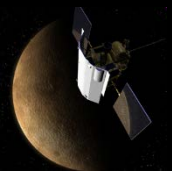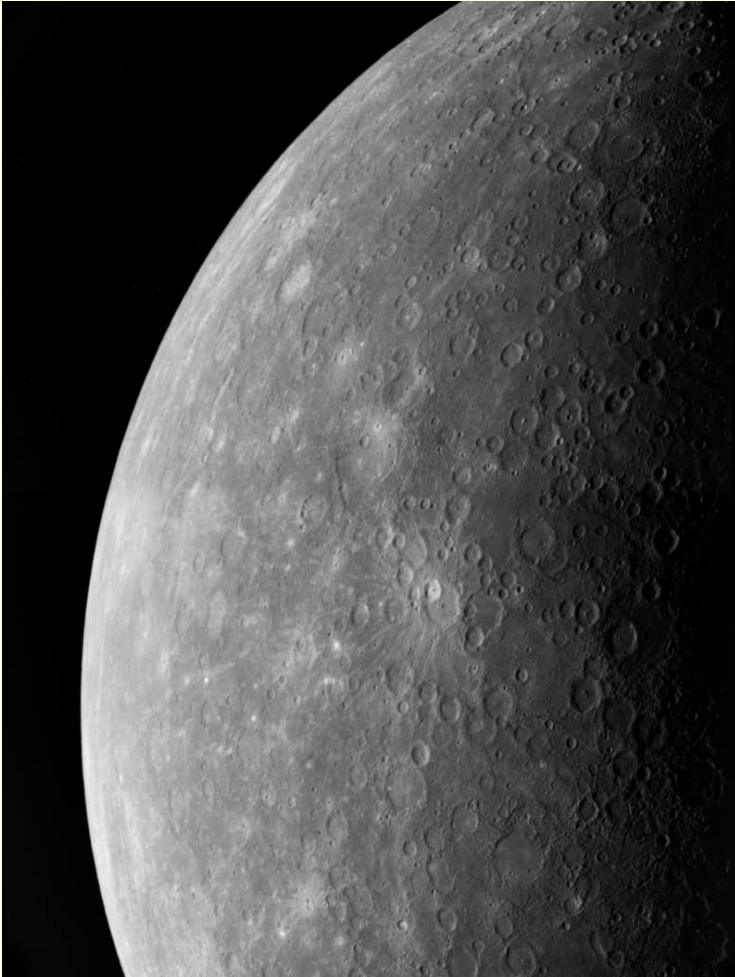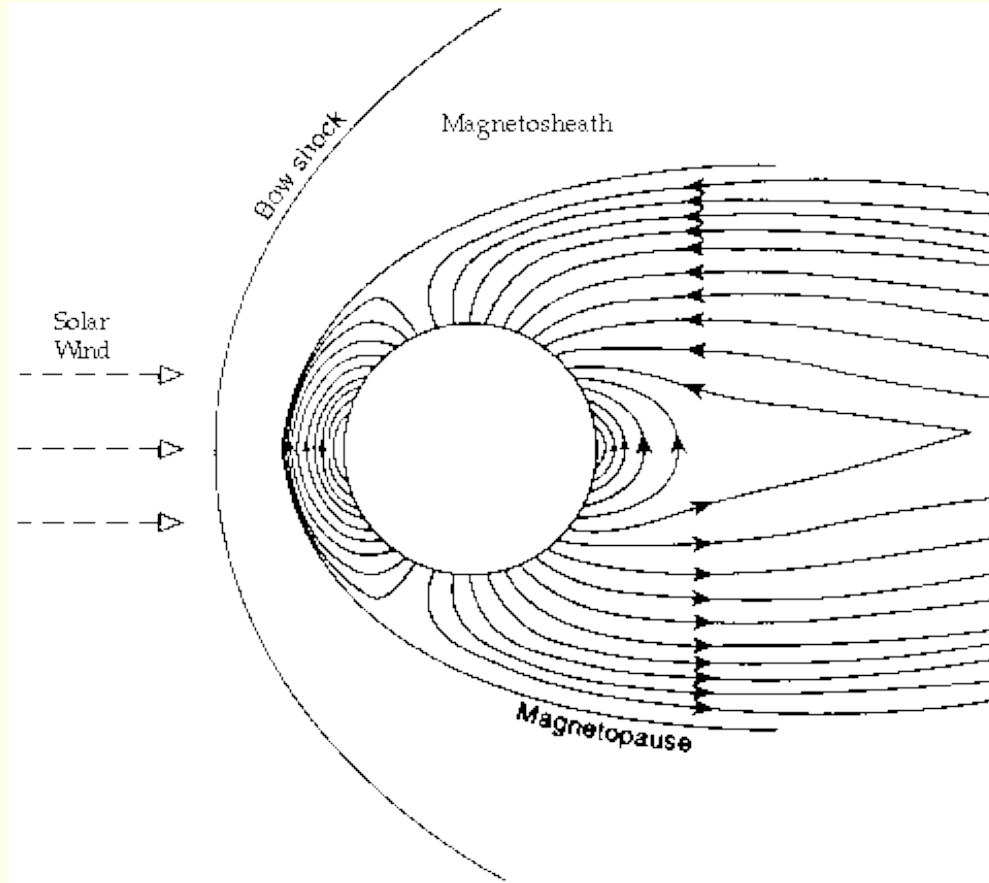
Cassini

Mercury

Photo from Mariner 10

- $r_M = 0,38\ r_E$

- $m_M = 0,06\ m_E$

- distance from sun: 0,39 AU

- no or extremely thin atmosphere

Mercury's magnetosphere

- rather large magnetic field

- the high solar wind density close to the sun makes the magneto-sphere very small
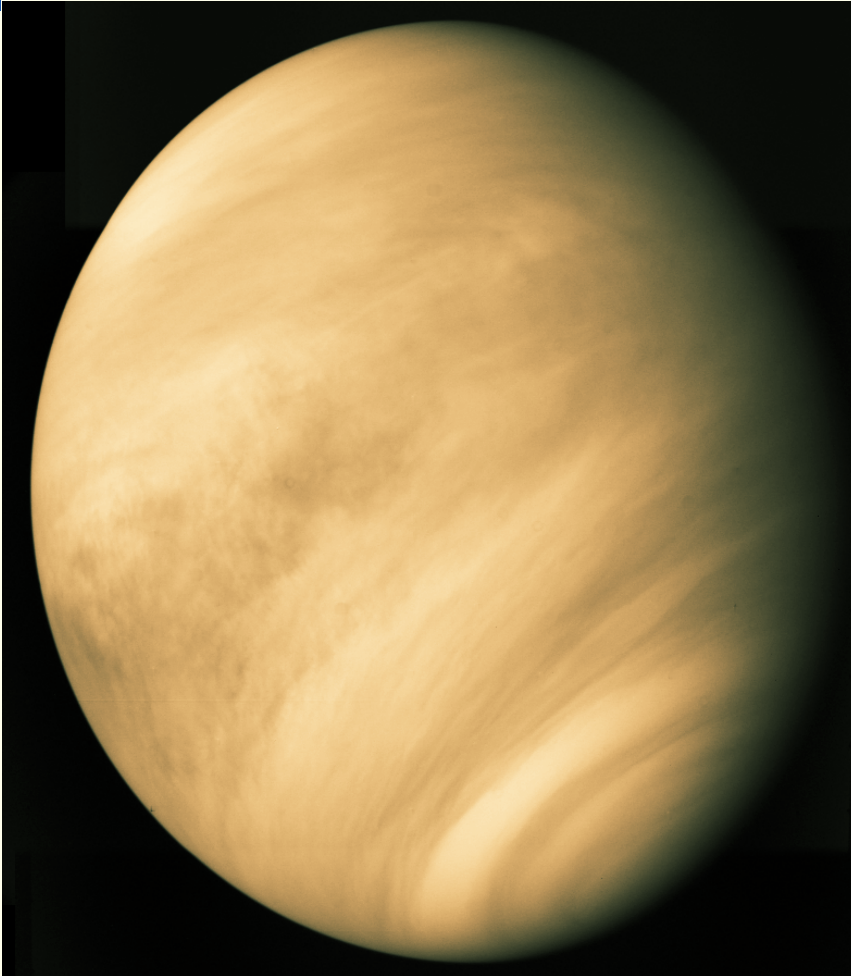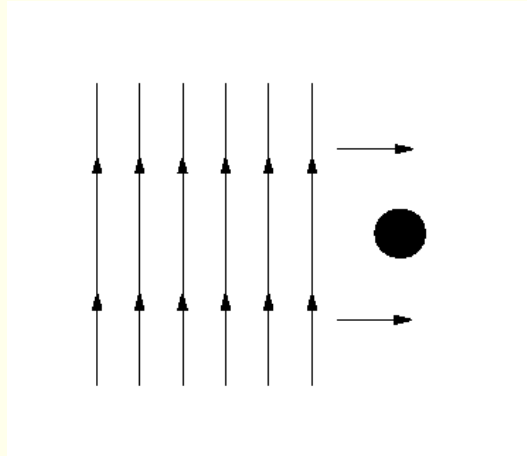
- no ionosphere

Venus

Photo from Galileo

- $r_V = 0{,}95\ r_E$

- $m_V = 0{,}82\ m_E$

- distance from sun : 0,72 AU

- very dense atmosphere
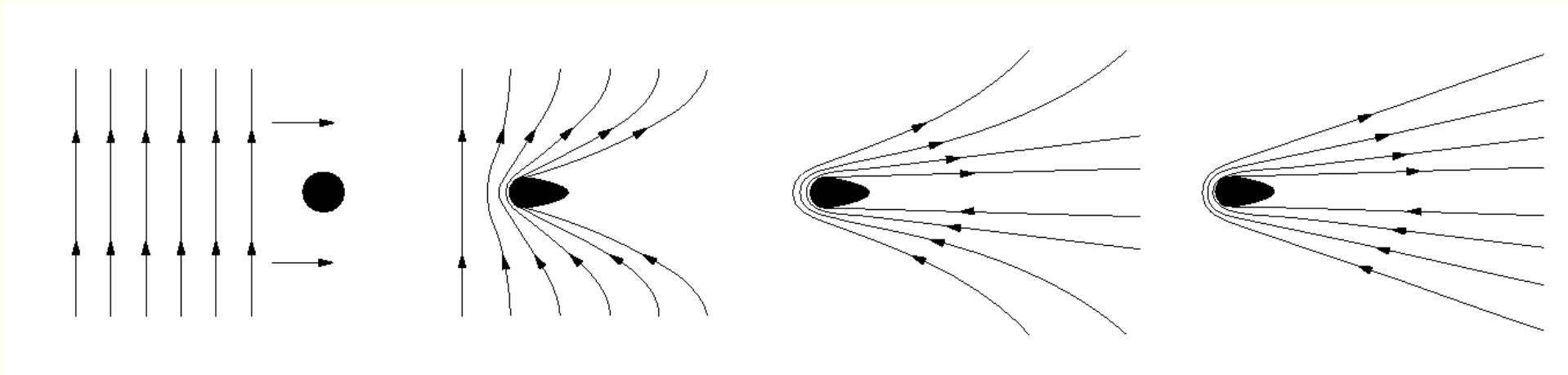
  – ~ 90 atm

  – 96% CO_2

- very weak magnetic field

Comets, induced magnetotail

- The *coma* of the comet is ionized when the comet gets close to sun

What will happen when the interplanetary magnetic field (which is frozen into the solar wind) hits the coma?

Comets, induced magnetotail

- The *coma* of the comet is ionized when the comet gets close to sun

- This plasma stops the field lines from passing the comet, due to the frozen-in magnetic field

- Venus and Mars have similar induced, weak "magnetospheres"

Mars

Photo from Hubble Space Telescope

- $r_M = 0{,}53\ r_E$

- $m_M = 0{,}11\ m_E$

- distance from sun : 1,52 AU

- very thin atmosphere
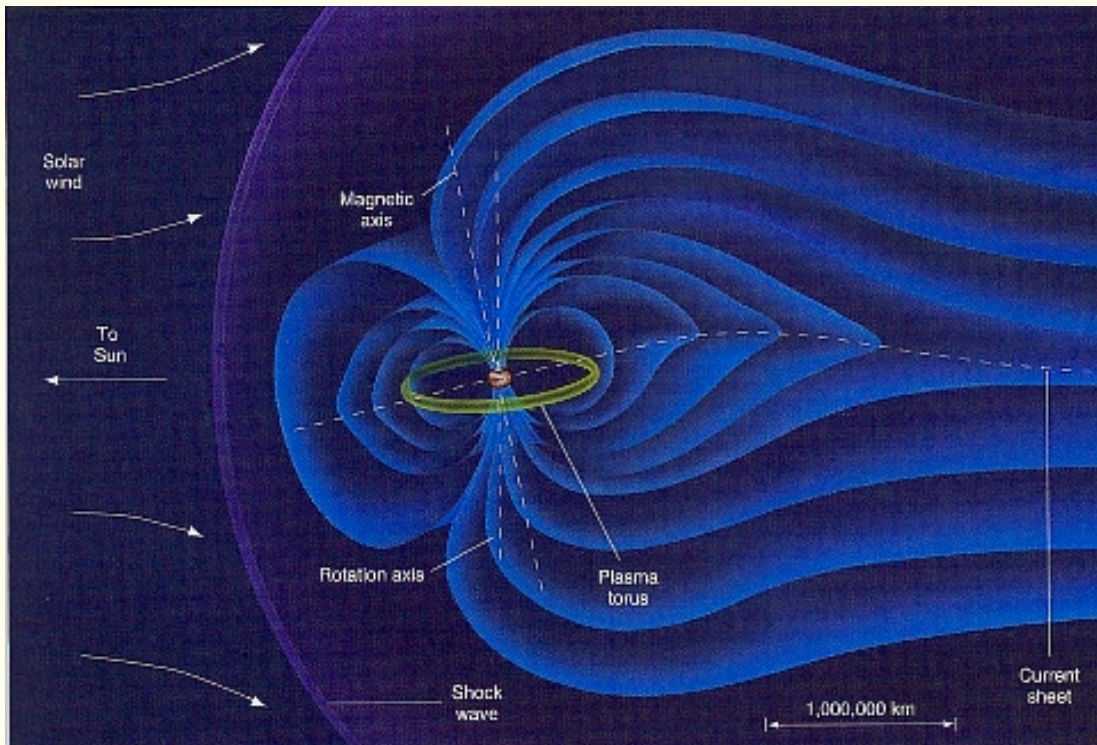
  - ~ 0.01 atm.

  - 95% CO_2

- very weak magnetic field
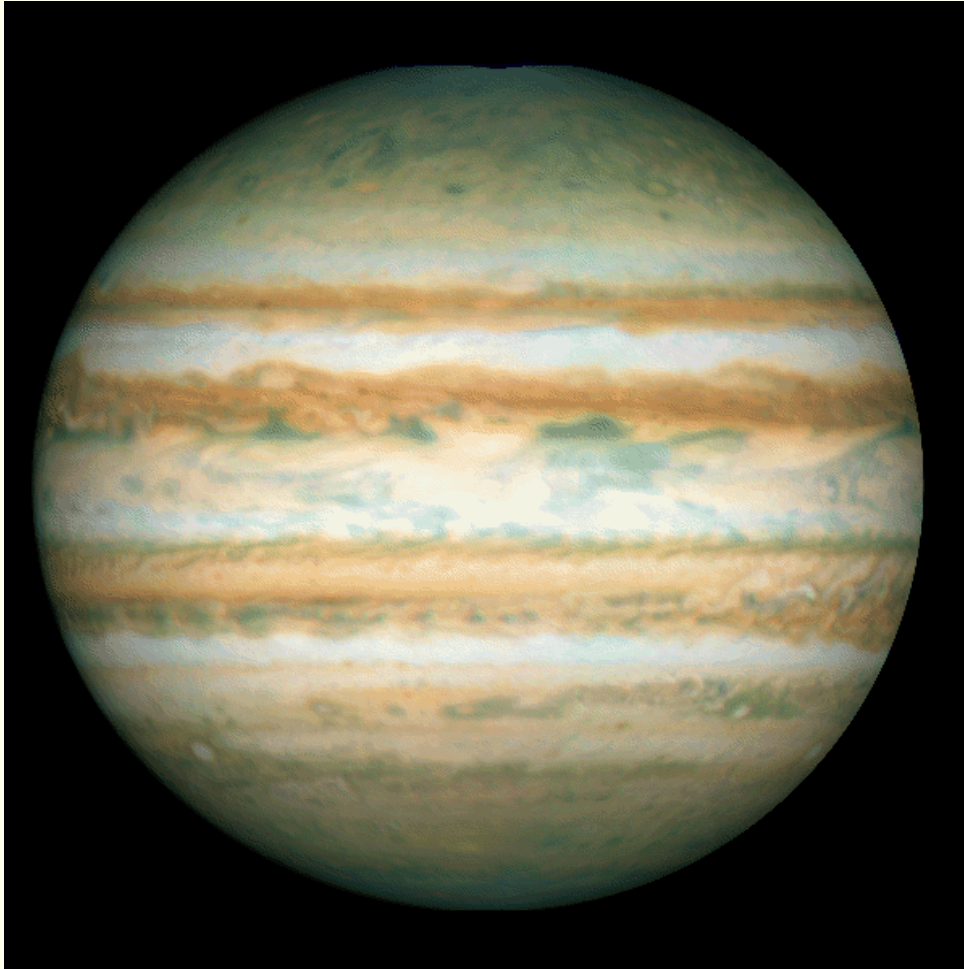
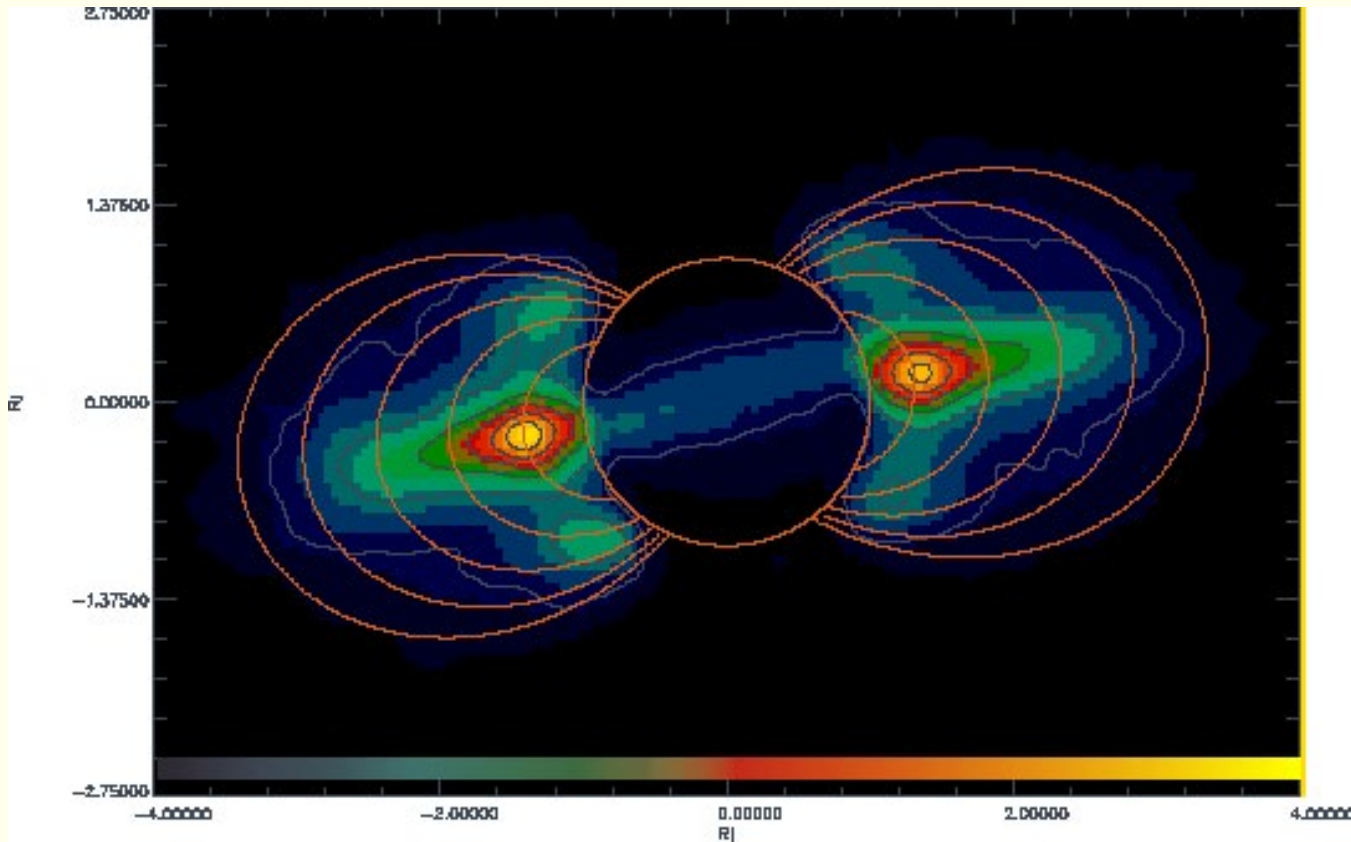# Jupiter

Photo from Hubble Space Telescope

- $r_J = 11{,}2 \, r_E$

- $m_J = 318 \, m_E$

- distance from sun: 5,20 AU

- gas giant with very dense atmosphere containing hydrogen, helium, ammonium, methane, etc.

- ~ 60 moons (+ weak ring system)

Jupiter's magnetosphere

- high plasma density, Io is an important source

- plasma pressure thus becomes an important factor for balancing the solar wind pressure

- the plasma co-rotates with Jupiter, which gives the magnetosphere a flattened look

Syncrotron radiation from Jupiter's radiation belts

- Gyrating electrons emit "syncrotron radiation" with frequencies ~ $f_{ce} = eB/(2\pi m_e)$

- The emitted power is proportional to the electron temperature:

  $$P = CT_e$$

- In this way you can get a picture of the radiation belts

Galilean satellites
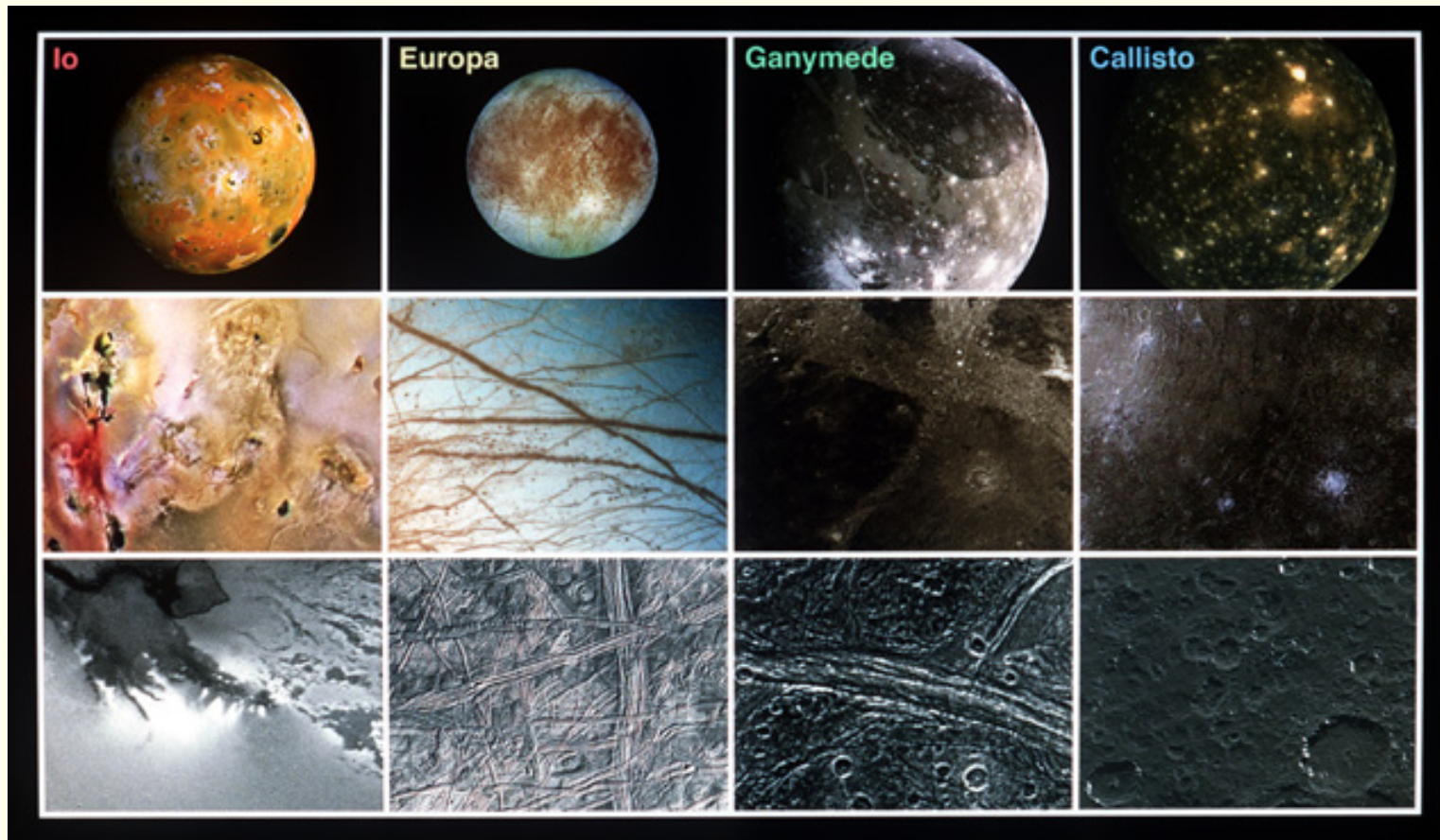
Volcanic activity, source for plasma.

Oceans under the ice?

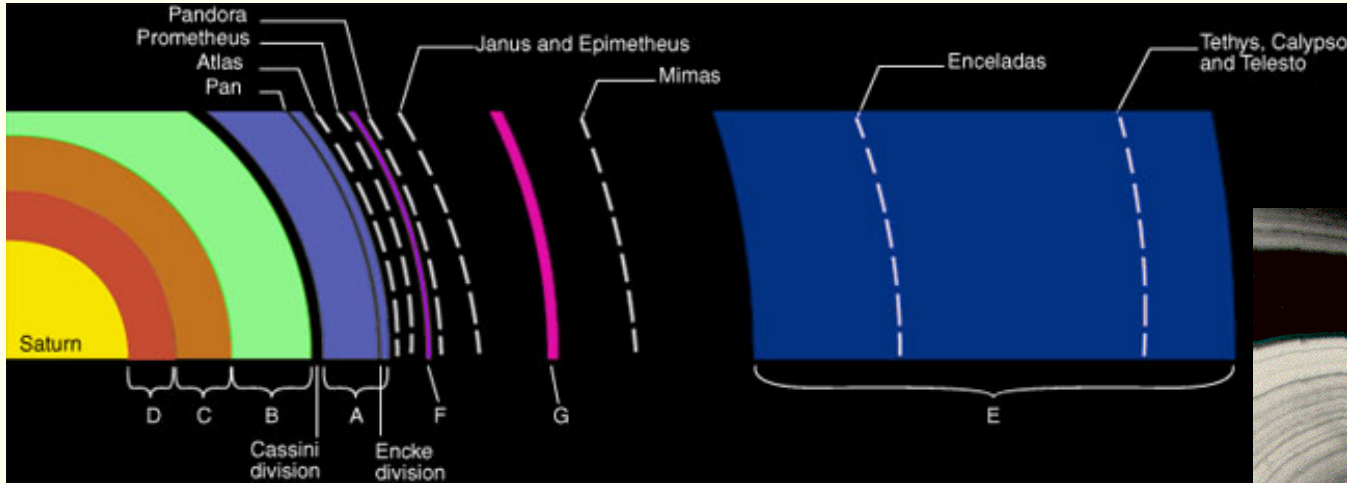Has its own magnetosphere the size of Mercury's

Weak magnetic field

Saturn
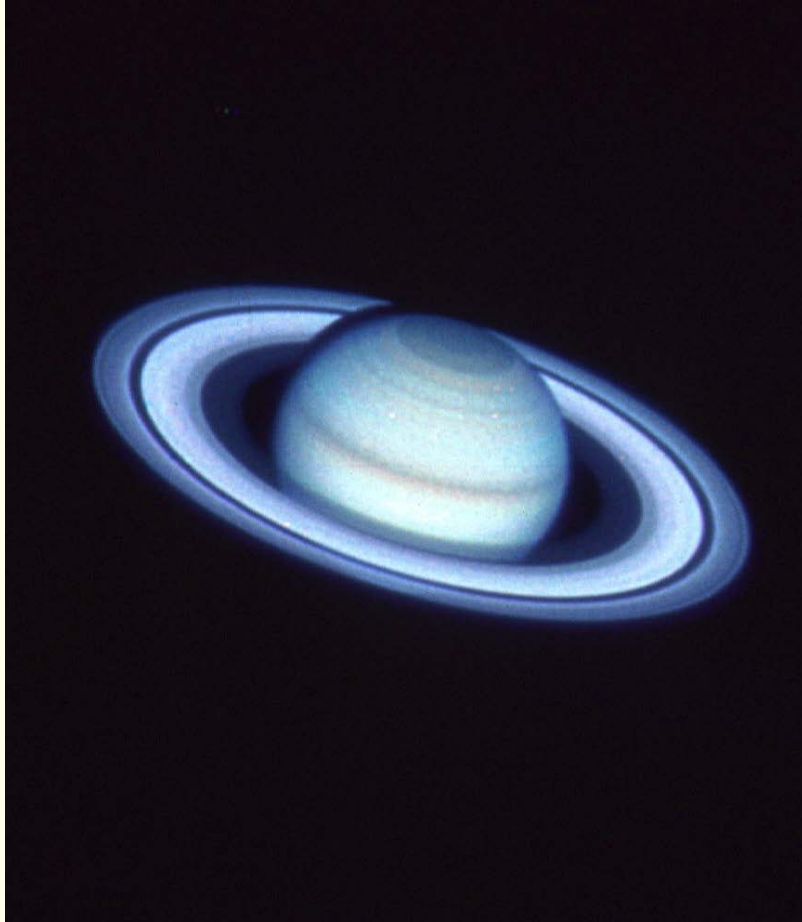
Photo from Hubble Space Telescope

- $r_s = 9,42\ r_E$

- $m_S = 95\ m_E$

- distance from sun: 9.53 AU

- gas giant with very dense atmosphere containing sulphur, hydrogen, helium, ammonium, methane, etc.
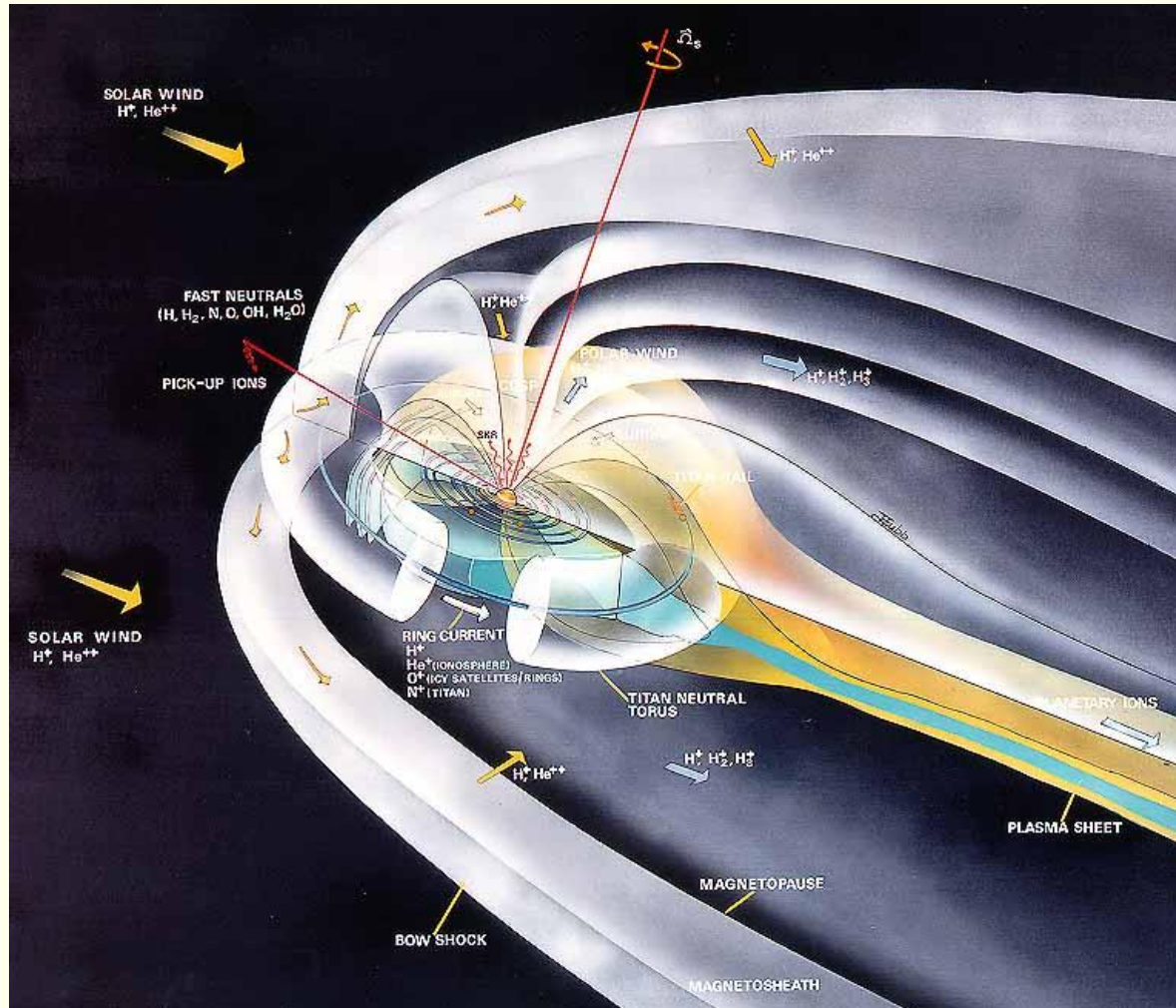
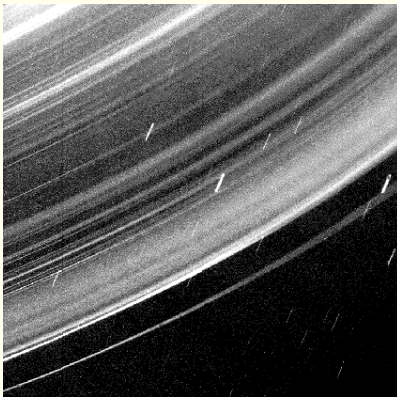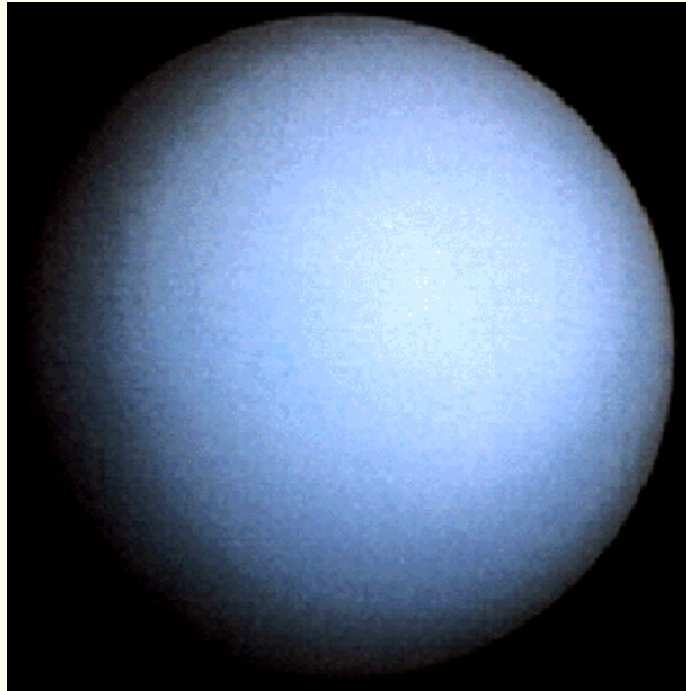- ~ 31 moons + ring system

Saturn's rings

- ring systemet is made up of ice and mineral particles from ~ 1 cm to ~ 1 km

- rings are only 1.5 km thick
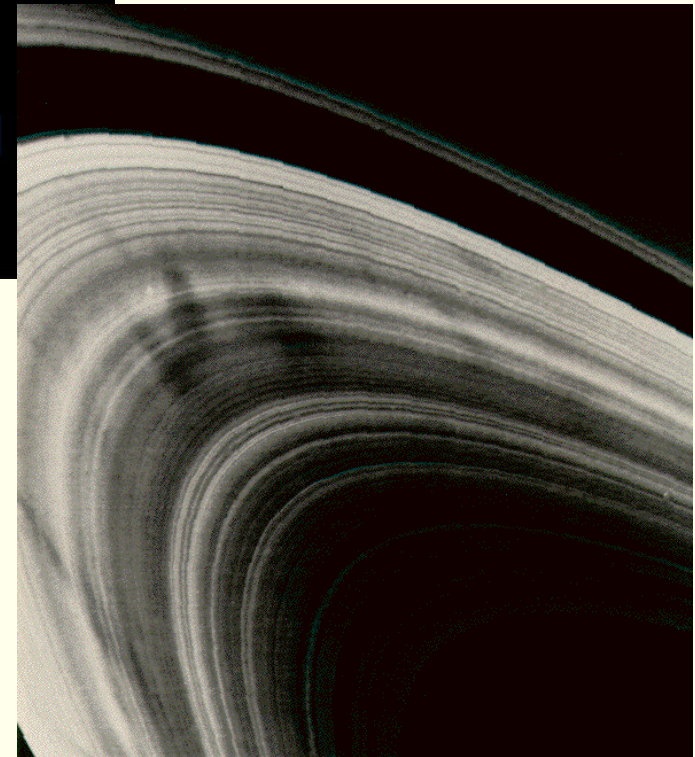
Saturn's magnetosphere

- ring systemet is both source and sink for plasma and limits the size of the plasmasphere

- plasma pressure important for balancing solar wind pressure, just as for Jupiter

- Intense radiation belt with 50 MeV protons

Uranus

- $r_U = 3{,}84 \, r_E$

- $m_U = 14{,}5 \, m_E$

- distance from sun: 19,2 AU

- gas giant with very dense atmosphere containing mainly methane

- 20 moons + ring system

Uranus
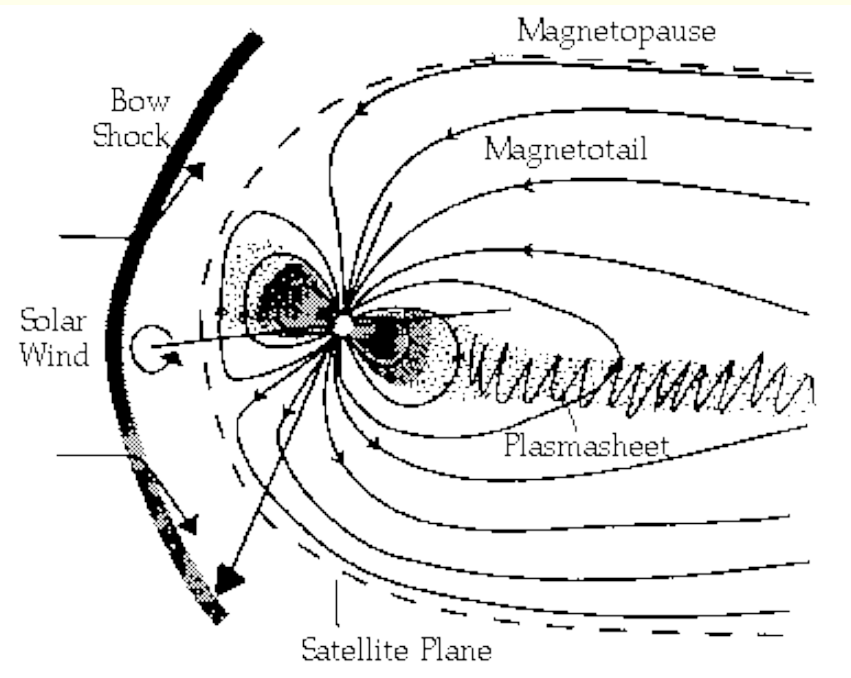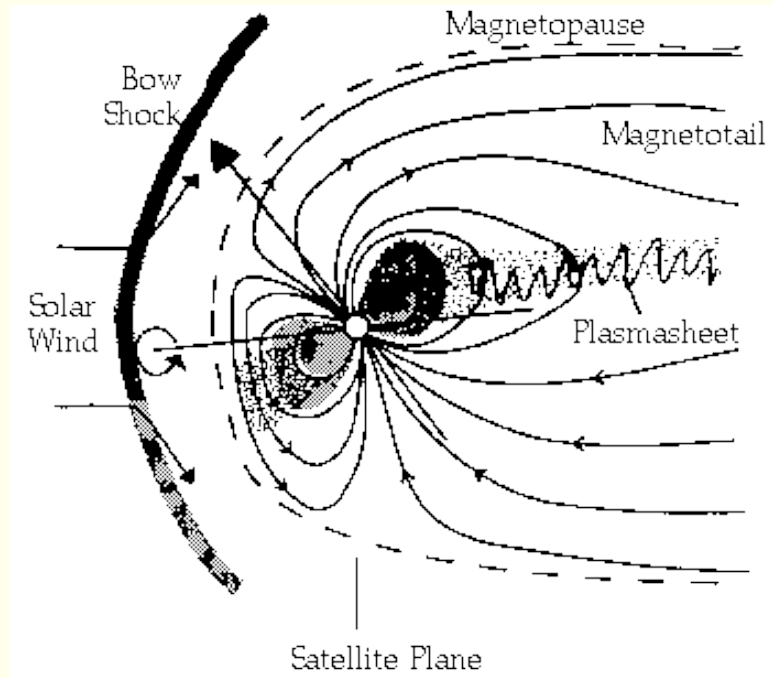
- Uranus' rotational axis almost in ecliptic plane

- magnetic field axis makes an angle of around 60° with rotational axis

- this gives enourmous daily variations of the structure of the magnetosphere

Neptune

Photo from Hubble Space Telescope

- $r_N = 3{,}93 \; r_E$

- $m_N = 17{,}2 \; m_E$

- distance from sun : 30.1 AU

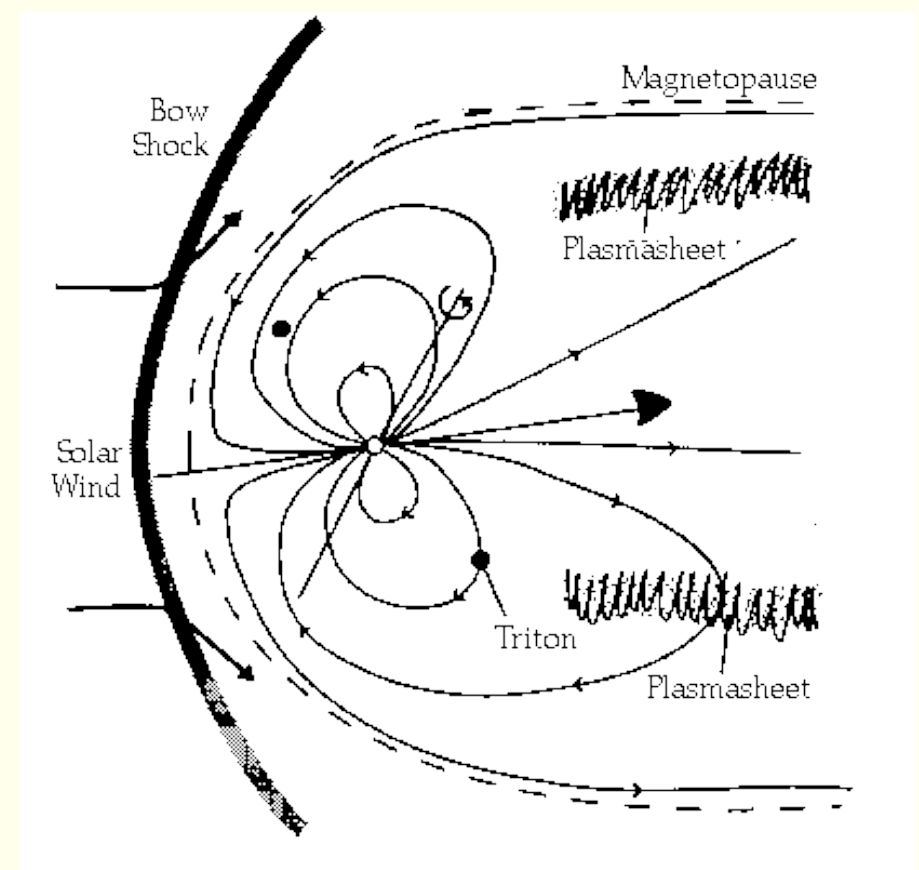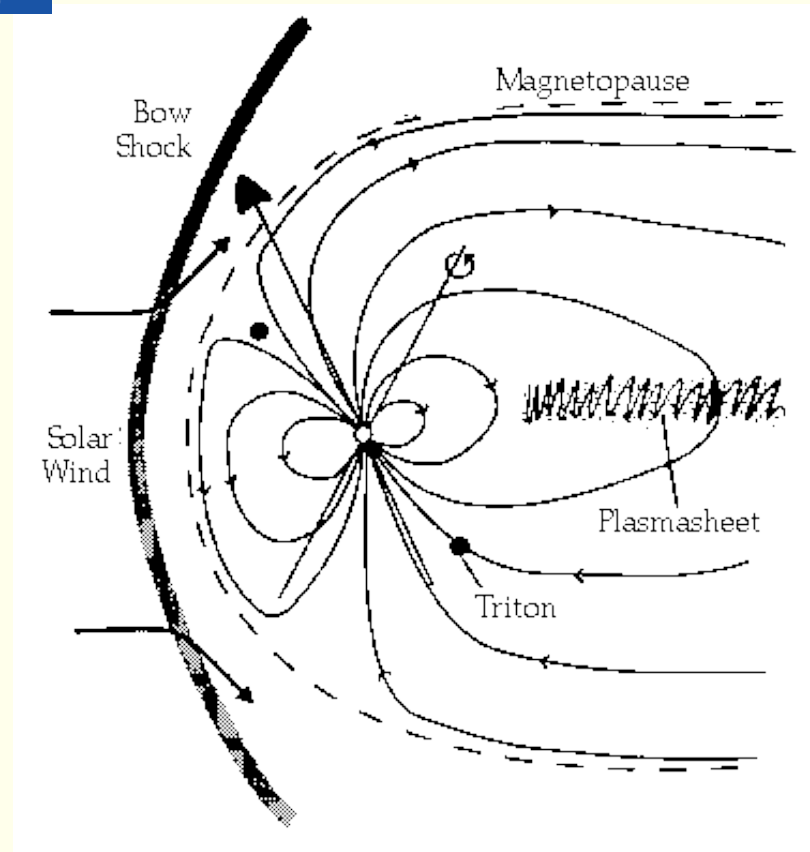- gas giant with very dense atmosphere containing mainly methane

- 11 moons + ring system
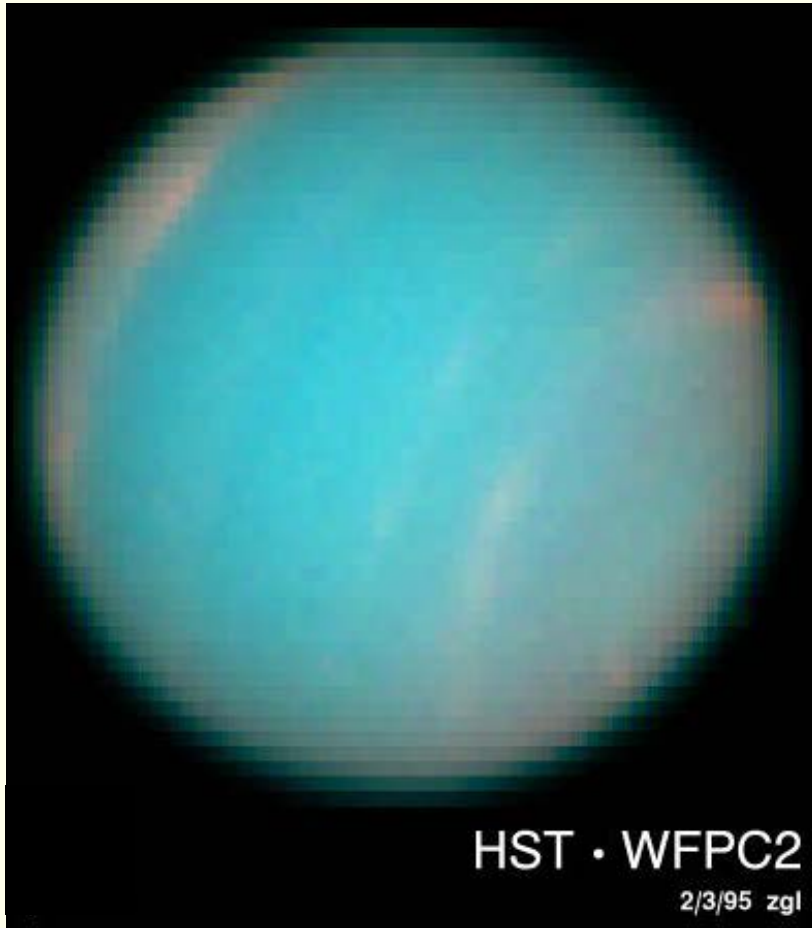
Neptune

- magnetic field axis makes an angle of around 43° with rotational axis

- this gives enourmous daily variations of the structure of the magnetosphere also for Neptune
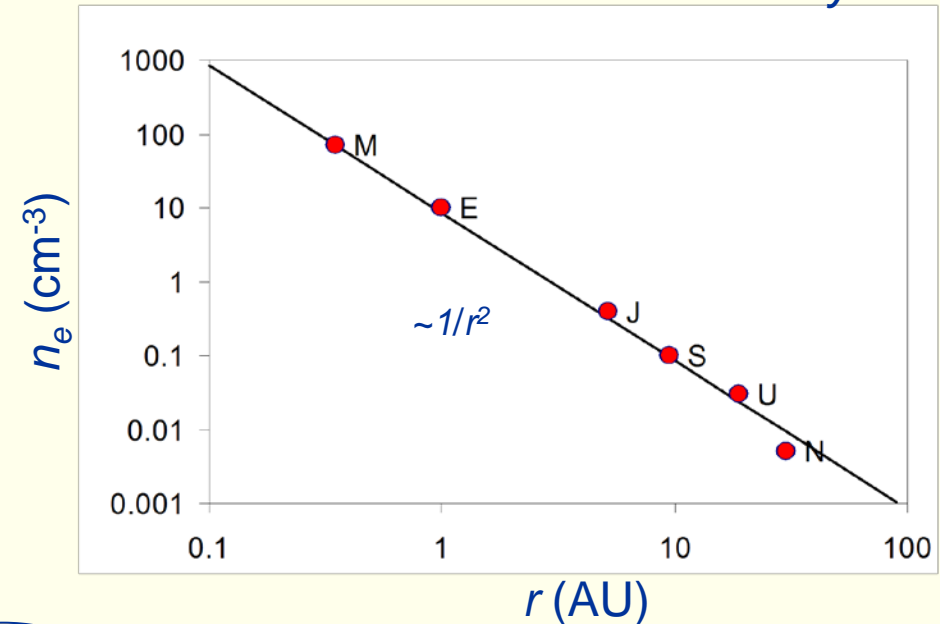
Comparative magnetospheres
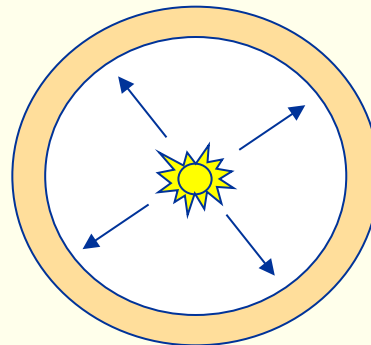## Solar wind properties

Solar wind velocity

Solar wind electron density

n_e (cm^{-3})

$\sim 1/r^2$

M

E

J

S

U

N

r (AU)
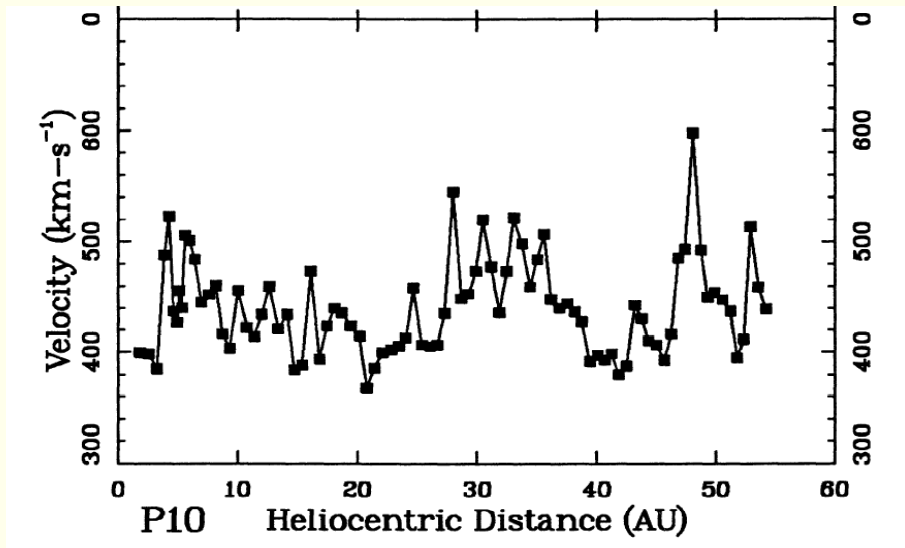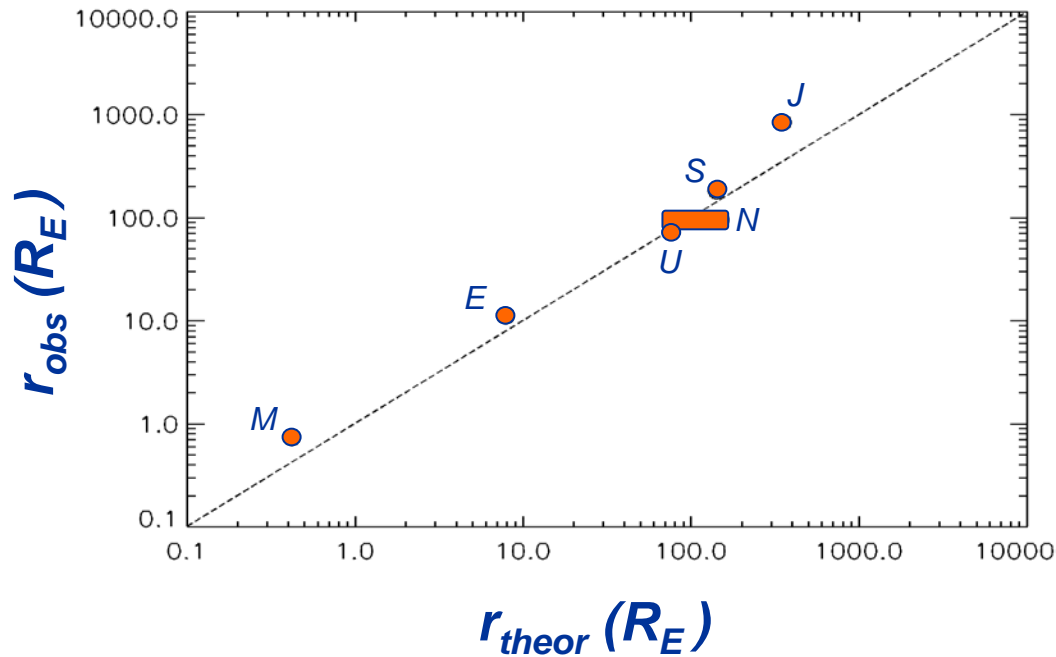
Pioneer 10, measurements
[Grazin et al., 1994]

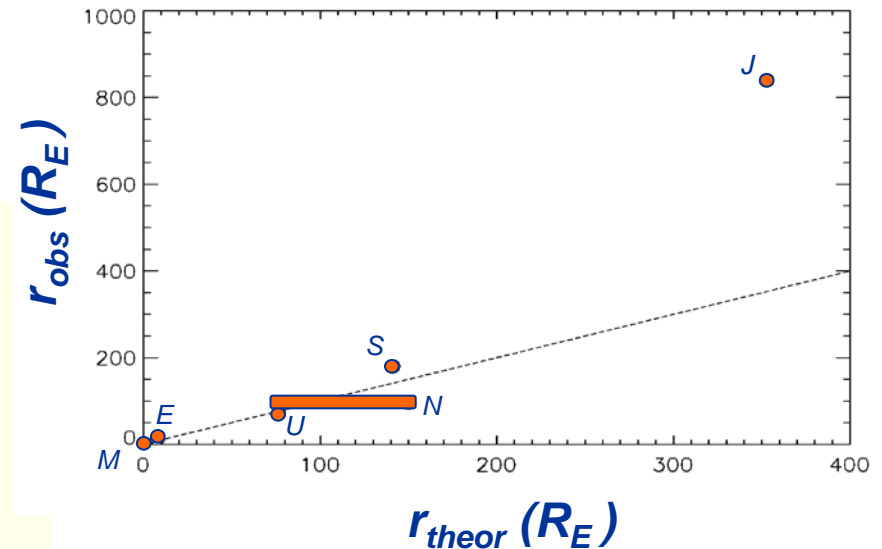*[Blanc et al., 2005]*

$$dV = 4\pi r^2 dr$$

Comparative magnetospheres
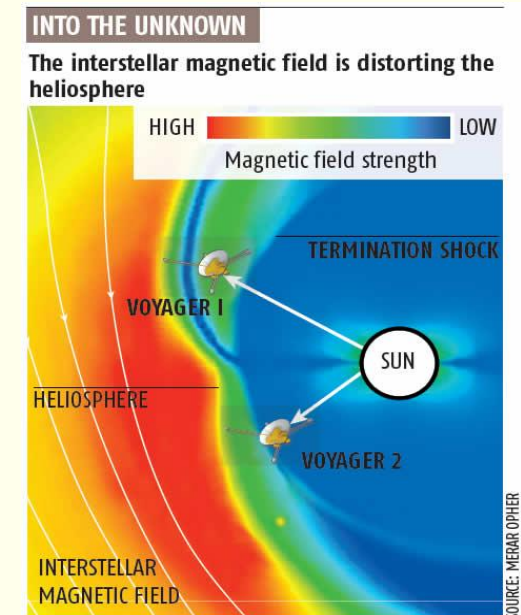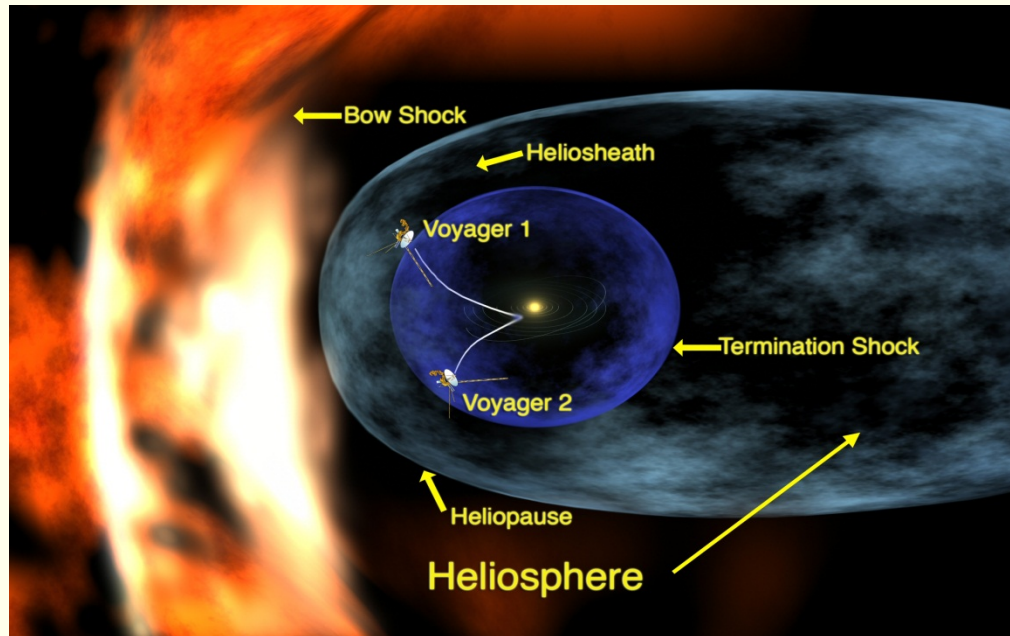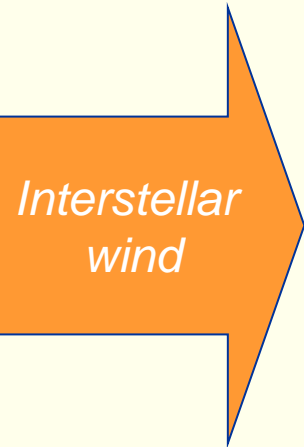
Observed vs. theoretical standoff-distance

$$r_{theor} = \left(\frac{\mu_0 a}{4\pi} \right)^{1/3} \left(2\mu_0 \rho_{SW} v_{SW}^2 \right)^{-1/6}$$

- *Model reasonably valid over three orders of magnitude*

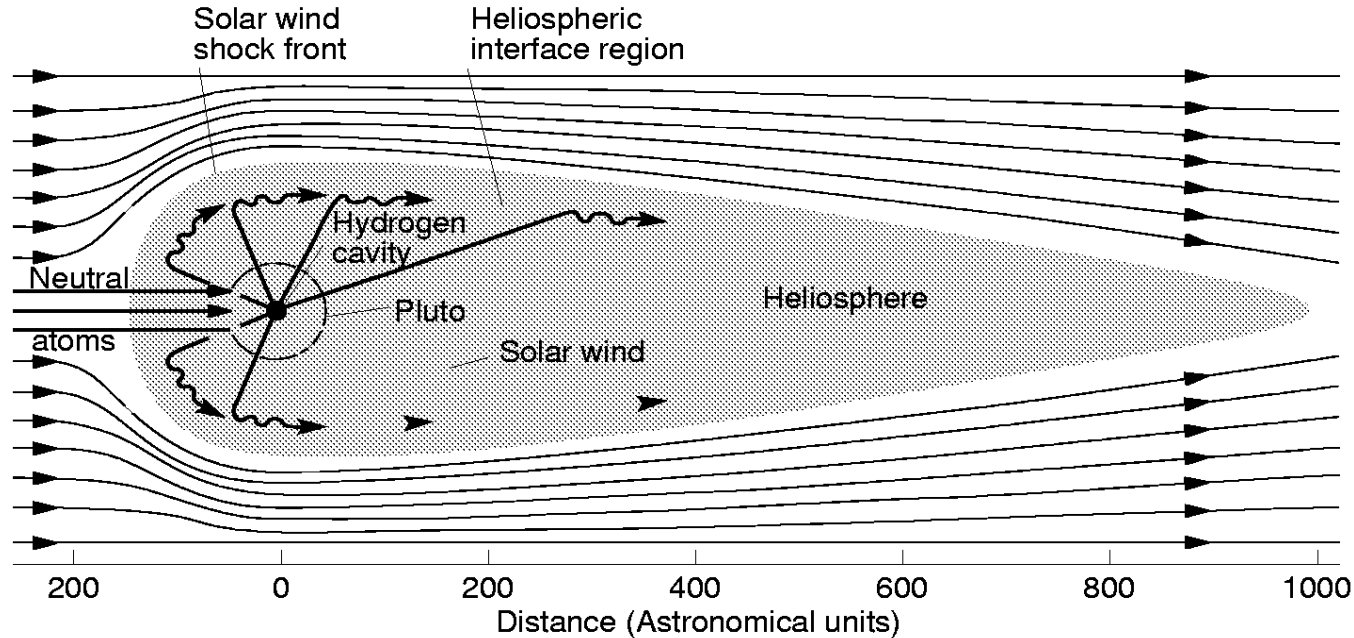- *Size of Jupiter's (and maybe Saturn's) magnetosphere underestimated*

Other other magnetospheres
Heliosphere

[Opher, 2007]

Heliosphere
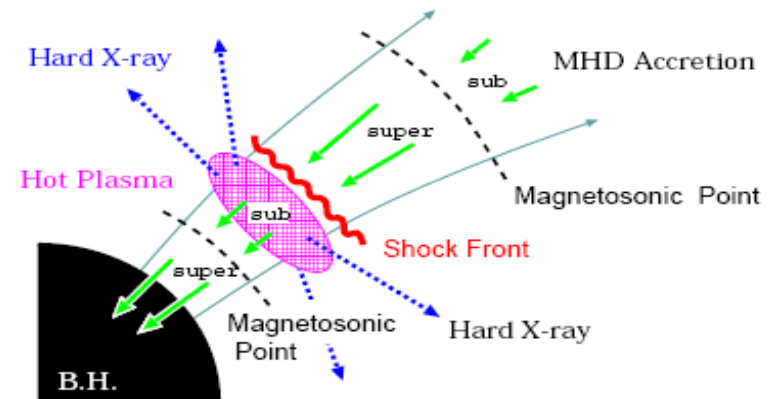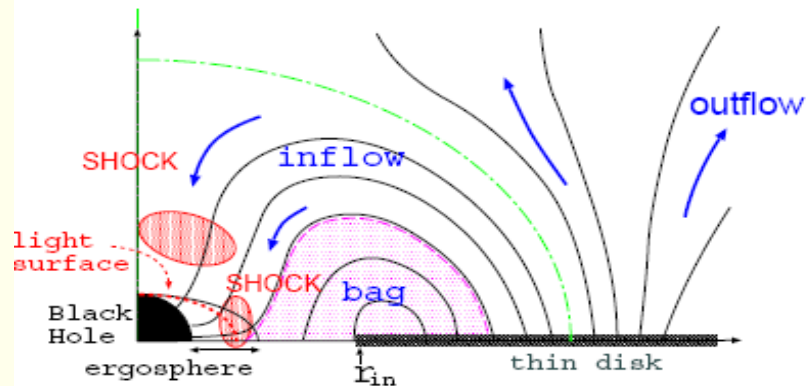

- Reaches approximately 100 AU into space (=1.5x10^{13} m)

- Voyager sonds are approaching/encountering the heliopause right now
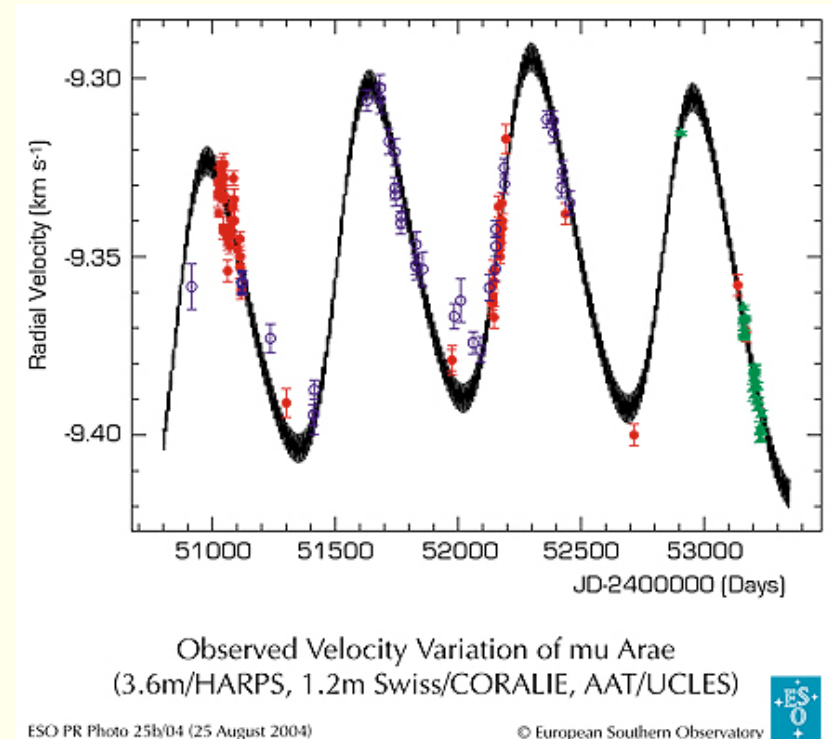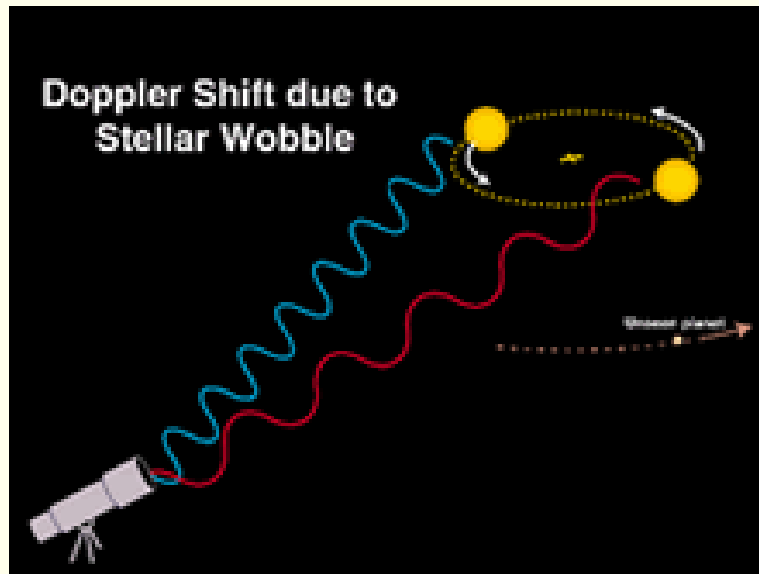
Other other magnetospheres
Exotic magnetospheres

"Black Hole Magnetosphere" = Loop (bag) + Disk–BH (inflow) + BH (Disk) − r_∞ (outflow)

Exoplanets

Doppler Shift due to Stellar Wobble

Observed Velocity Variation of mu Arae
(3.6m/HARPS, 1.2m Swiss/CORALIE, AAT/UCLES)

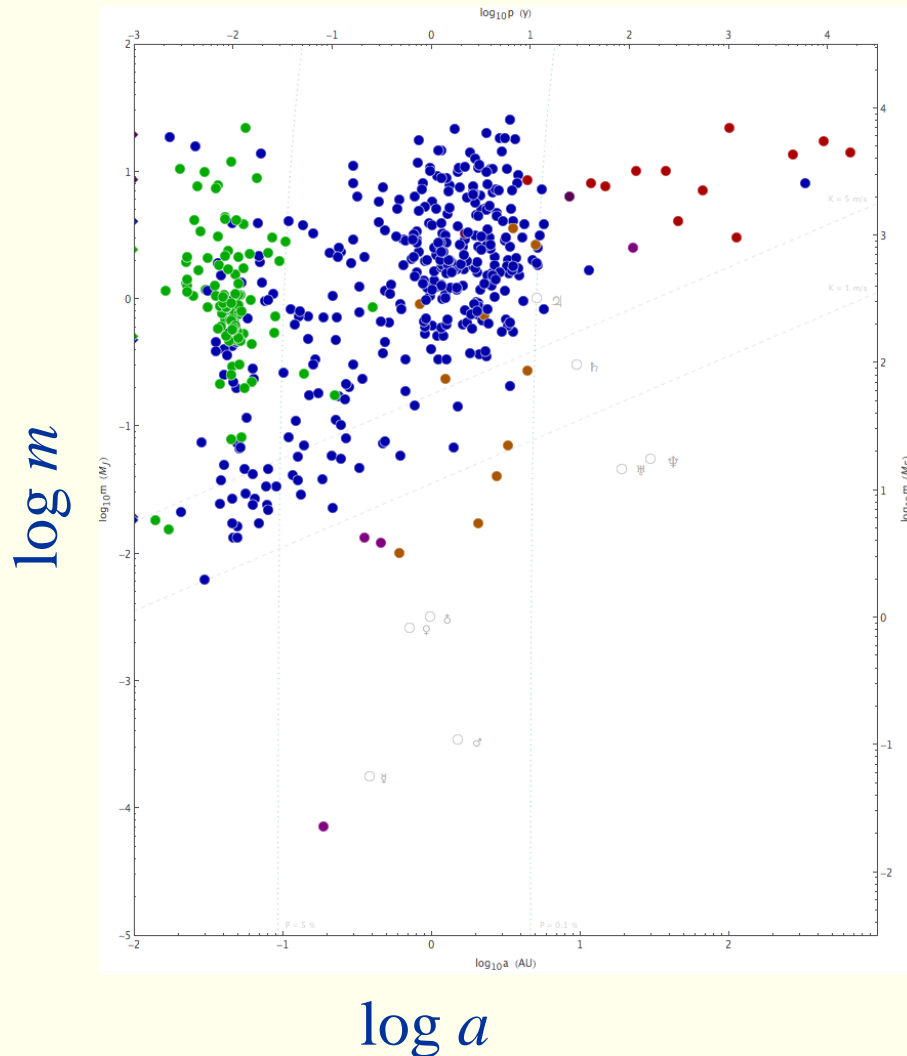ESO PR Photo 25b/04 (25 August 2004) © European Southern Observatory

Mostly detected by doppler shifts in starlight, or by dimming of the emitted starlight during transit of planet.

Magnetospheres of exoplanets

- 728 exoplanets found up to January 23, 2012

- Nothing is known about their atmospheres, ionospheres or magnetospheres

- Can possibly be detected by

  - radio emissions from auroral activity or from radiation belts

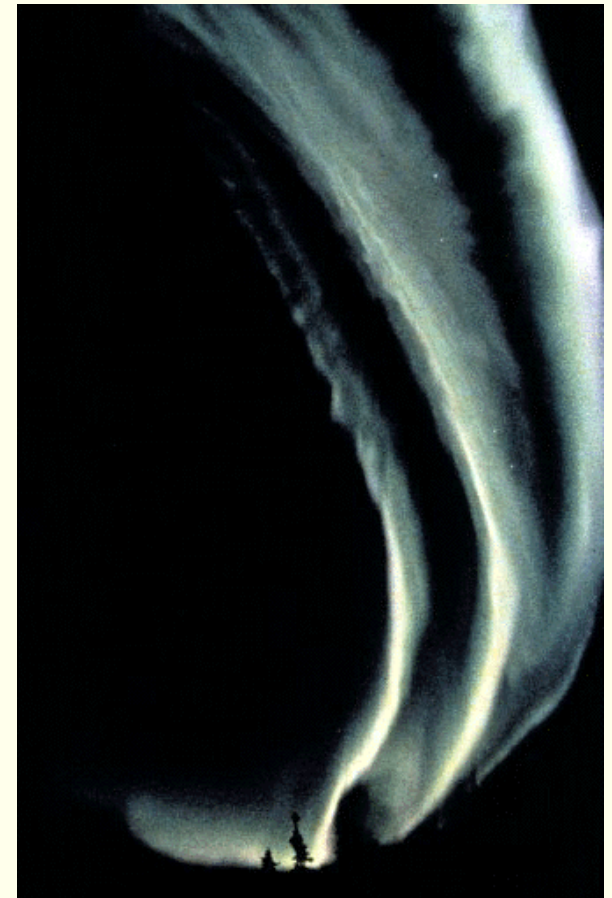 - spectroscopy when the magnetosphere is in front of its sun

The aurora

2005-01-10 12:00:04 Alaska

The aurora

The aurora

© AURORA EXPERIENCE

The aurora

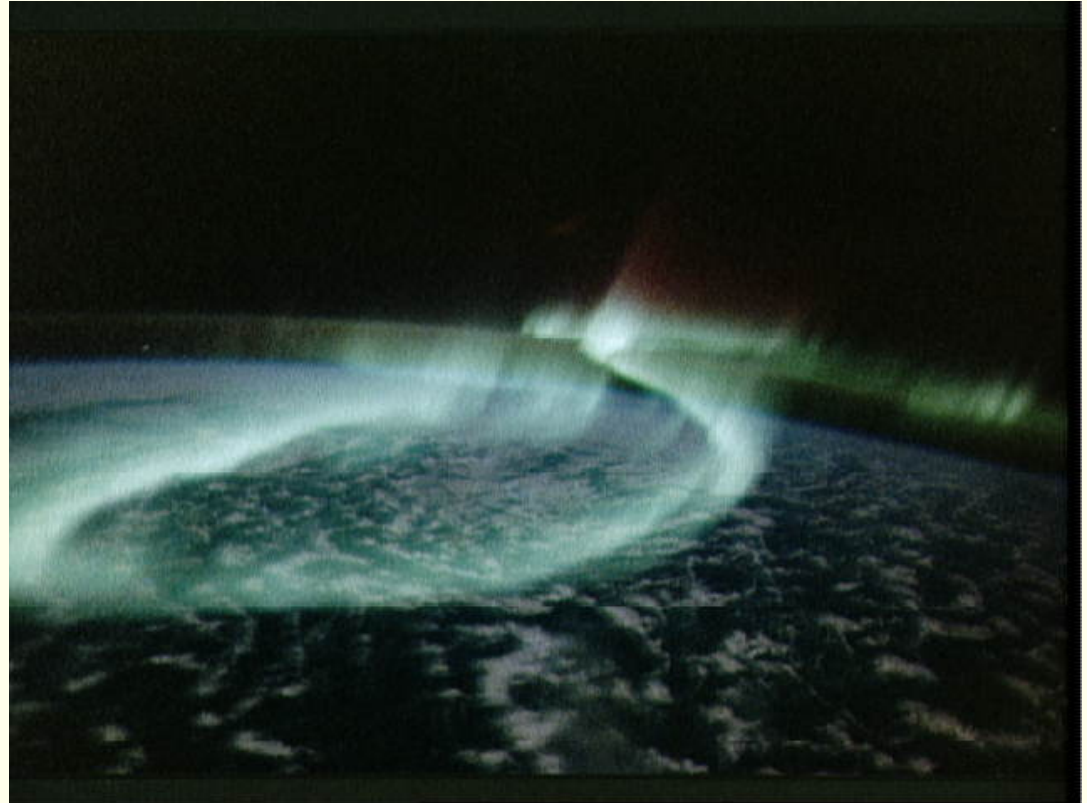# Homogenous auroral arcs

Rays, curtains

Rays are formed in the direction of the local magnetic field.

Photo by David Fritts

Drapes develop from homogenous arcs, often when they increase in intensity.
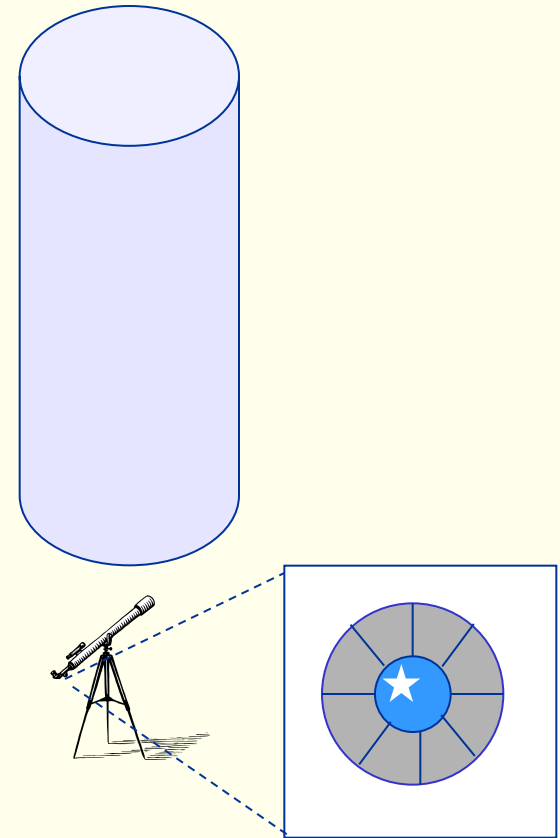
Auroral spirals

Develop when arcs become unstable

Auroral corona

Geometric effect of perspective when you look towards magnetic zenith. Compare the figure.
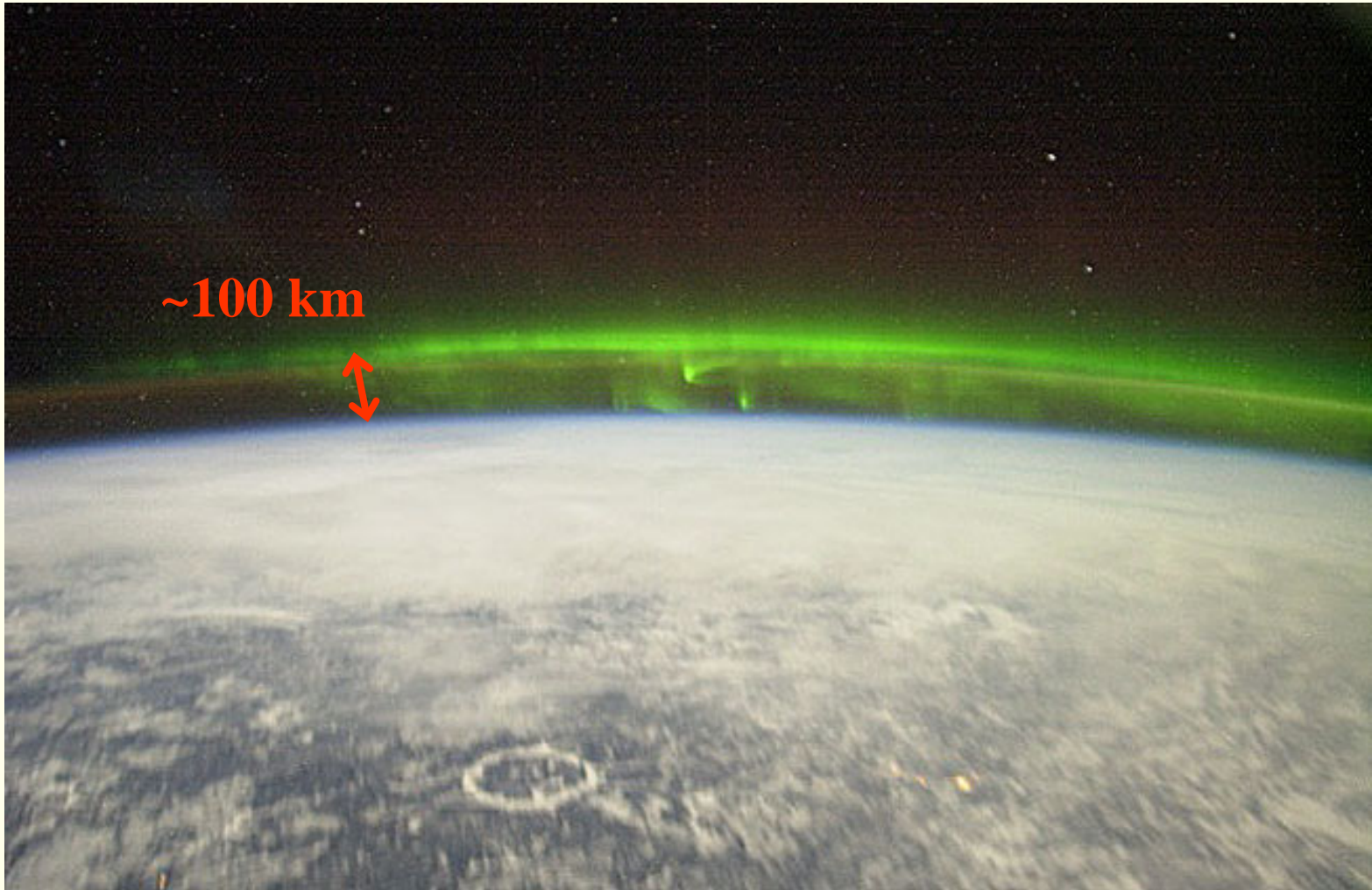
Aurora - altitude

~100 km

Foto from International Space Station

Early notions

Woodcut from Böhmen 1570.

Anders Celsius documented that compass needles where strongly affected during auroral activity in 1733.
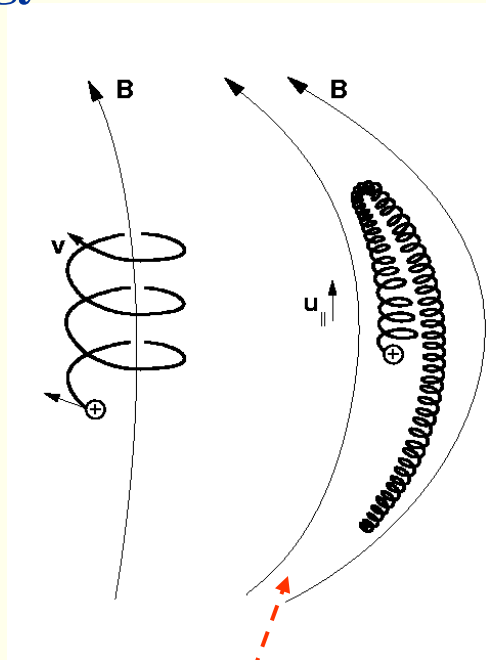
What causes the aurora?
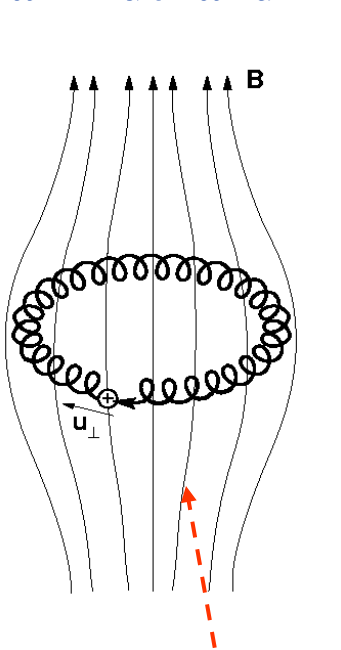
Particle motion in geomagnetic field
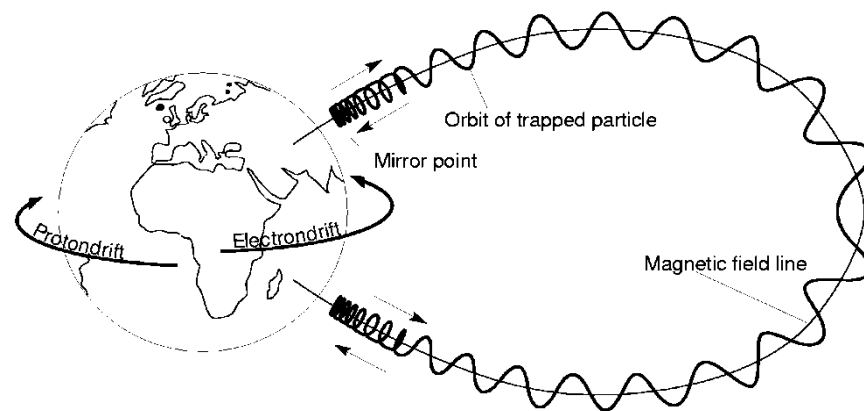

longitudinal oscillation

gyration

azimuthal drift

Magnetic mirror

grad B drift

Magnetic mirror
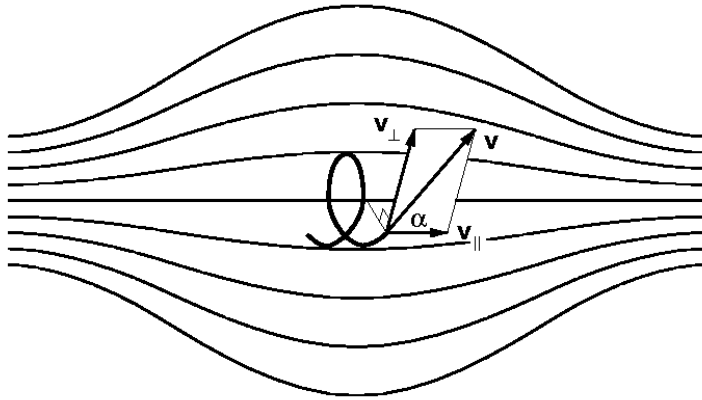
mv²/2 constant (energy conservation) ➡

$$\frac{\sin^2 \alpha}{B} = konst$$

particle turns when $\alpha = 90°$ ➡

$$B_{turn} = B / \sin^2 \alpha$$

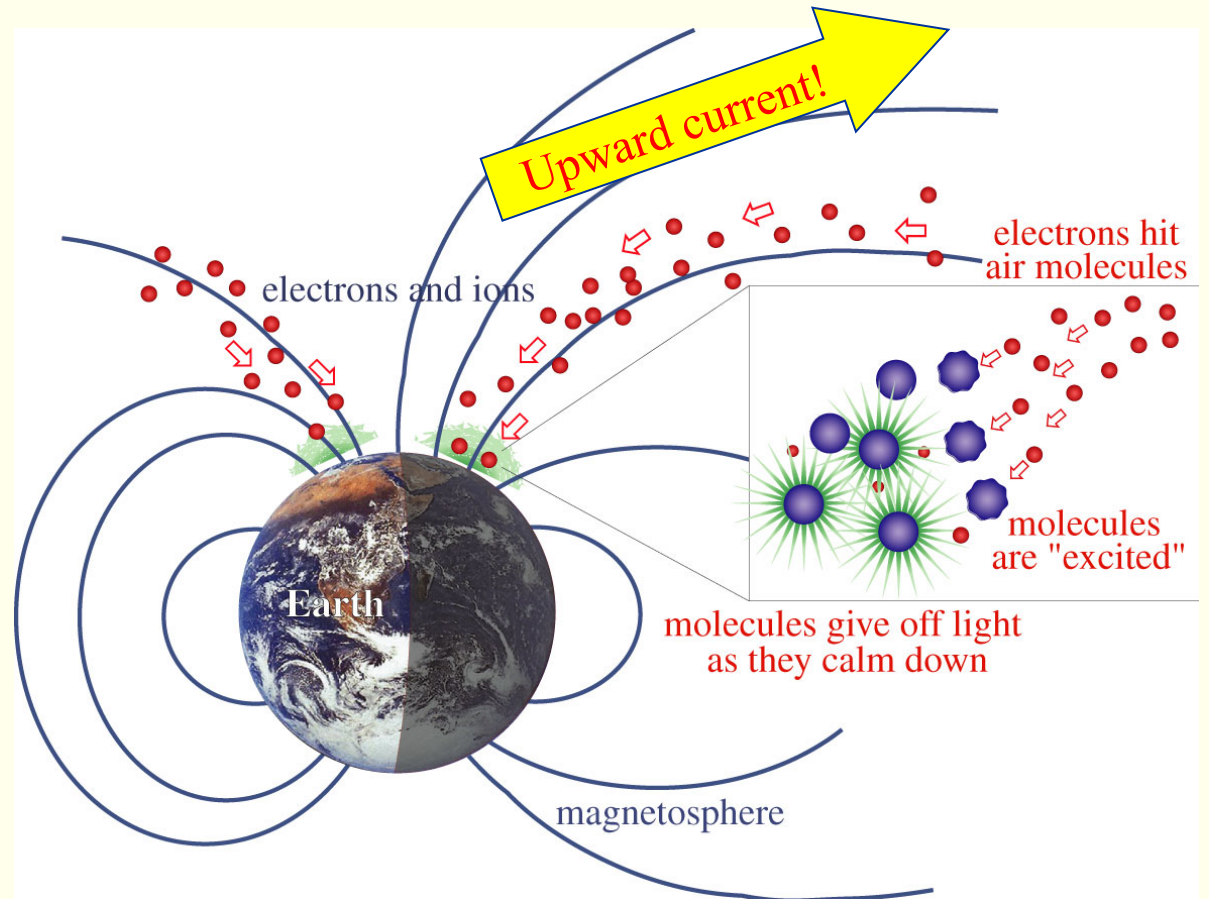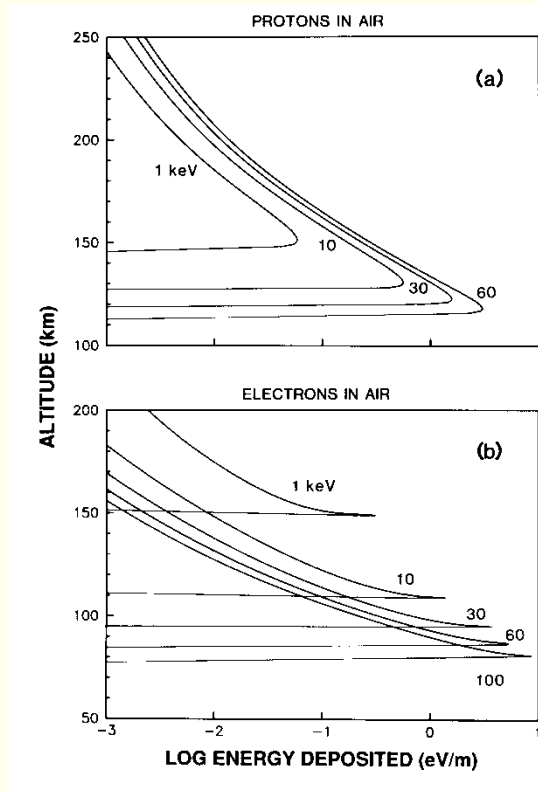If maximal B-field is B_{max} a particle with pitch angle α can only be turned around if

The magnetic moment μ is an *adiabatic invariant*.

$$B_{turn} = B / \sin^2 \alpha \leq B_{max}$$ ➡

$$\alpha > \alpha_{lc} = \arcsin \sqrt{B / B_{max}}$$

$$\mu = \frac{mv_\perp^2}{2B} = \frac{mv^2 \sin^2 \alpha}{2B}$$

Particles in *loss cone* :

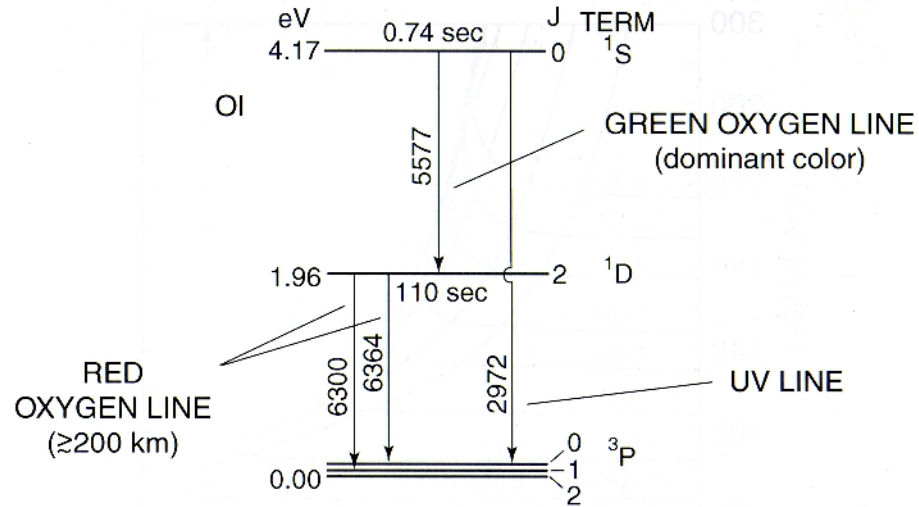$$\alpha < \alpha_{lc}$$

Collisions - emissions

Emissions
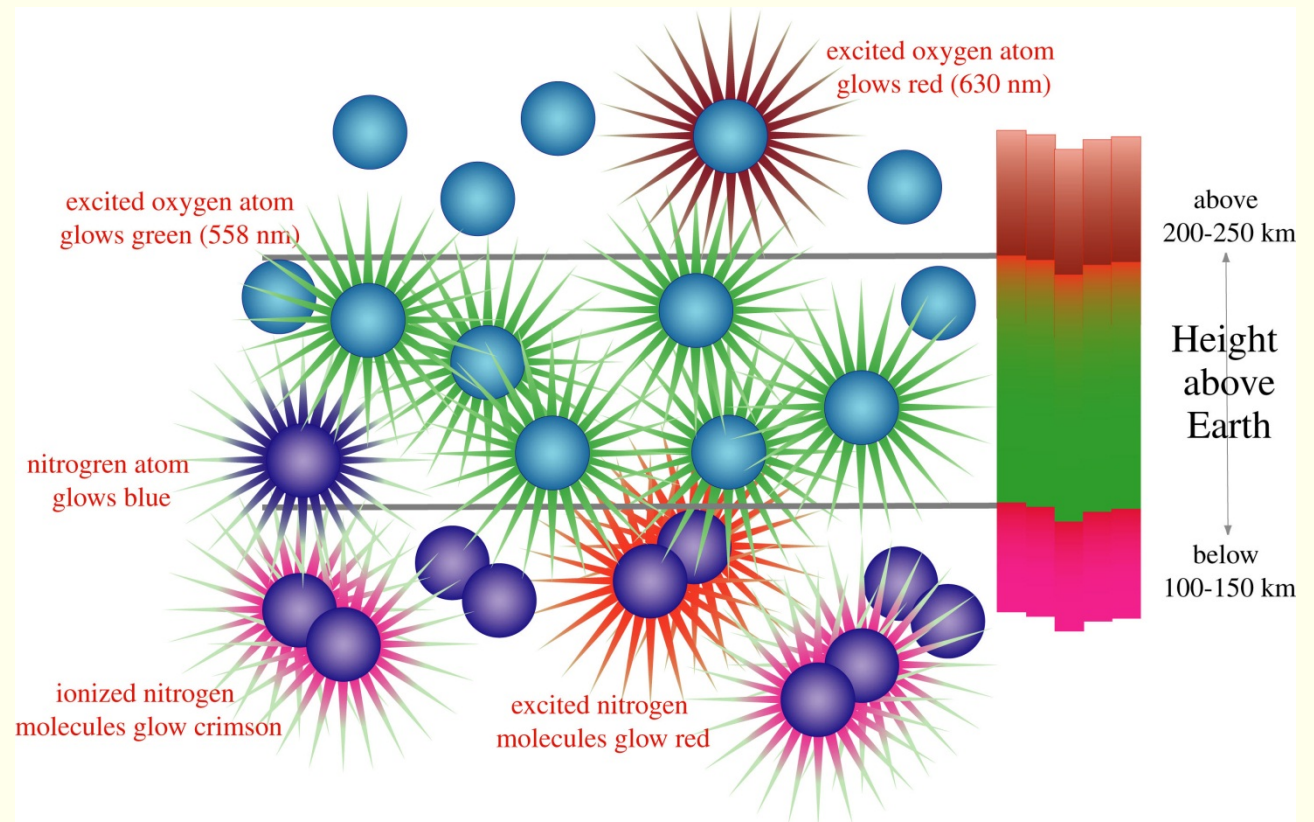
Oxygen emissions

Why is there no red emissions at lower altitude?

Oxygen emissions

The red emission line is suppressed by collisions at lower altitudes due the its long transition time. (When an excited atom collides with another atom, is is de-excited without any emission.)