Last lecture (6)

- Drift motion
- Ionospheric conductivities
- Particle motion in the magnetosphere

Today's lecture (7)

- Particle motion in the magnetosphere
- Other magnetospheres
- (Aurora)

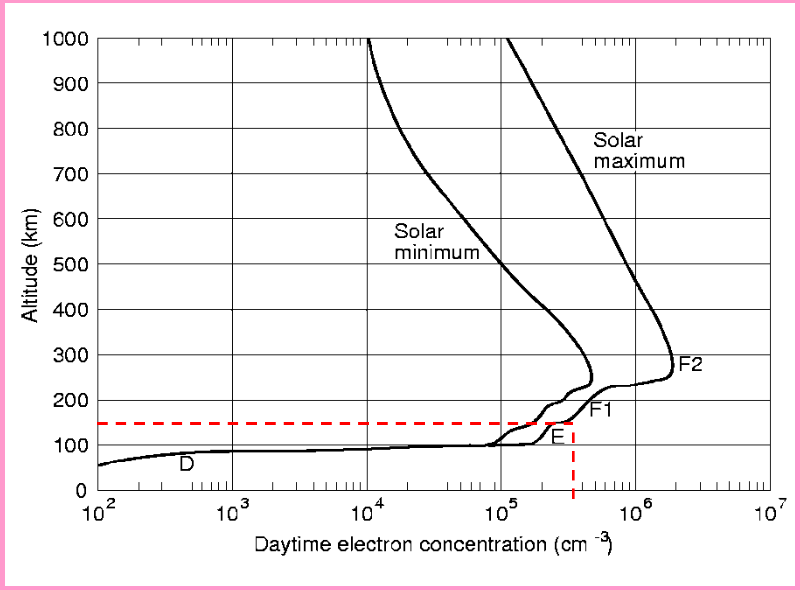
Mini-groupwork 3

a)

$$\frac{\partial n_e}{\partial t} = q - \alpha n_e^2$$

$$\frac{dn_e(t)}{dt} = 0 \quad \Rightarrow$$

$$\alpha = \frac{q}{n_e^2}$$



$q = 3.8 \cdot 10^4$ cm^{-3}s^{-1} = $3.8 \cdot 10^{10}$ m^{-3}s^{-1}

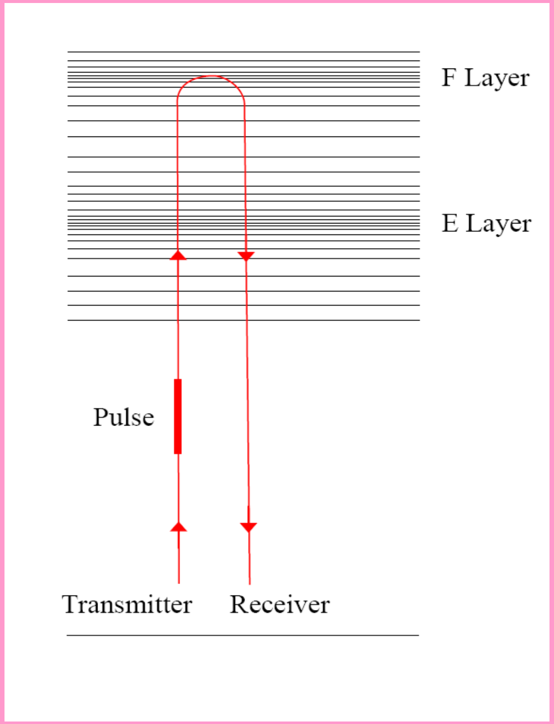
n_e(150 km) = $3 \cdot 10^5$ cm^{-3} = $3 \cdot 10^{11}$ m^{-3}

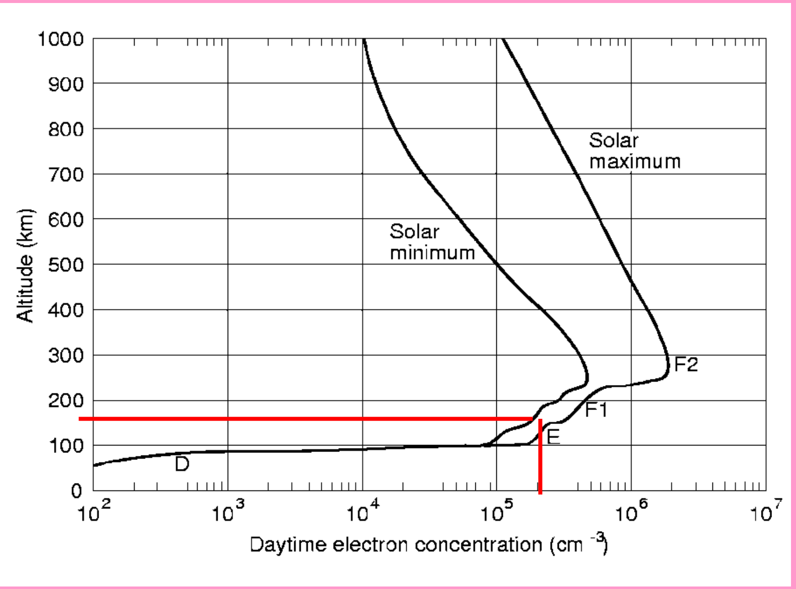
Thus

$\alpha = 4.2 \cdot 10^{-13}$ m^{3}s^{-1}

Mini-groupwork 3

b)





$$f_p = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \approx 9\sqrt{n_e}$$

$$f_p = 5\cdot 10^6 = 9\sqrt{n_e}$$

$$\Rightarrow$$

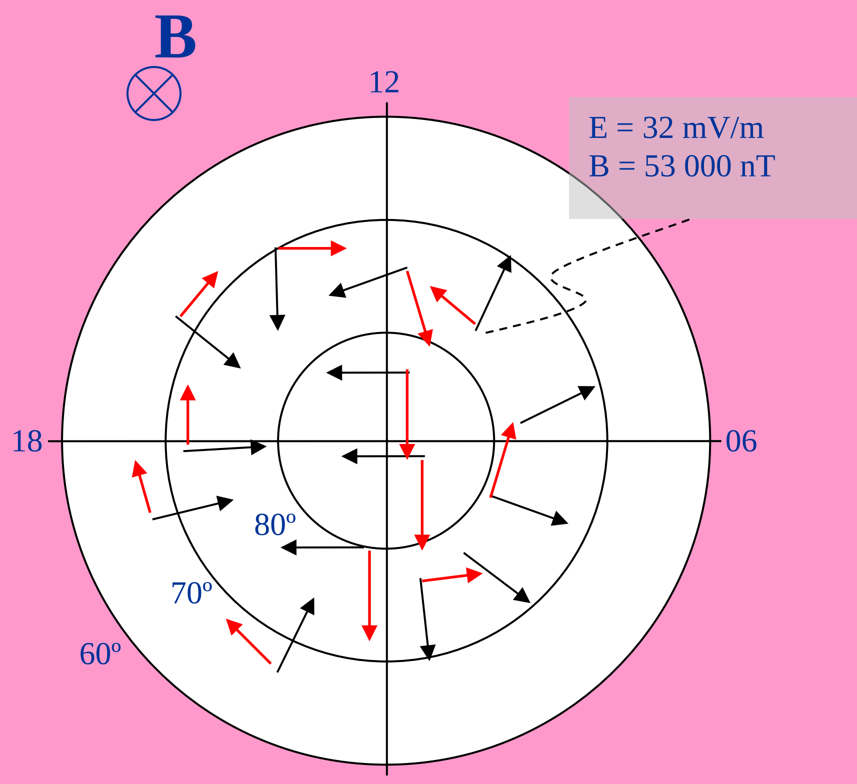
$$n_e = \left(\frac{5\cdot 10^6}{9}\right)^2 = 3\cdot 10^{11}\, m^{-3}$$

$$h = 150\ km$$

$$t = \frac{2h}{c} = \frac{300\cdot 10^3}{3\cdot 10^8} = 10^{-3}\, s$$

Mini-groupwork 3

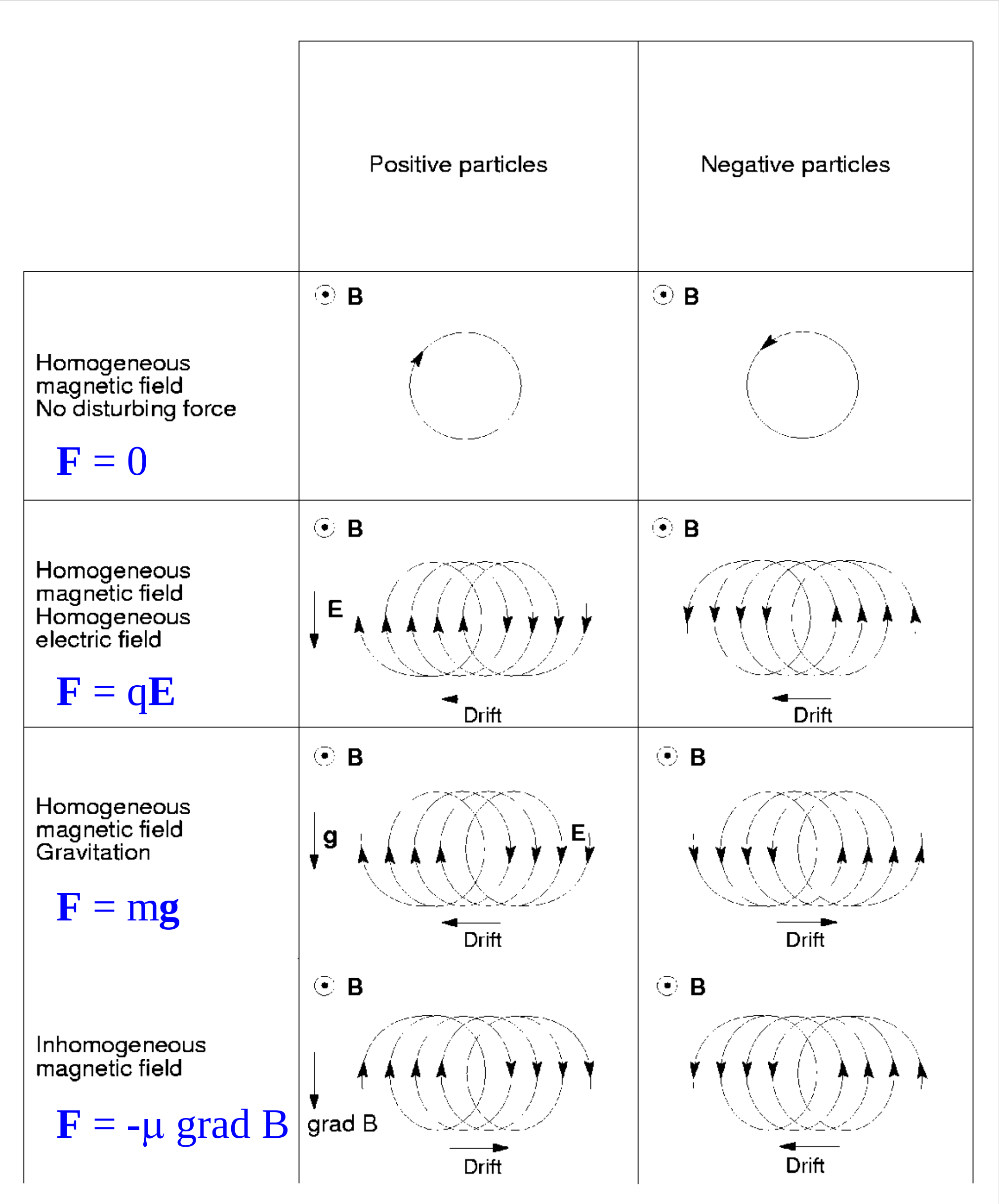
c)



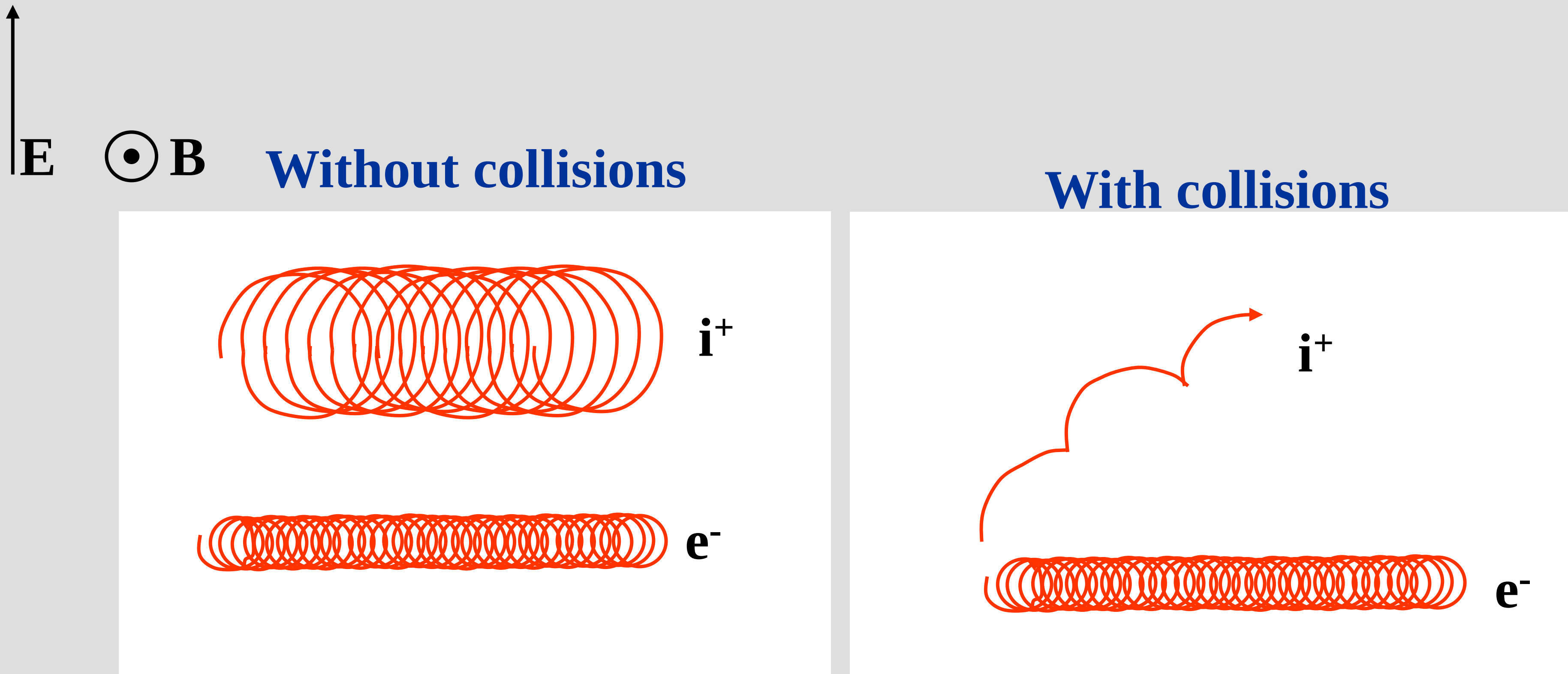
$$v_d = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = \frac{E}{B} = \frac{32\cdot 10^{-3}}{53000\cdot 10^{-9}} = 604\ ms^{-1}$$

Drift motion

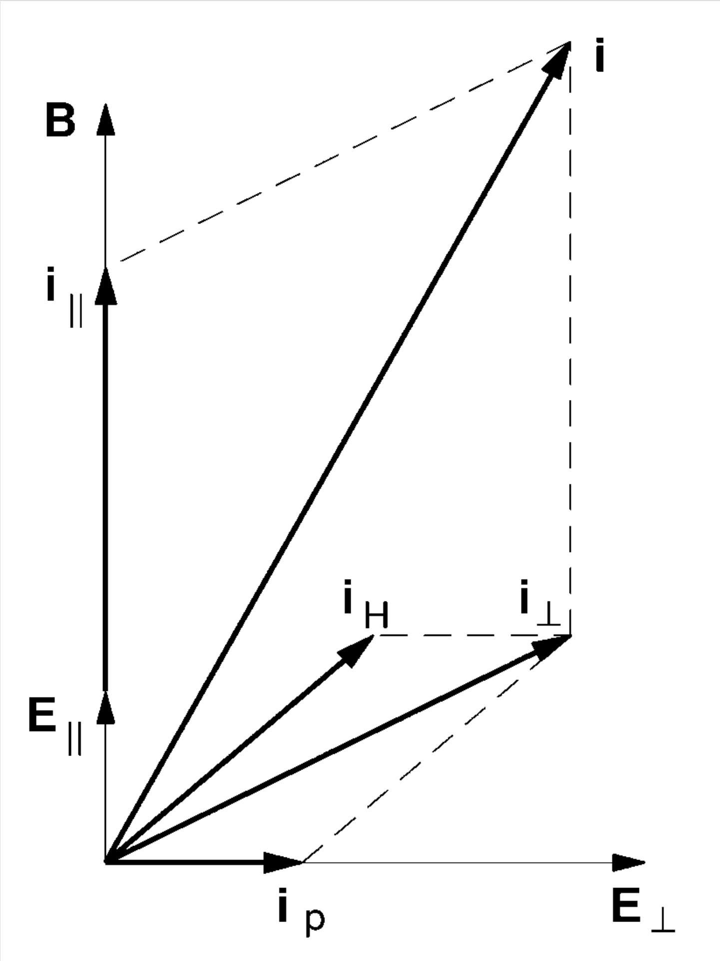
$$\mathbf{u}_{drift} = \frac{\mathbf{F} \times \mathbf{B}}{qB^2}$$



ExB-drift

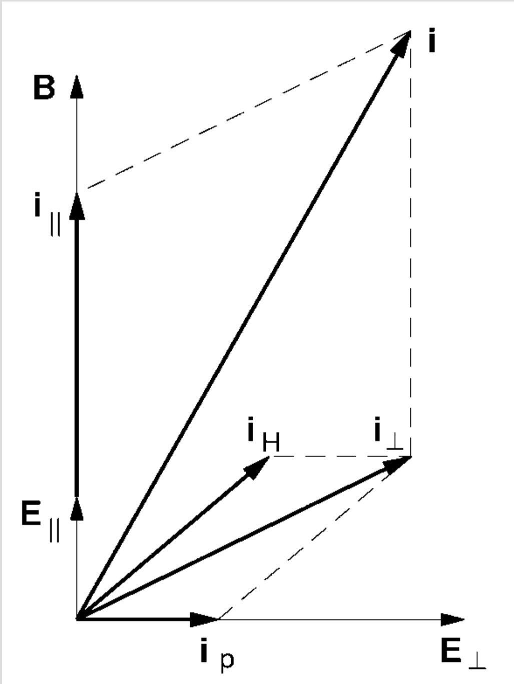


Electric conductivity in a magnetized plasma



- $i_{//}$ = parallel current
- i_P = Pedersen current
- i_H = Hall current

Electric conductivity in a magnetized plasma II



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

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

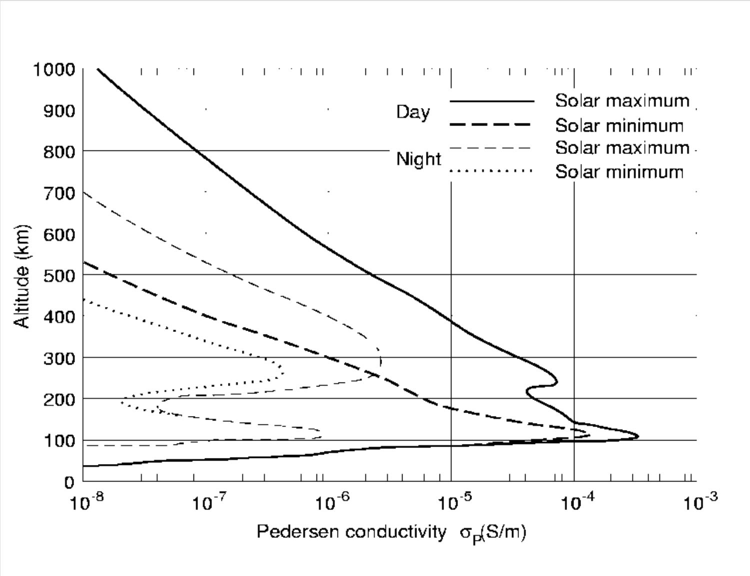
$$\sigma_{//} = \sigma_e + \sigma_i$$

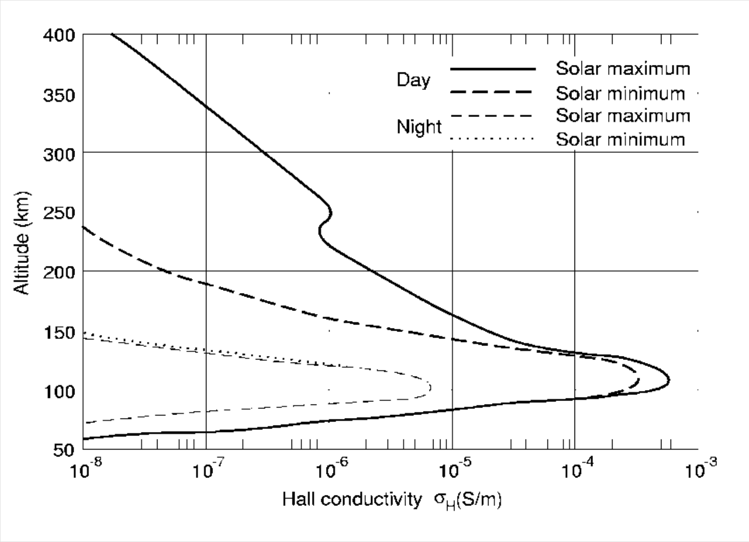
$$\sigma_e = e^2 n \tau_e / m_e \qquad \sigma_i = e^2 n \tau_i / m_i$$

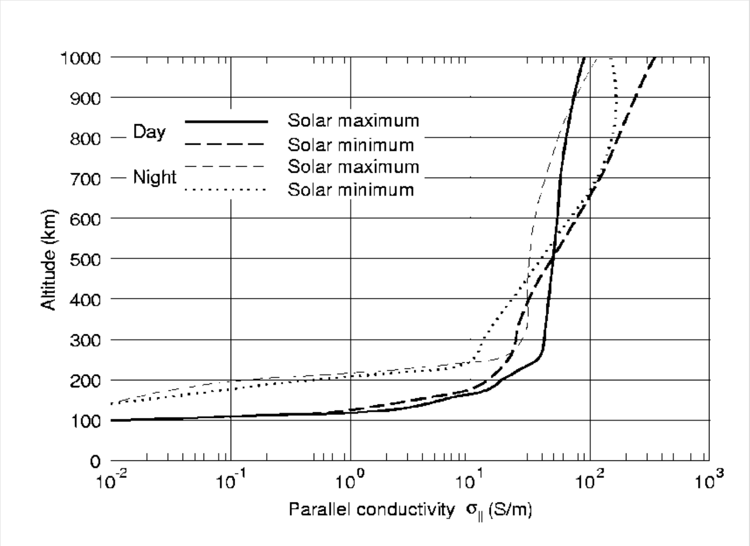
$$i_{//} = \sigma_{//} E_{//}$$

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

Ionospheric conductivities







Geomagnetic field

Approximated by a dipole close to Earth.

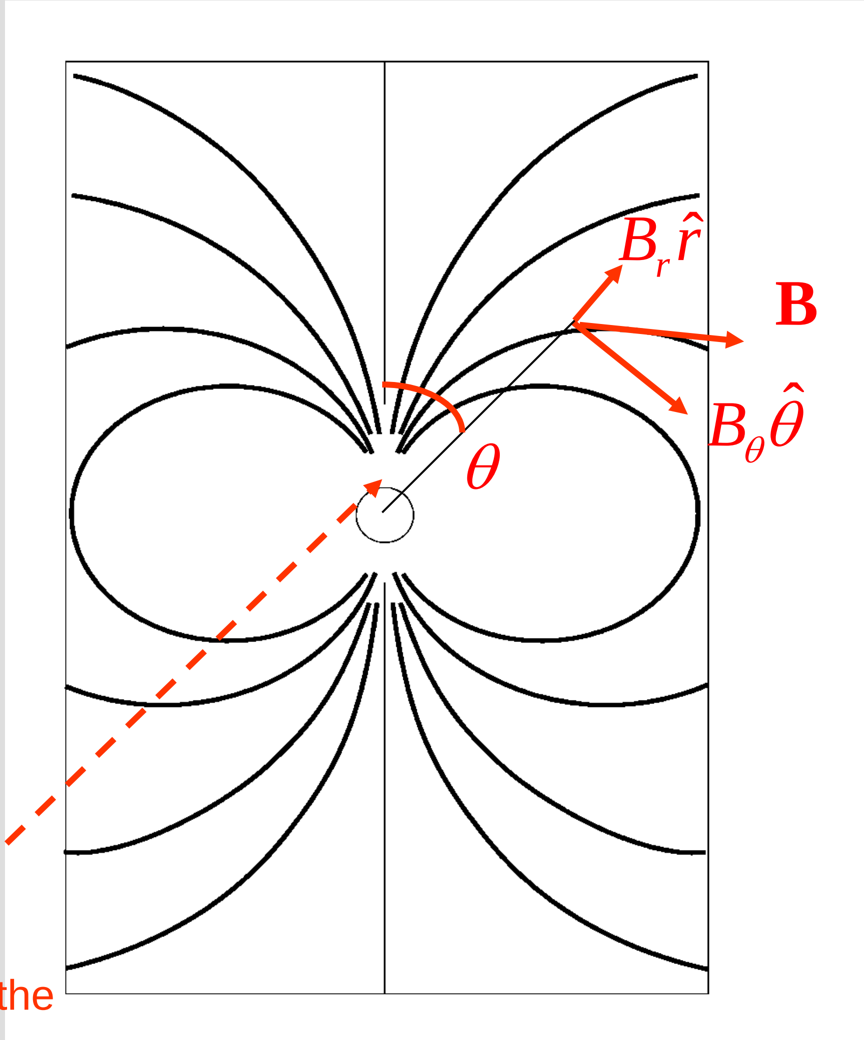
$$B_r = B_p\left(\frac{R_E}{r}\right)^3 \cos\theta$$

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

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

magnetic dipole moment

Magnetic field at the "north pole"



Geomagnetic field

Alternative formulation of dipole field

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

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

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

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

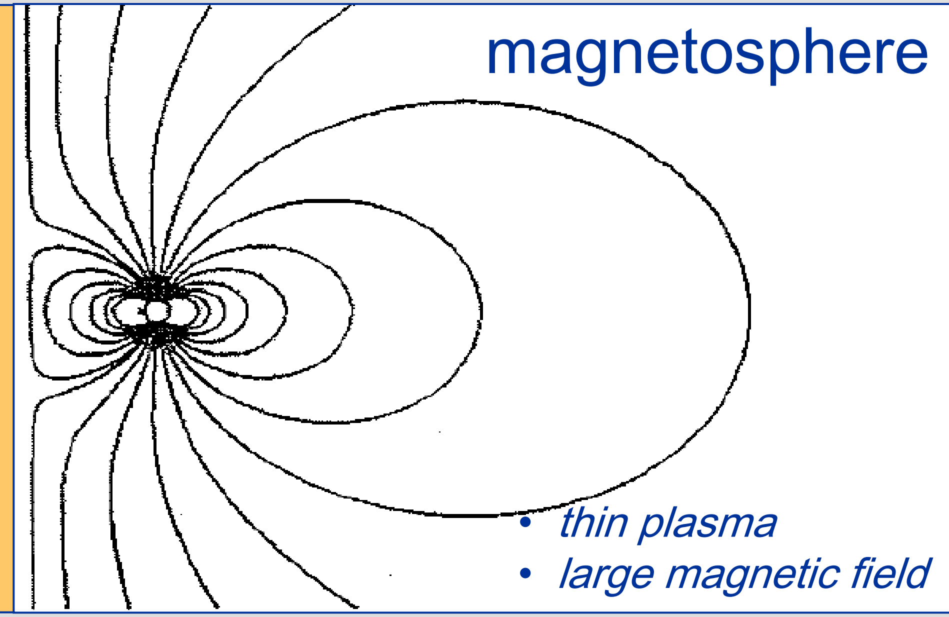
$$a = \frac{2\pi R_E^3 B_p}{\mu_0}$$

magnetic dipole moment

Stand-off distance from pressure balance

solar wind

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



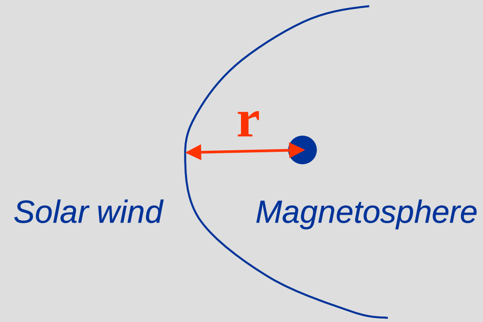
Dynamic pressure:

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

Magnetic pressure:

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

Magnetopause "stand-off distance"



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

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

Dipole field strength (in equatorial plane): $B = \dfrac{\mu_0 a}{4\pi} \dfrac{1}{r^3}$

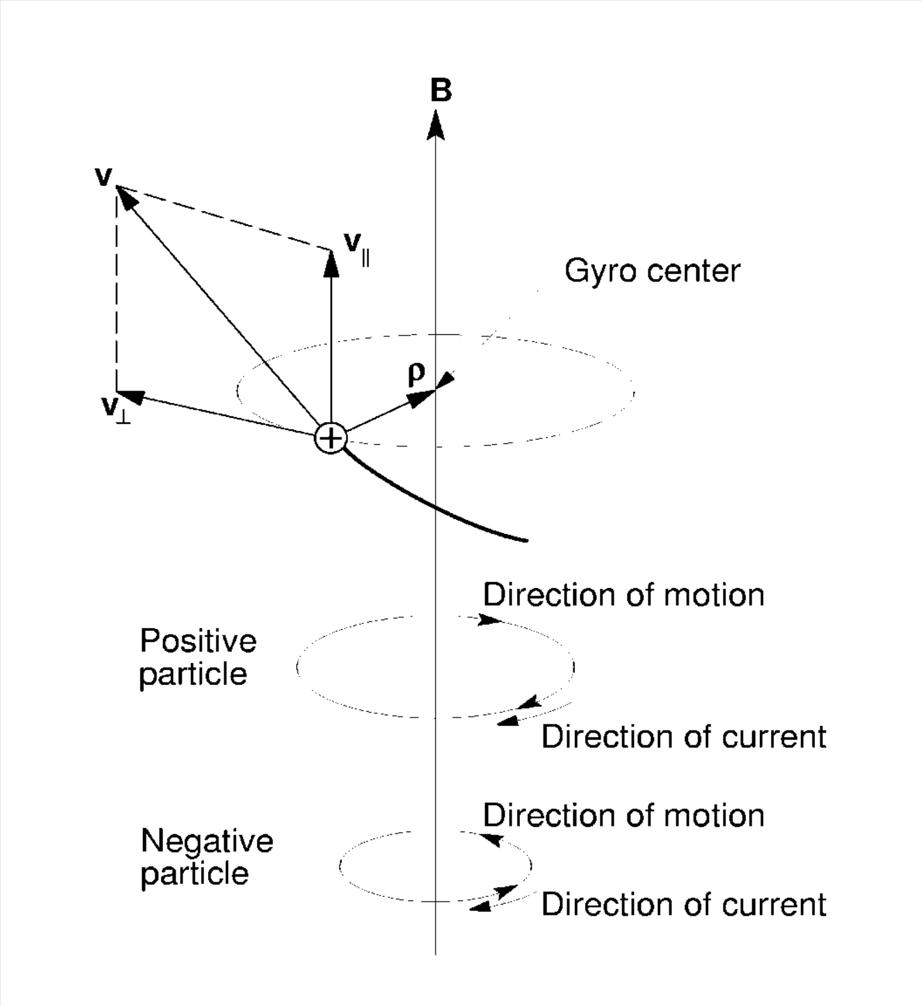
$$p_d = p_B \quad \Rightarrow \qquad \rho_{SW} v_{SW}^2 = \left[\frac{\mu_0 a}{4\pi} \frac{1}{r^3} \right]^2 / 2\mu_0 \quad \Rightarrow$$

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

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

r = 7 R_e (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:

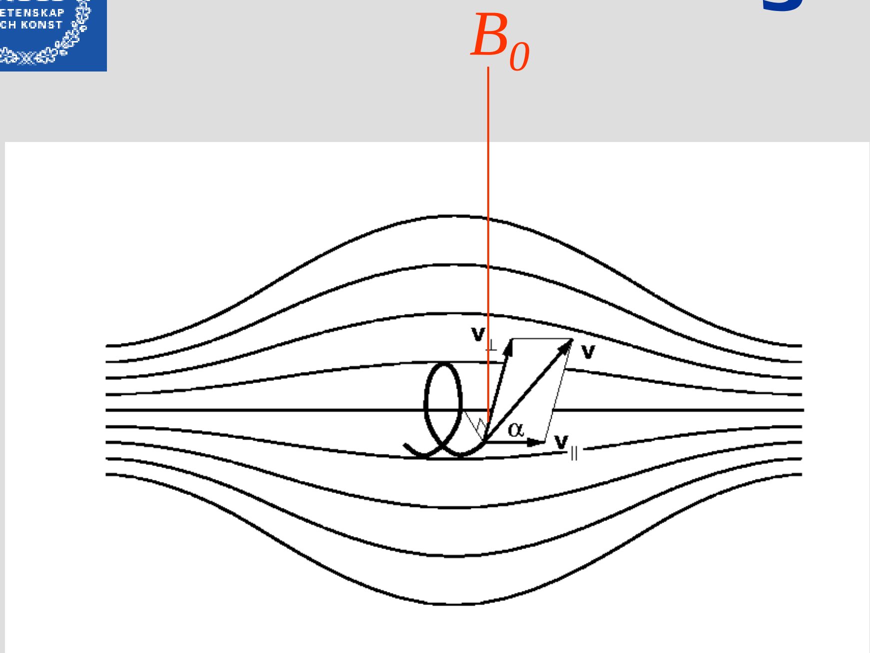
An **adiabatic invariant** is a property of a physical system which stays constant when changes are made slowly.

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



$mv^2/2$ constant (energy conservation)

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

particle turns when $\alpha = 90°$

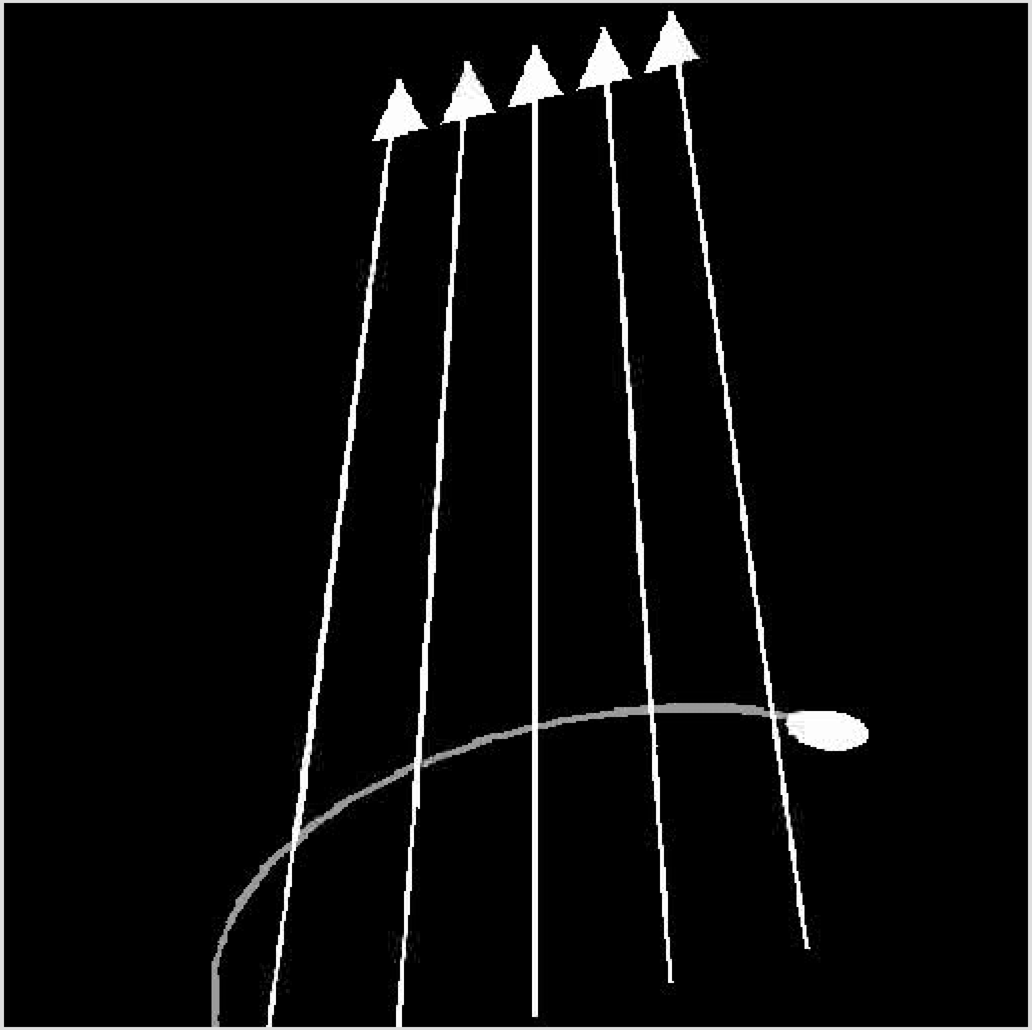
$$\frac{B_{turn}}{\sin^2 90^\circ} = \frac{B_0}{\sin^2\alpha}$$

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

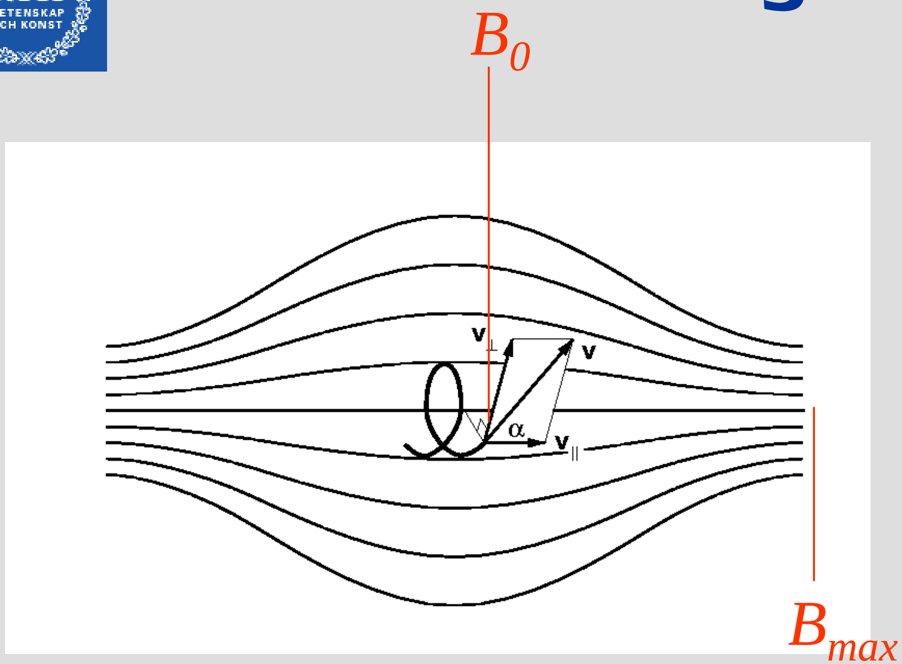
The magnetic moment μ is an ***adiabatic invariant***.

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

Magnetic mirror



Magnetic mirror



$mv^2/2$ constant (energy conservation) ⇒

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

particle turns when α = 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

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

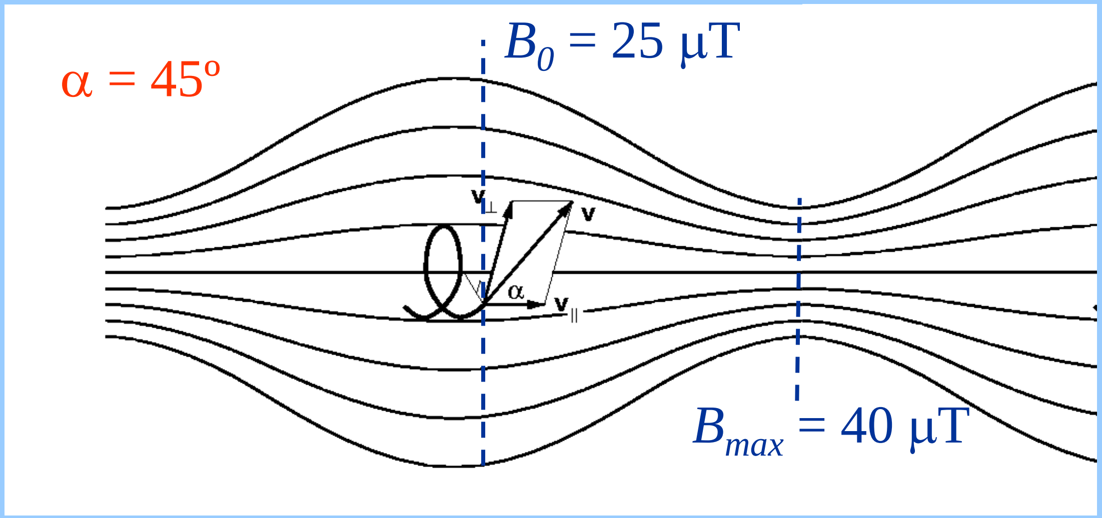
$$\alpha > \alpha_{lc} = \arcsin\sqrt{B_0 / B_{\max}}$$

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

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

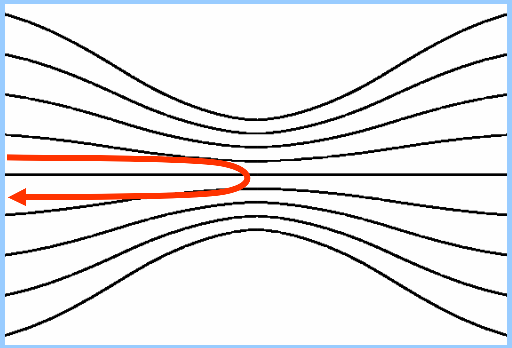
Particles in ***loss cone*** : $\alpha < \alpha_{lc}$

What will happen to the particle?

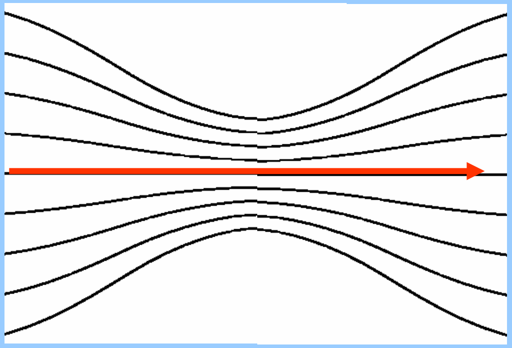


$$\alpha_{lc} = \arcsin \sqrt{B_0 / B_{\max}}$$

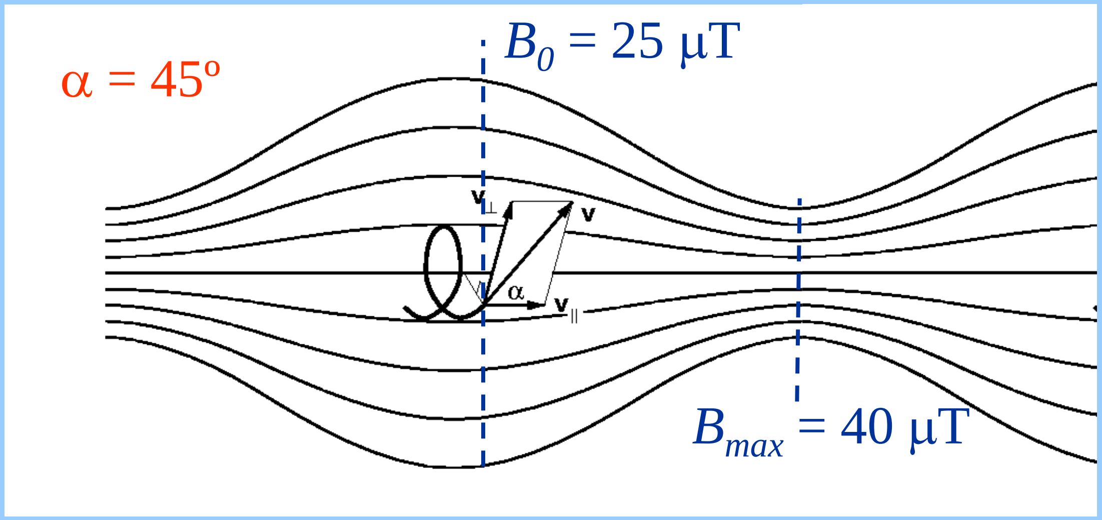
Blue It will mirror



Yellow It will escape

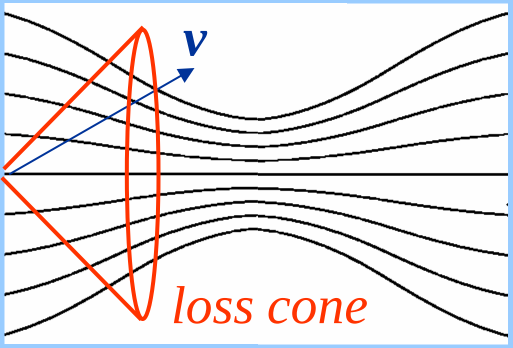


What will happen to the particle?



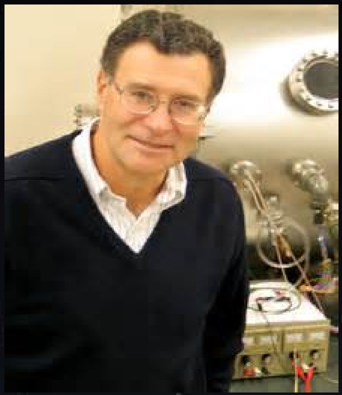
$$\alpha_{lc} = \arcsin\sqrt{B_0 / B_{\max}} =$$
$$\arcsin\sqrt{25/40} = 52°$$

Yellow It will escape



Alfvén Lecture 2014

Magnetospheric Multi-Scale, a multi-satellite mission to study the Mysteries of Magnetic Reconnection



Professor Roy Torbert

29 sept 2014 at 1300

Sal E1, Lindstedsvägen 3,
KTH, Stockholm

Professor Physics
Associate Director, EOS
University of New Hampshire
Durham, NH 03824
1-603-862-1638

and

Director, SwRI-EOS,
Southwest Research Institute
162 Morse Hall,
Durham, NH 03824
1-603-609-8720

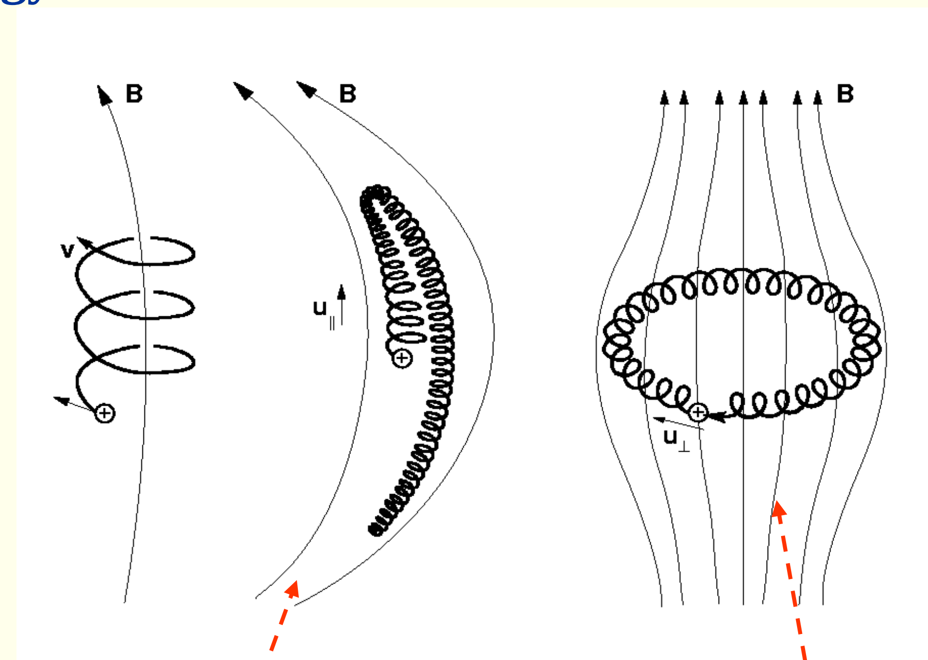
4 identical satellites in formation,
in eccentric orbits around Earth
Launch & operations: 2014-2016

***Reconnection** is a universal space plasma process, transferring energy and momentum between magnetic fields & charged particles*

KTH Space Centre Open Lecture programme

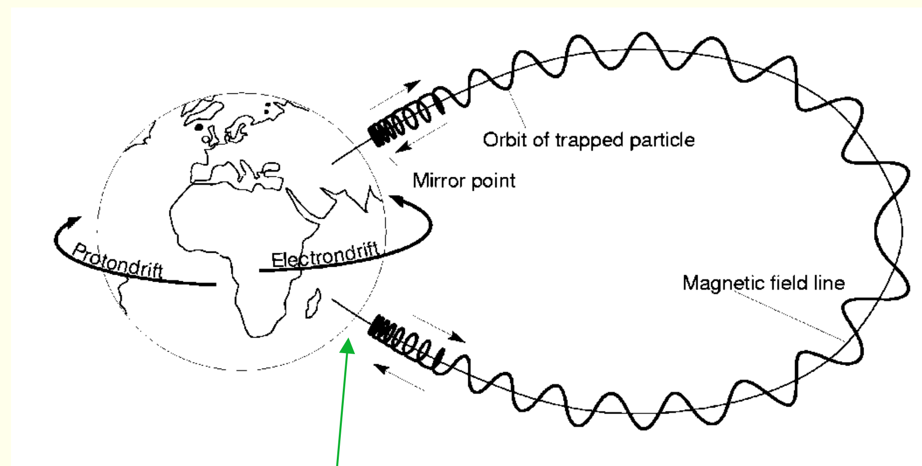
Particle motion in geomagnetic field

gyration longitudinal oscillation azimuthal drift



Magnetic mirror

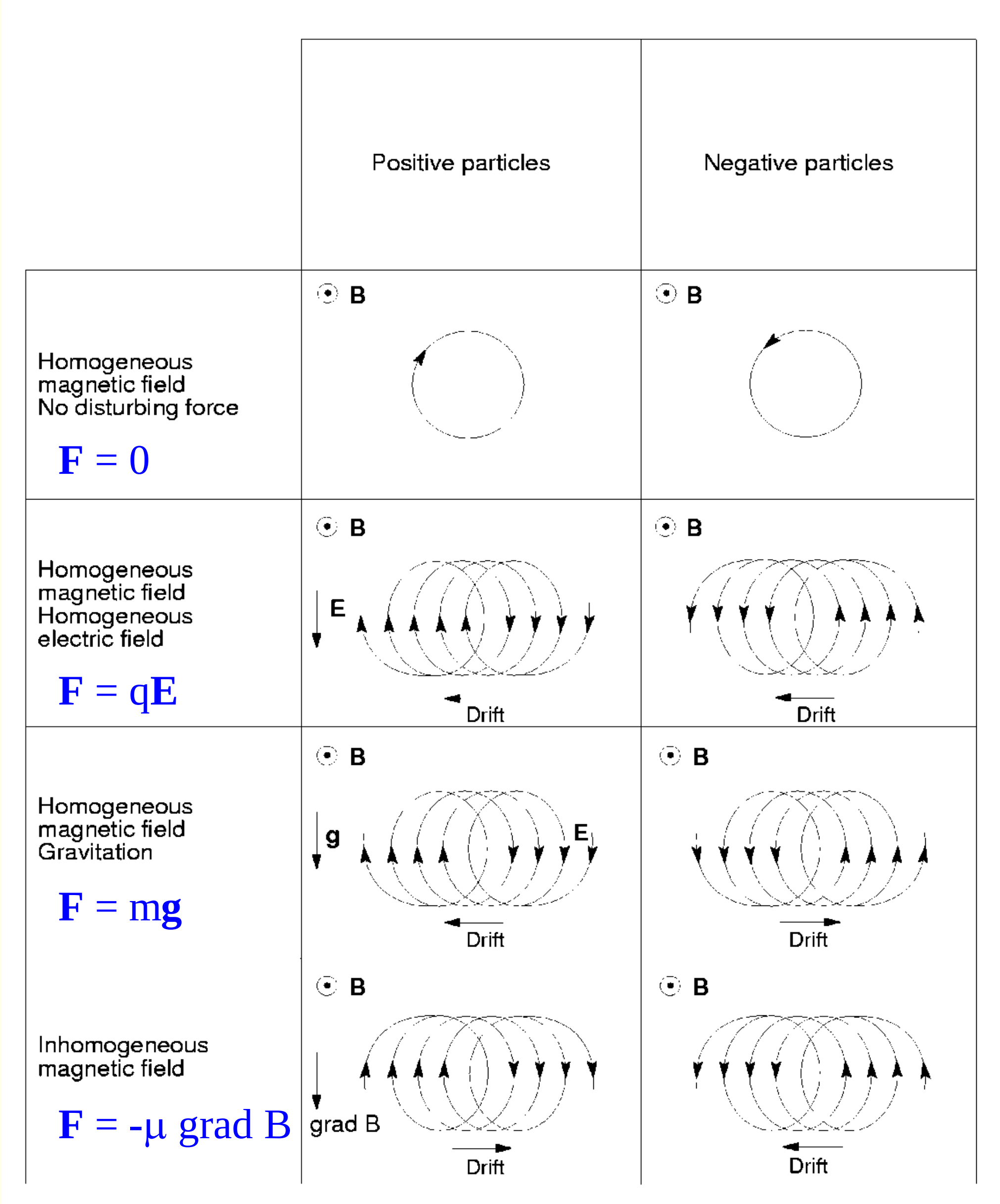
grad B drift



Particles in the loss cone create the aurora!

Drift motion

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

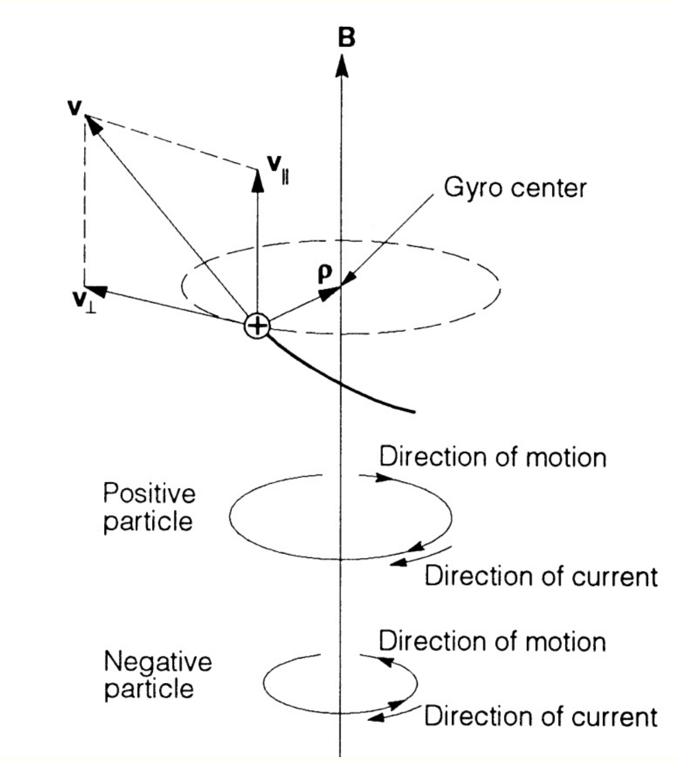


Force on magnetic dipole

$$\boldsymbol{\mu} \sim -\mathbf{B} \quad \Rightarrow \quad \boldsymbol{\mu} = -\mu \frac{\mathbf{B}}{B}$$

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

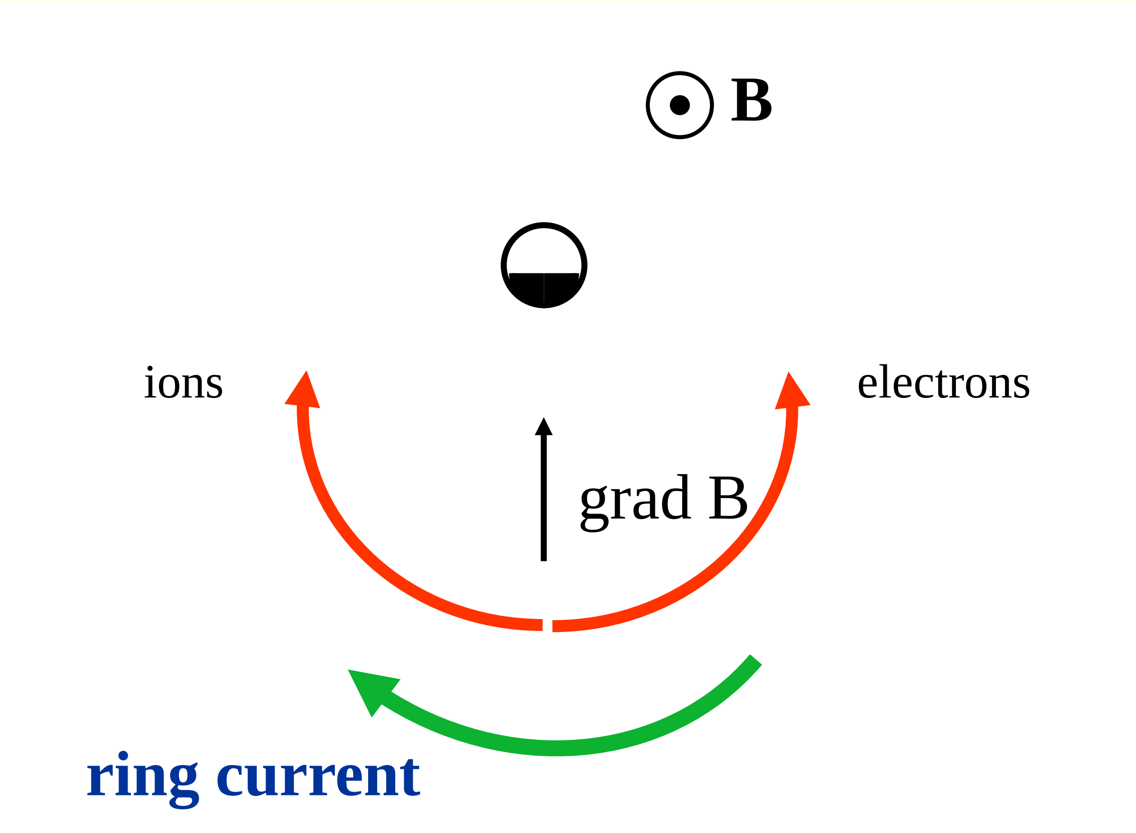
$$= -\mu \nabla \left(\frac{B^2}{B} \right) = -\mu \nabla B$$



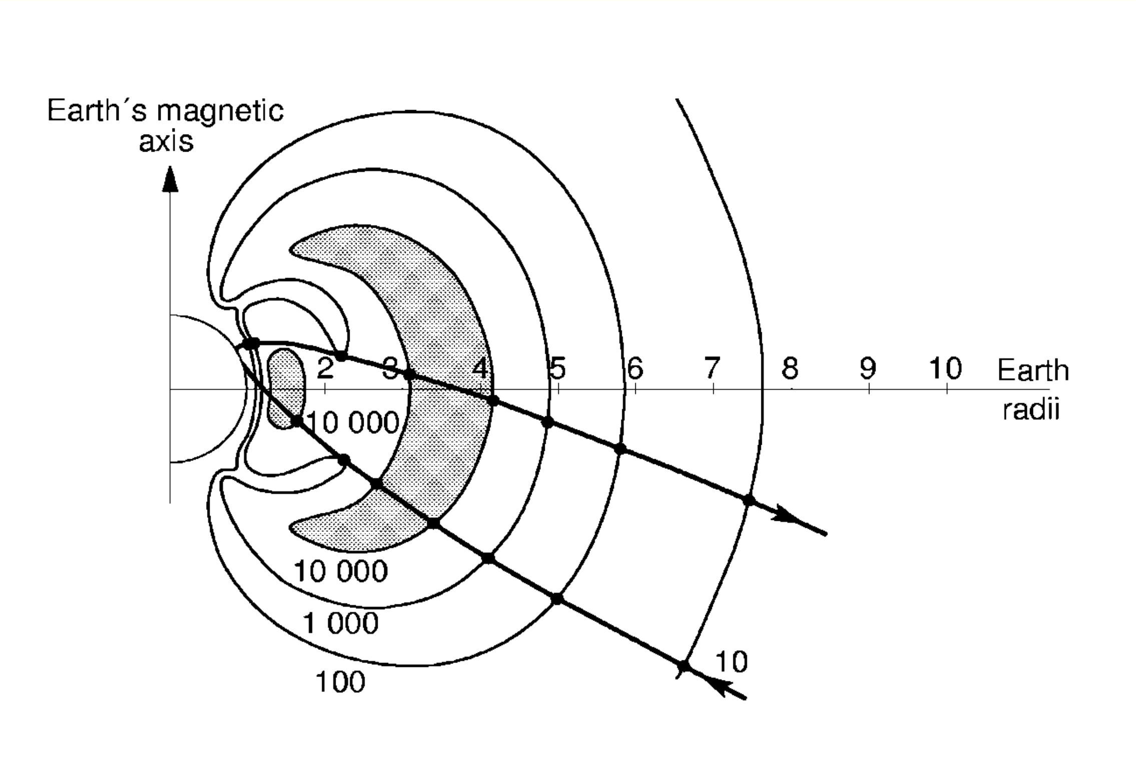
Ring current and particle motion

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

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



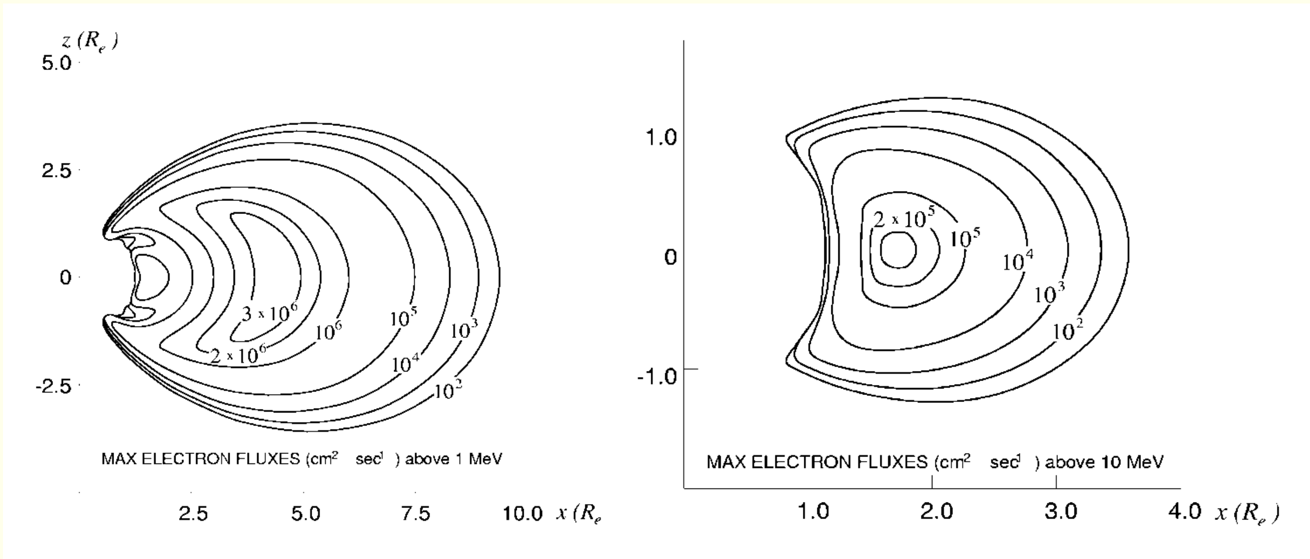
Radiation belts



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



- 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

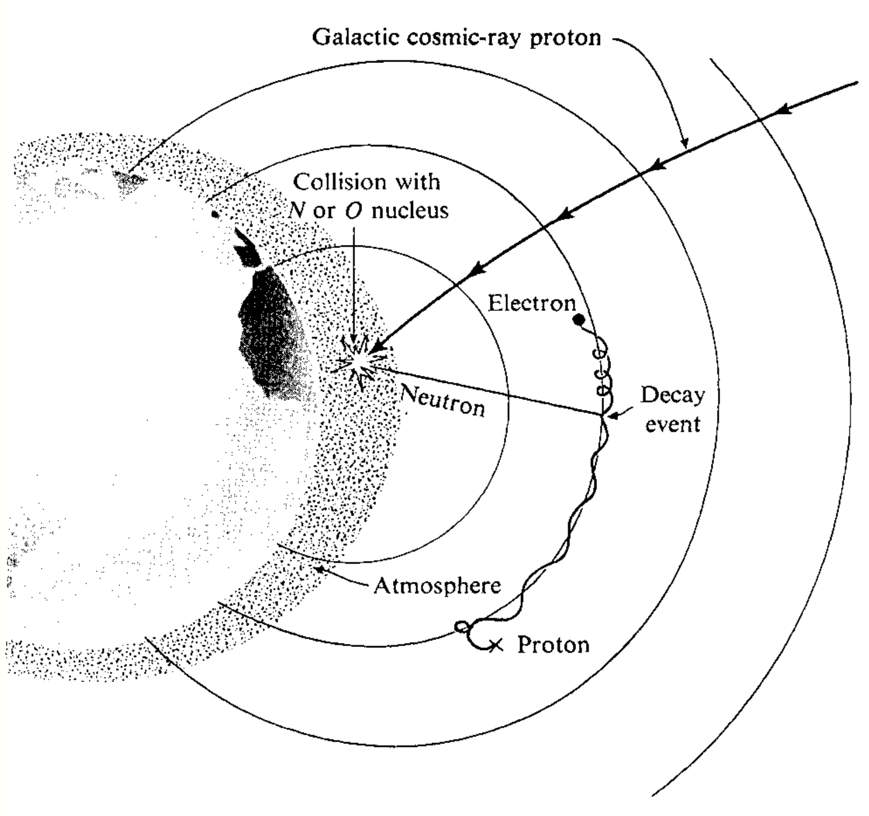
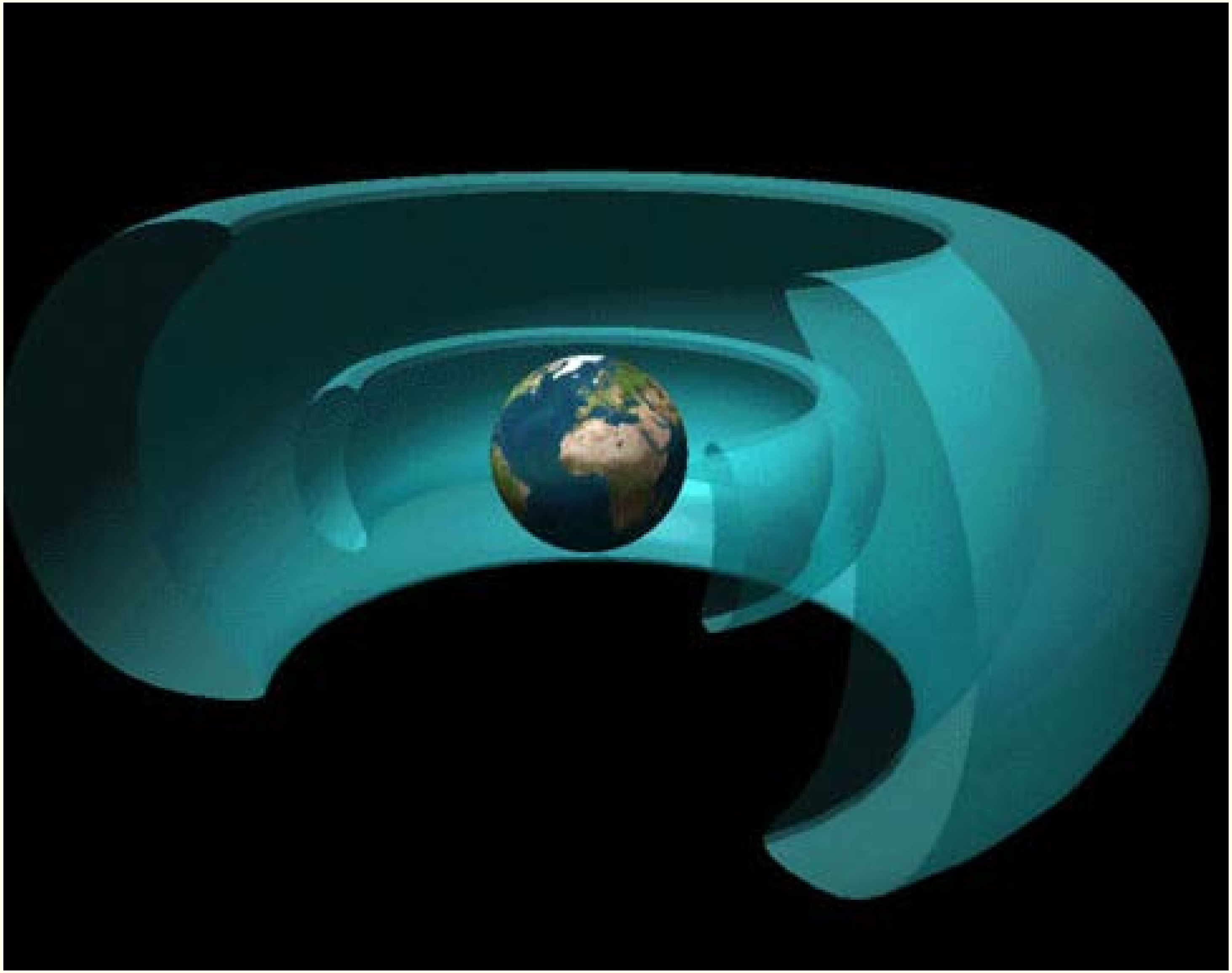


Figure 8. An illustration of the CRAND process for populating the inner radiation belts [Hess, 1968].

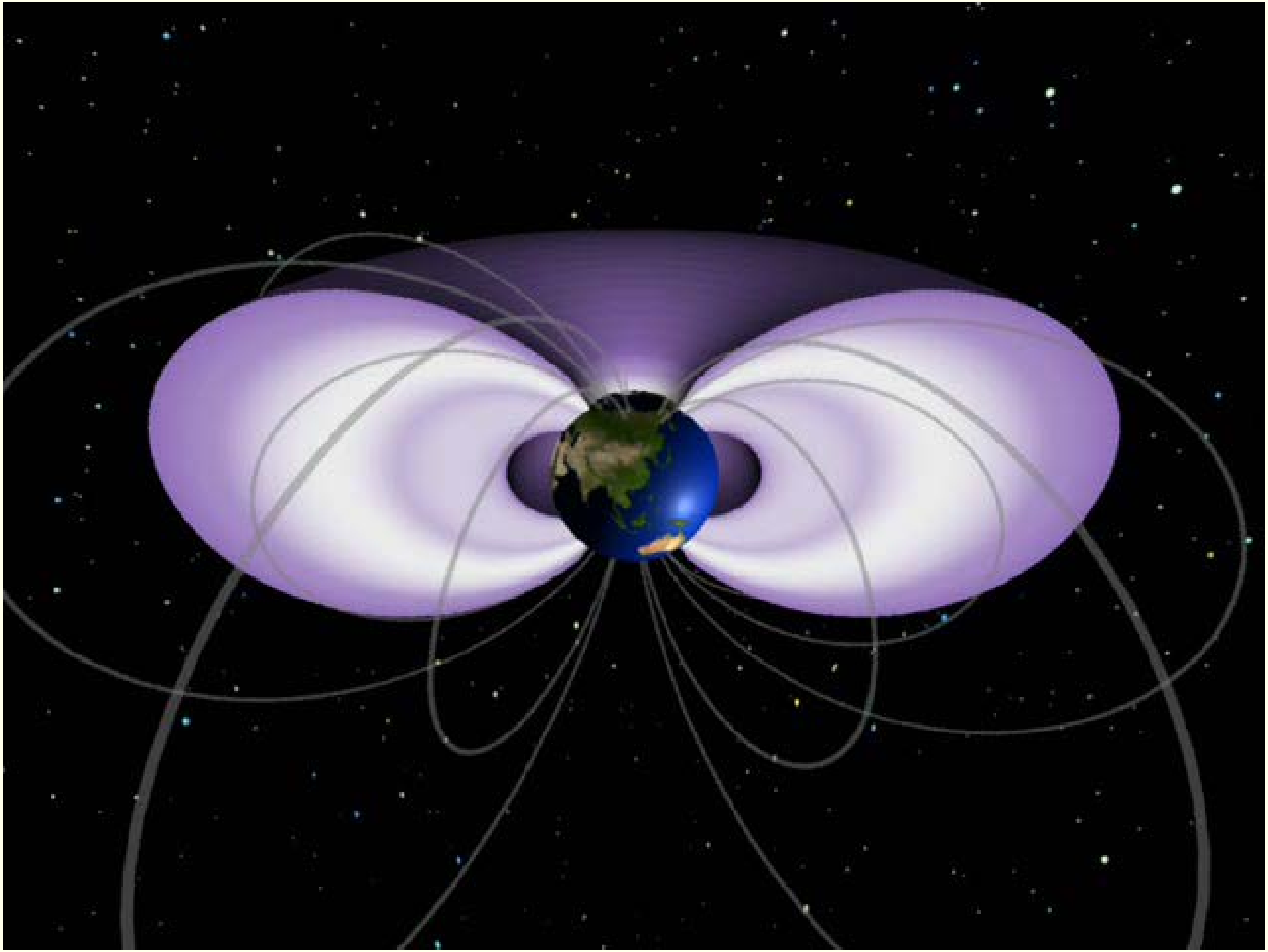
Collisions between cosmic ray particles and the Earth create new particles. Among these are neutrons, that are not affected by the magnetic field. They decay, soom eof them when they happen to be in the radiation belts. The resulting protons and electrons are trapped in the radiation belts.

This contribution to the radiation belts are called the ***neutron albedo***.

Radiation belts



Radiation belts

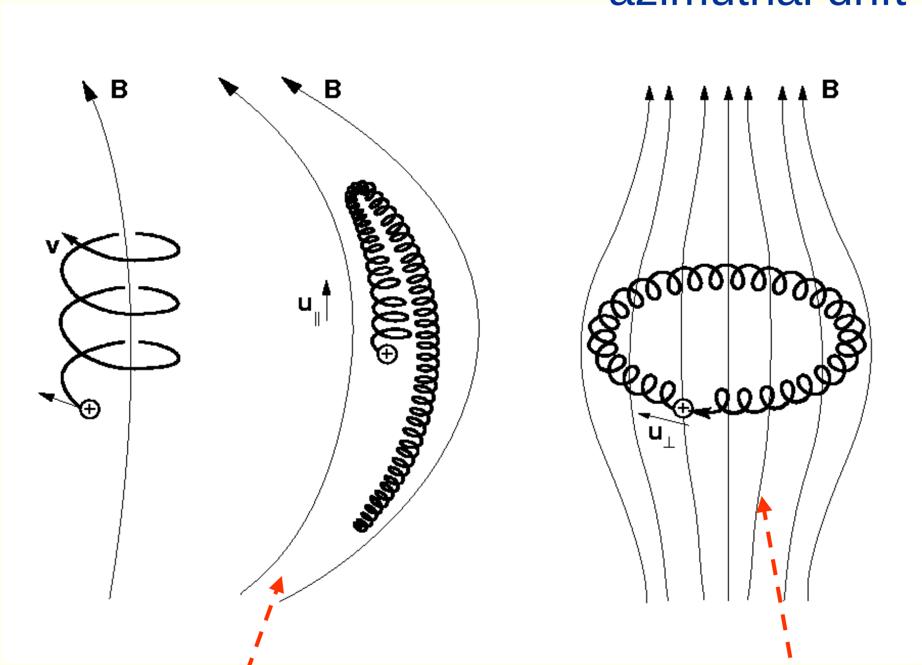


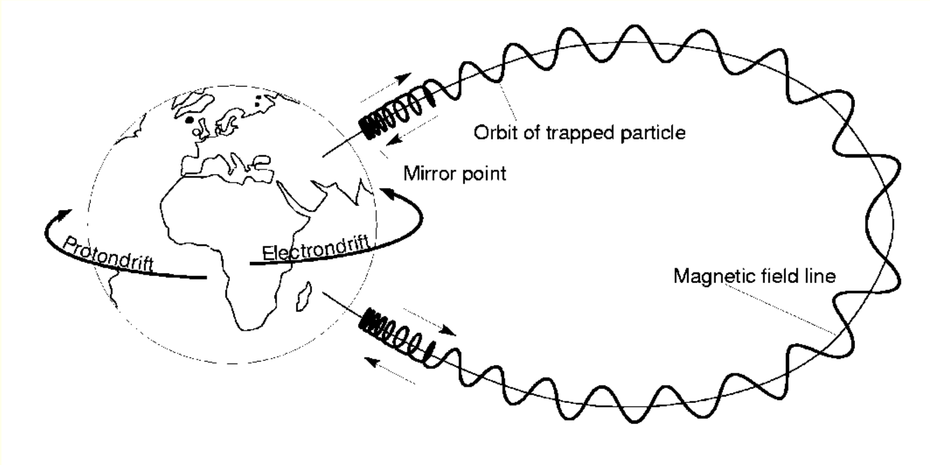
Particle motion in geomagnetic field

longitudinal oscillation

gyration

azimuthal drift

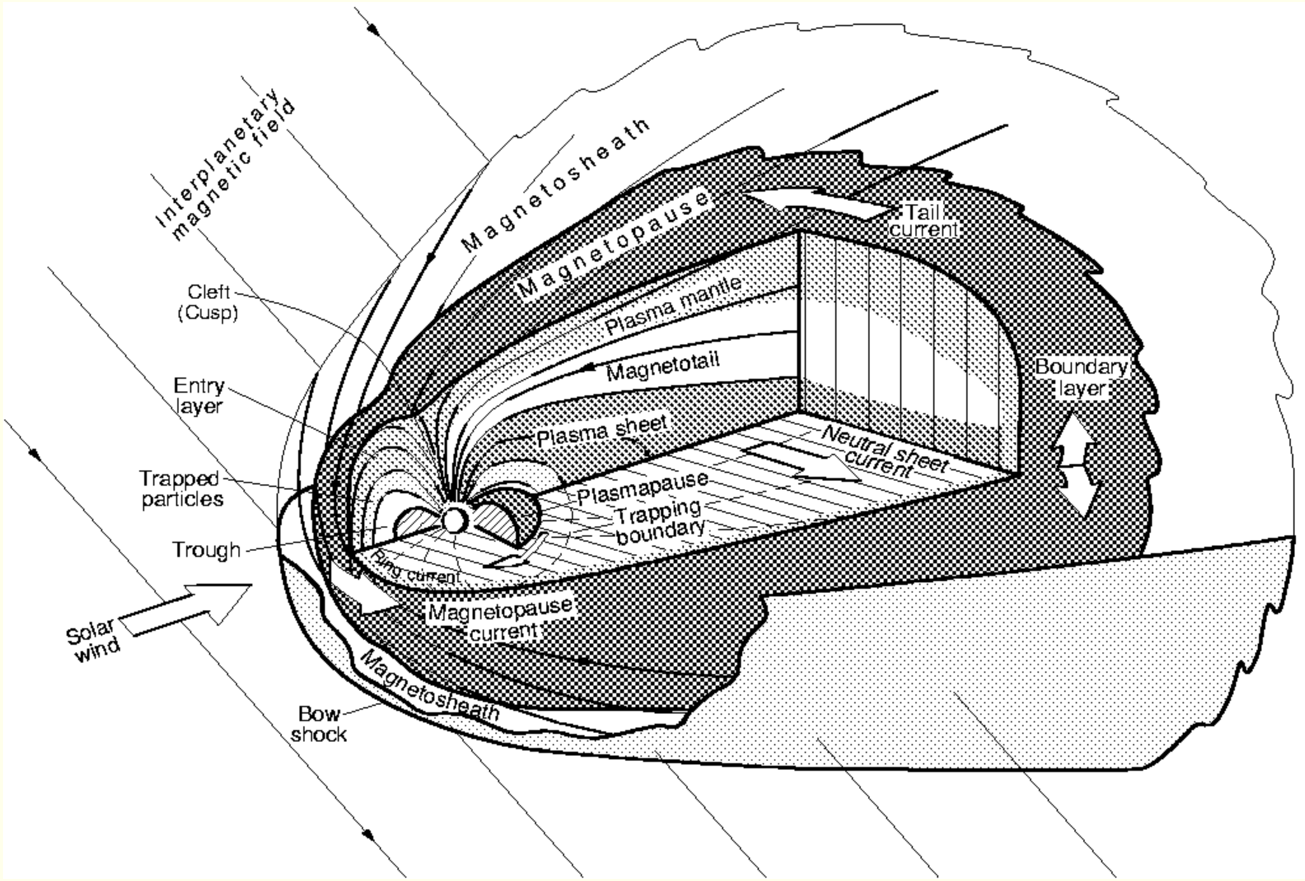




Magnetic mirror

grad B drift

Structure of magnetosphere

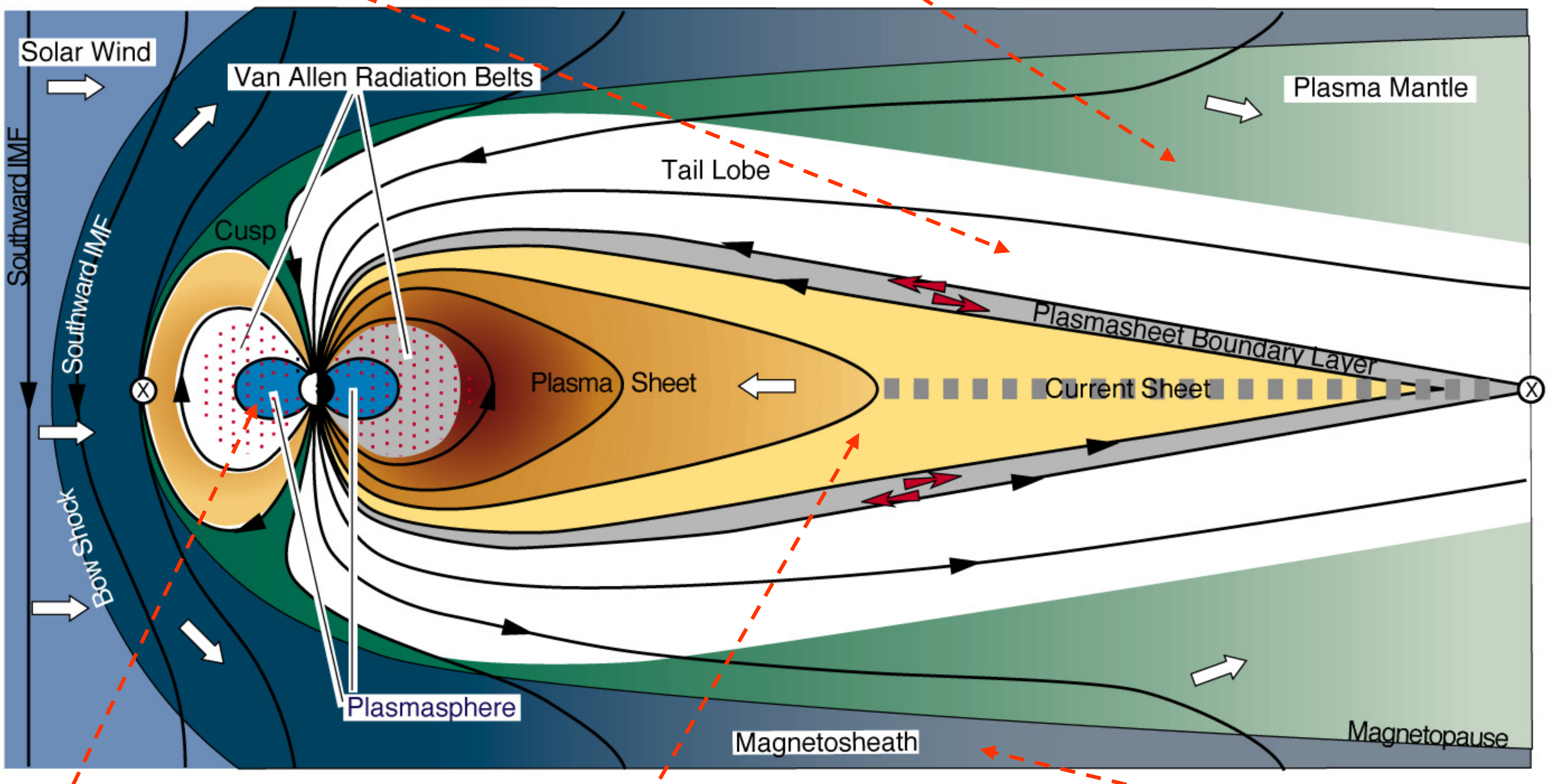


- The plasma in the is made up of approximately equal parts of H^+ and O^+.
- Plasma populations organized by geomagnetic field.
- Particles will mirror between northern and southern hemispheres on closed field lines

Magnetospheric structure

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

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

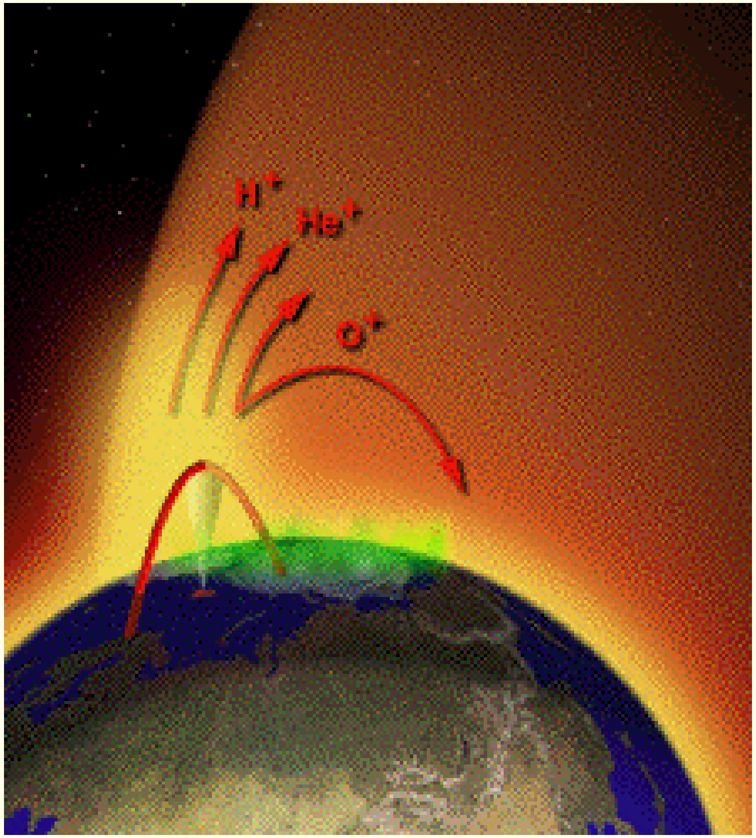


plasmasphere:
$n_e \sim 10\text{-}100\ \mathrm{cm}^{-3}$, $T_e \sim 1000$ K

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

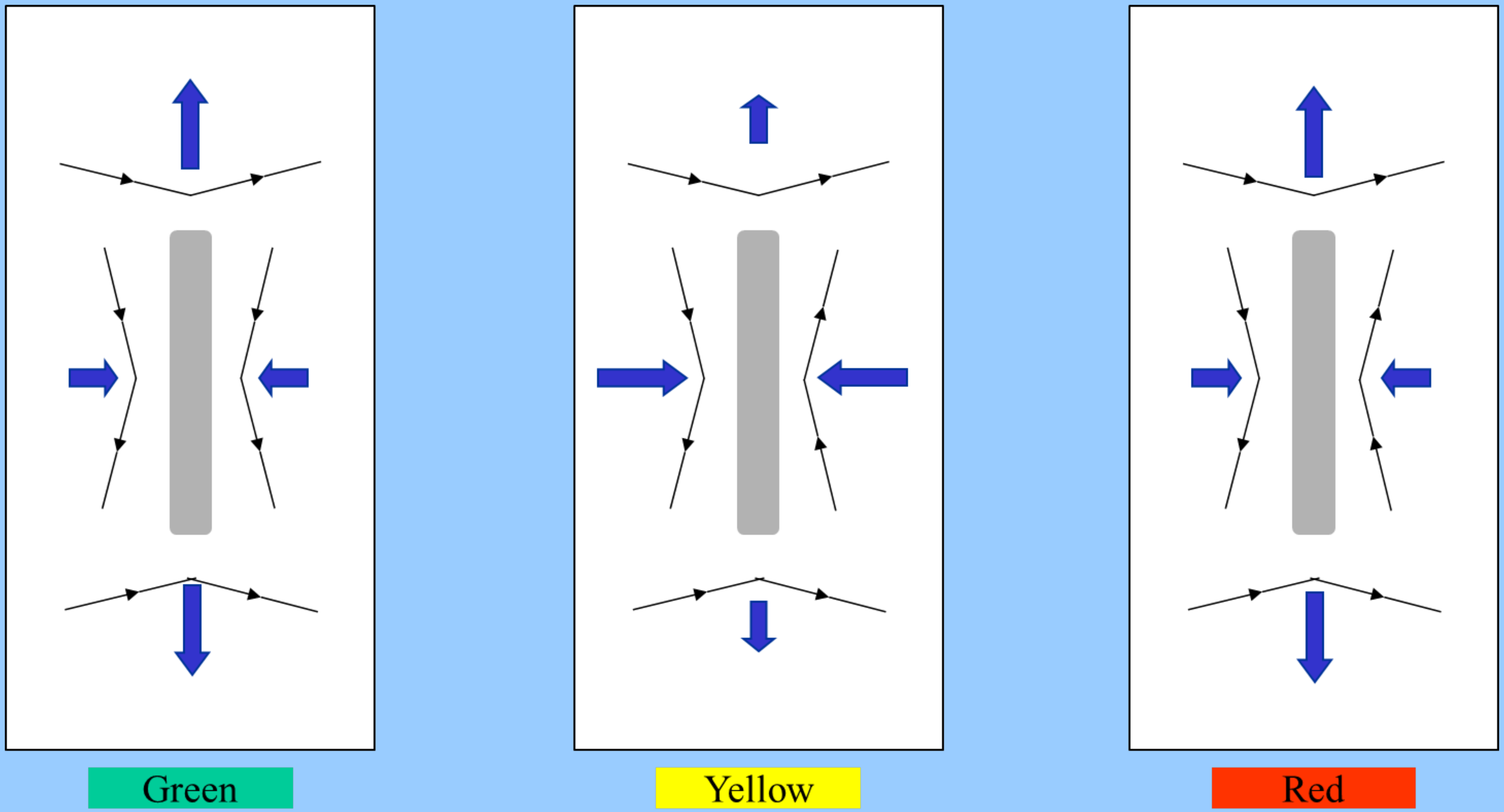
magnetosheath:
$n_e \sim 5\ \mathrm{cm}^{-3}$, $T_e \sim 10^6$ K

Outflow from the ionosphere

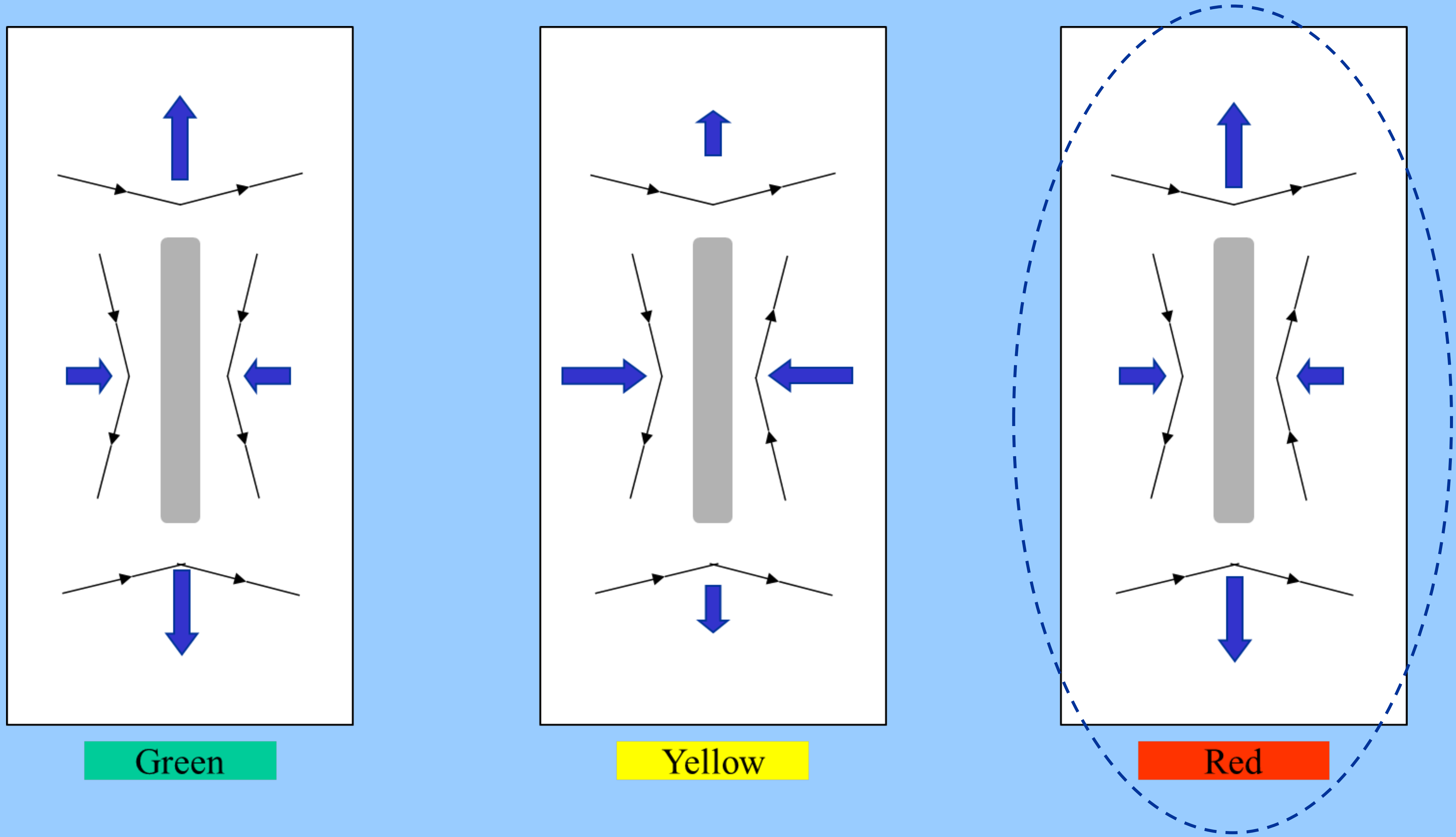


An important source for the magnetospheric plasma. Research is ongoing.

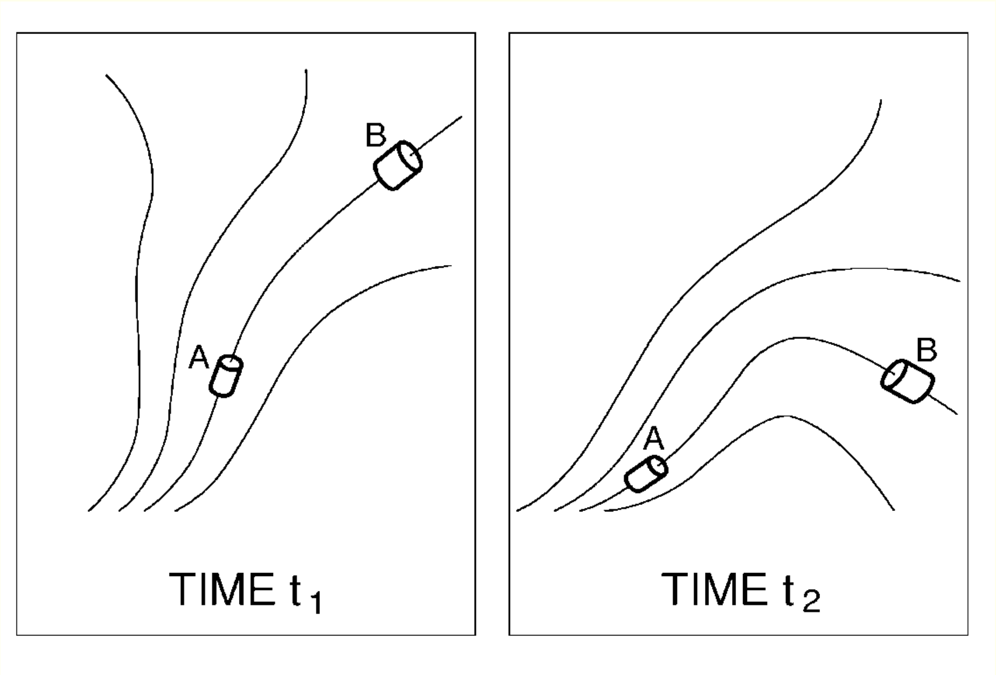
Magnetic reconnection



Magnetic reconnection



Frozen in magnetic field lines



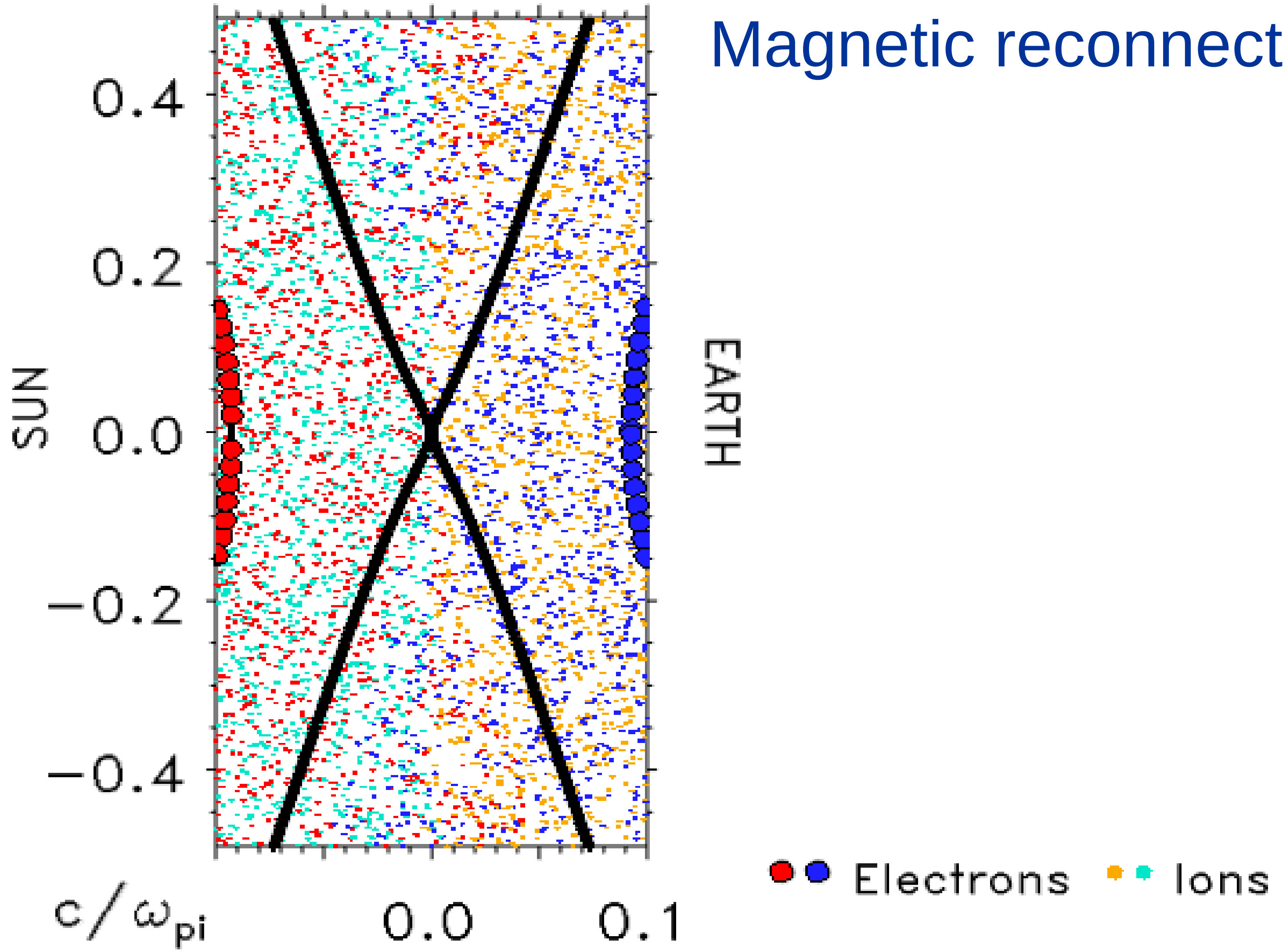
In fluid description of plasma two plasma elements that are connected by a common magnetic field line at time t_1 will be so at any other time t_2.

This applies if the magnetic Reynolds number is large:

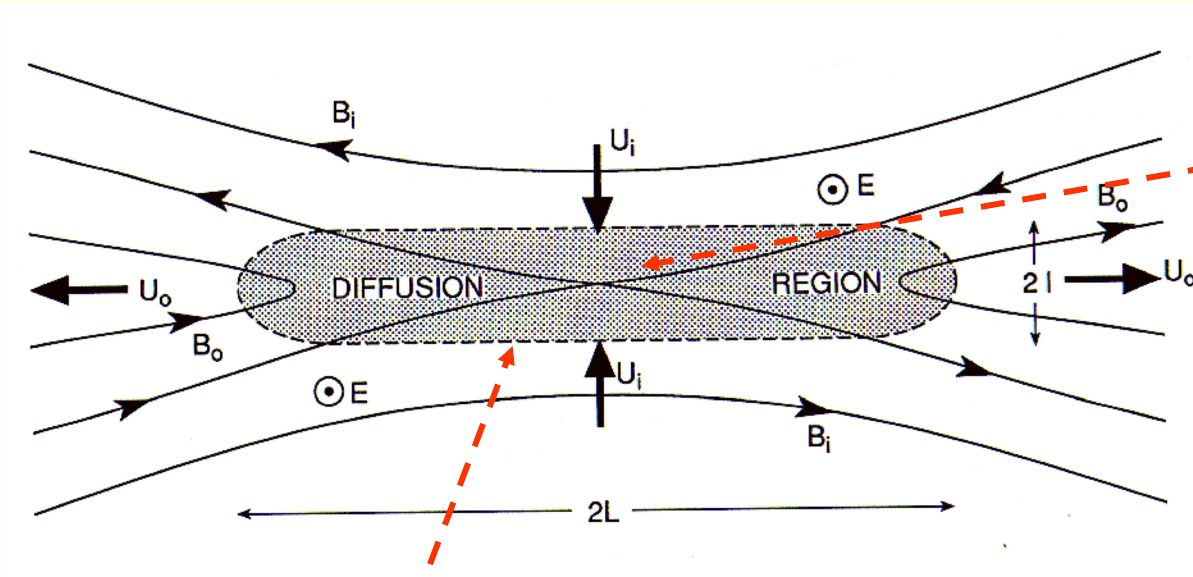
$$R_m = \mu_0 \sigma l_c v_c >> 1$$

An example of the collective behaviour of plasmas.

Magnetic reconnection



Reconnection



In 'diffusion region':

$R_m = \mu_0 \sigma l v \sim 1$

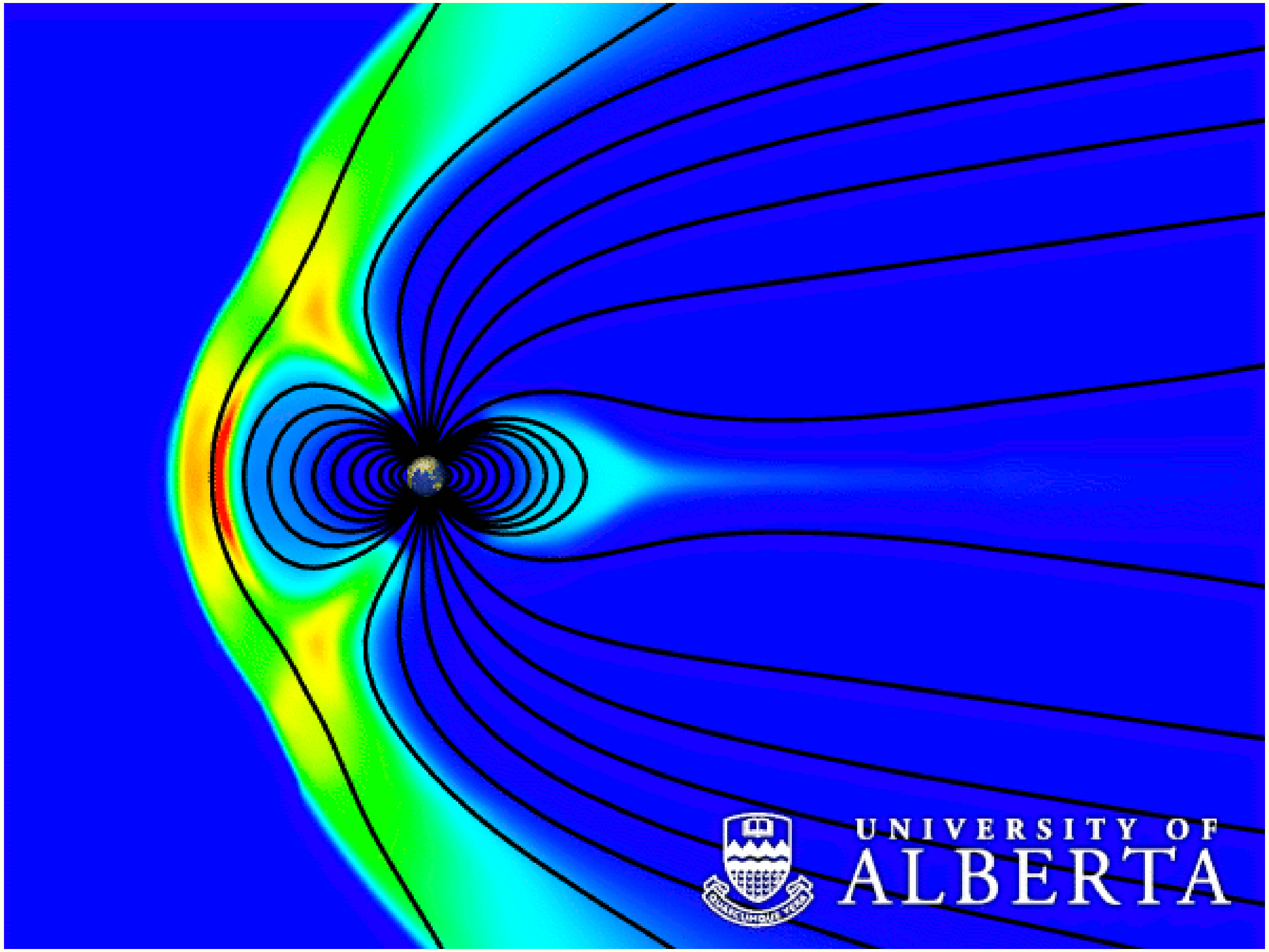
Thus: condition for frozen-in magnetic field breaks down.

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 ($U_o >> U_i$)**
- **Plasma from different field lines can mix**

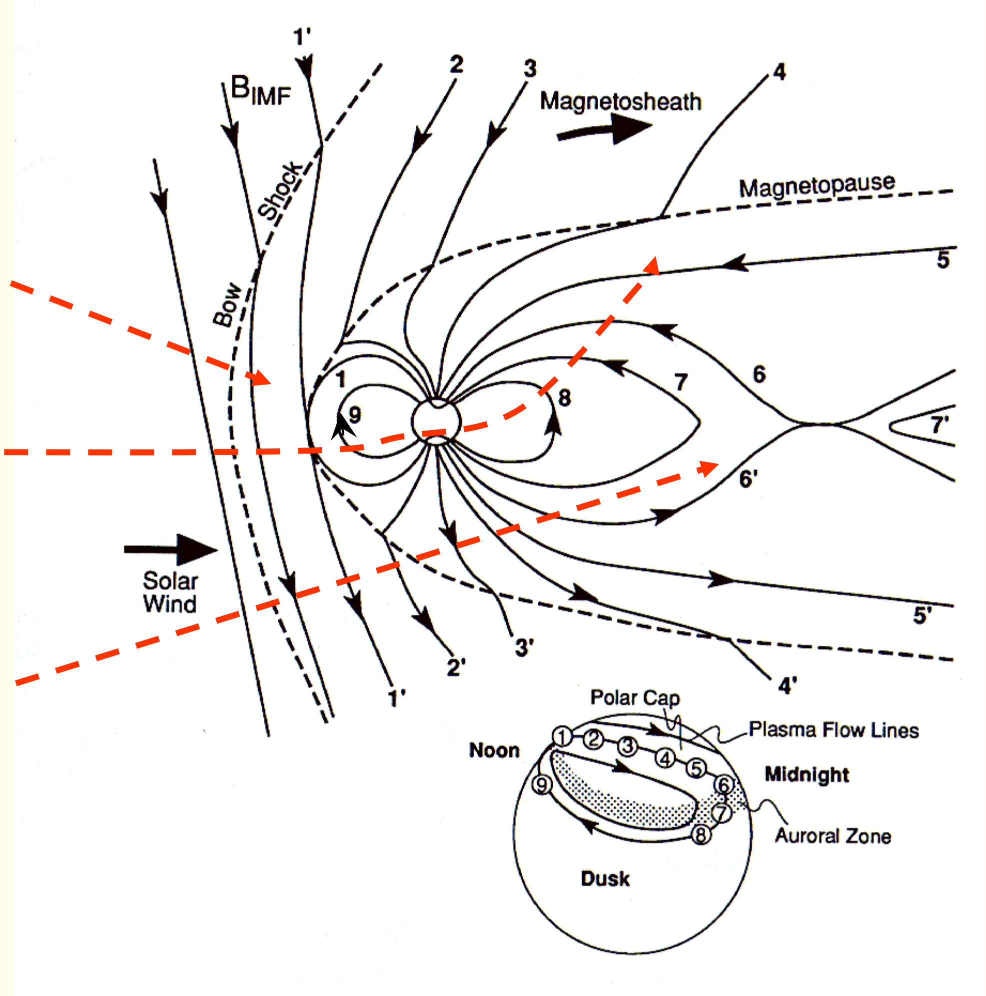
Reconnection and plasma convection

Solar wind

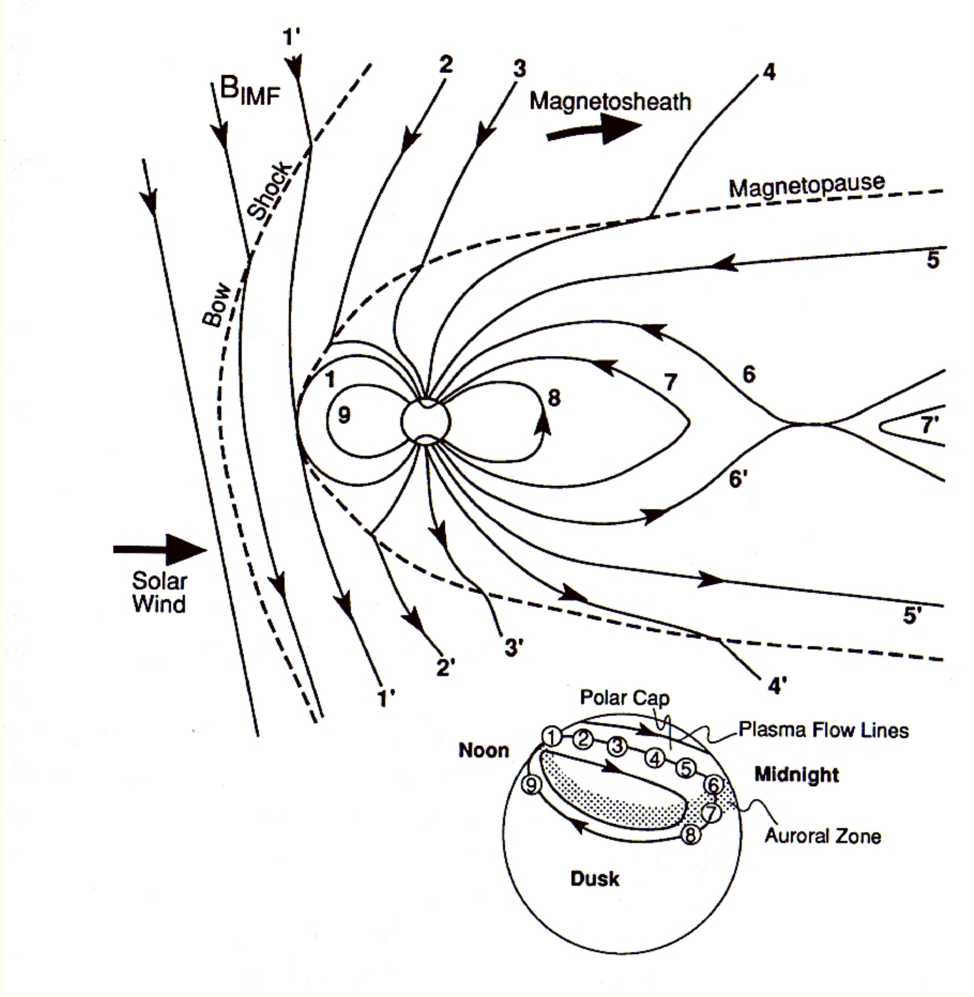


Reconnection och plasma convection

- 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.

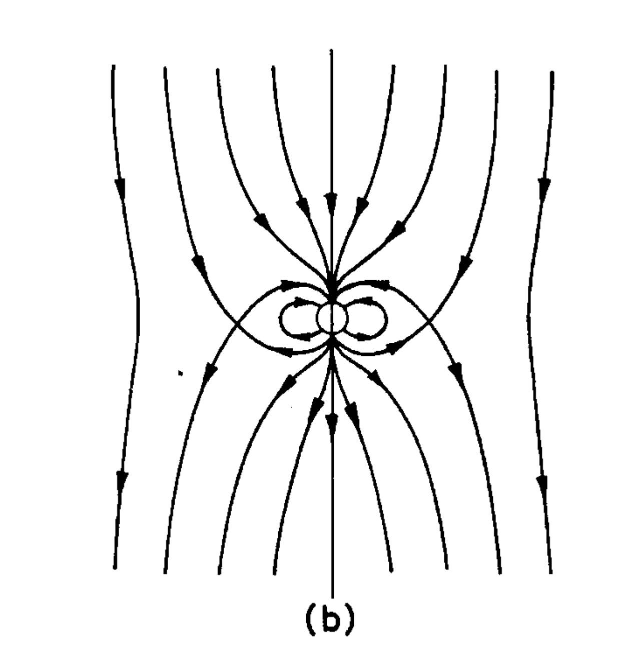


What happens if IMF is northward instead?

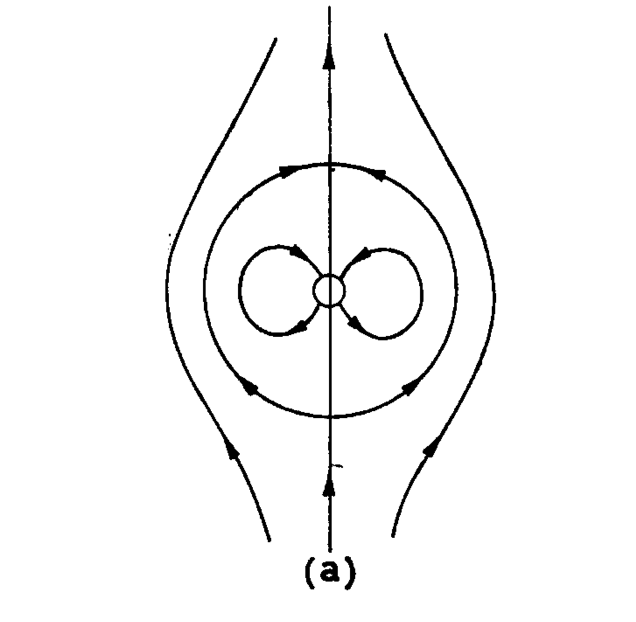


Magnetospheric dynamics

open magnetosphere



closed magnetosphere



southward

Interplanetary magnetic field (IMF)

northward

What do the magnetospheres of the other planets look like?

Planetary magnetospheres

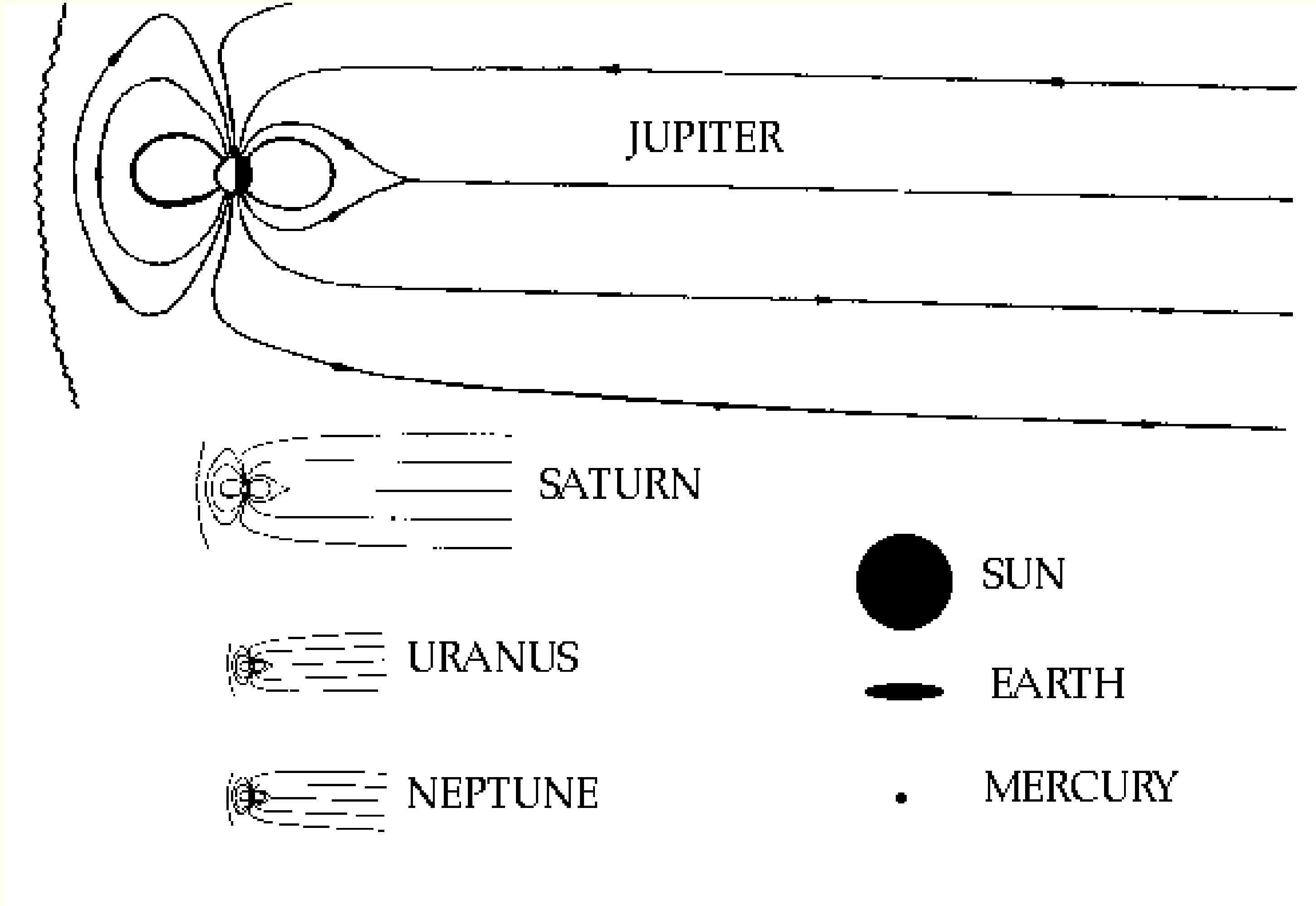
	Radius Earth radii	Spin period (days)	Equatorial field strength (μT)	Magnetic axis direction relative to spin axis	Polarity relative to Earth´s	Typical magneto-pause distance (planetary radii)
Mercury	0.38	58.6	0.35	10^o	Same	1.1
Venus	0.95	243	< 0.03	-	-	1.1
Earth	1.0	1	31	11.5^o	Same	10
Mars	0.53	1.02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

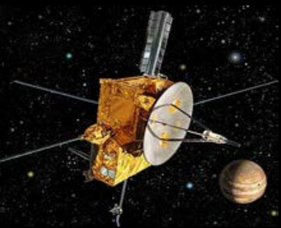


Comparative magnetospheres
In situ observations

Space probe	*Celestial body*	*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*
Rosetta	Churymov-Gerasimenko	*2014 - 2015*

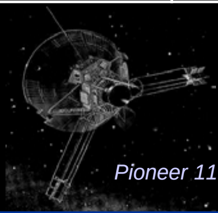
** Orbiters*


Mariner 10


Ulysses

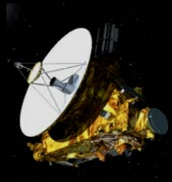

Rosetta

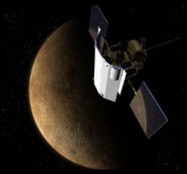

Pioneer 10


Pioneer 11


Voyager 1 and 2


Galileo


New Horizons


Messenger


Cassini

Mercury

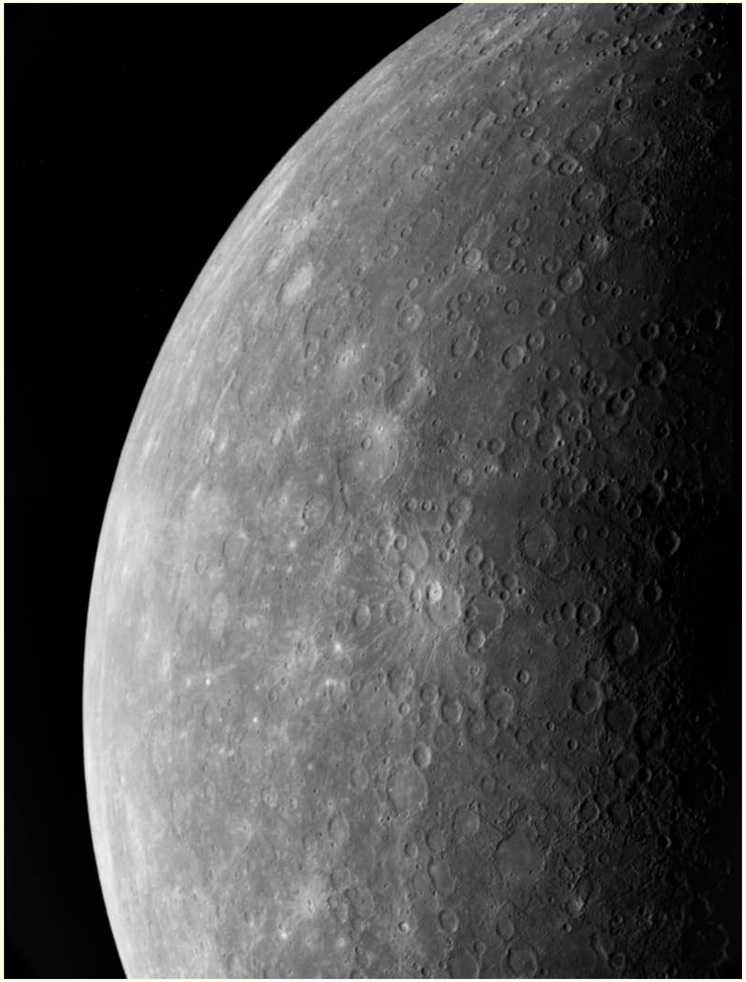
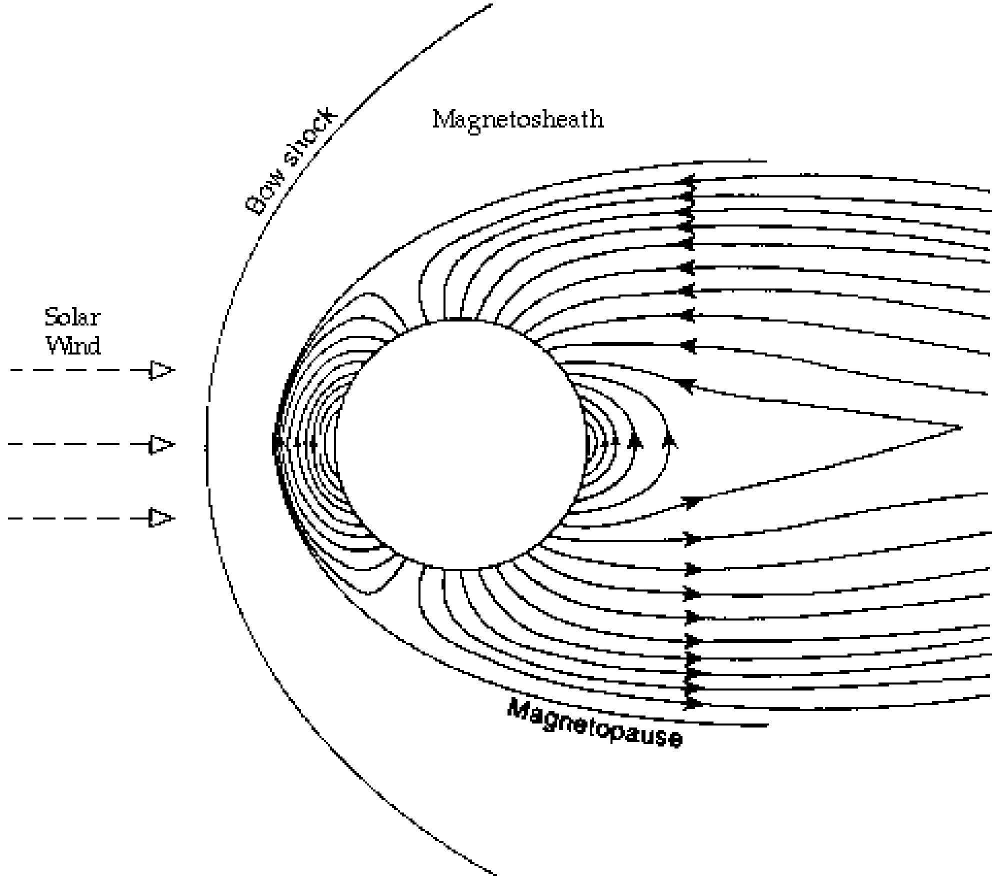


Photo from Mariner 10

- $r_M = 0,38\ r_E$
- $m_M = 0,06\ m_E$
- 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

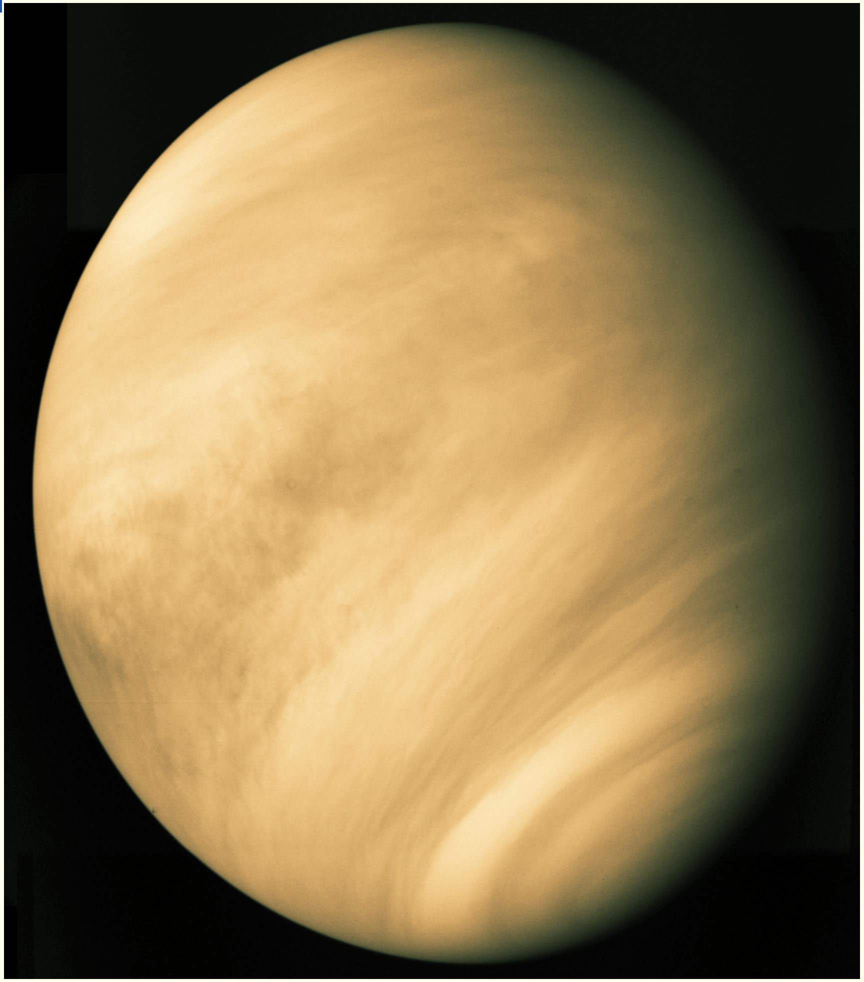
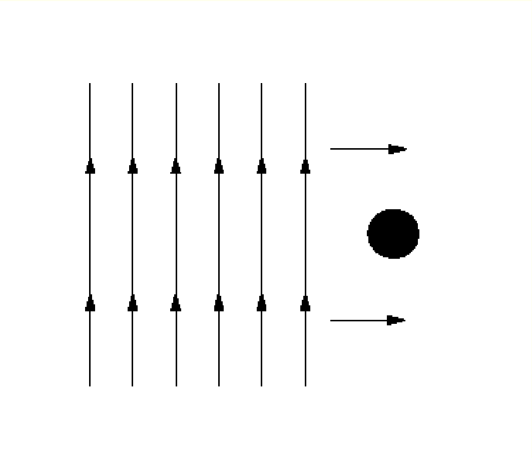


Photo from Galileo

- $r_V = 0{,}95\ r_E$
- $m_V = 0{,}82\ m_E$
- distance from sun : 0,72 AU
- very dense atmosphere
  - ~ 90 atm
  - 96% CO_2
- very weak magnetic field

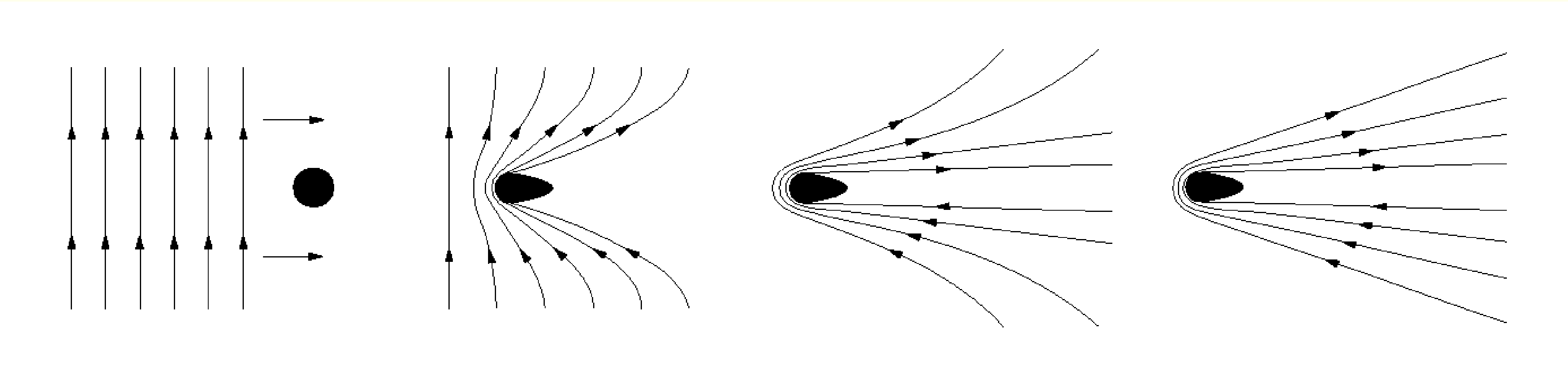
Comets, induced magnetotail



- 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

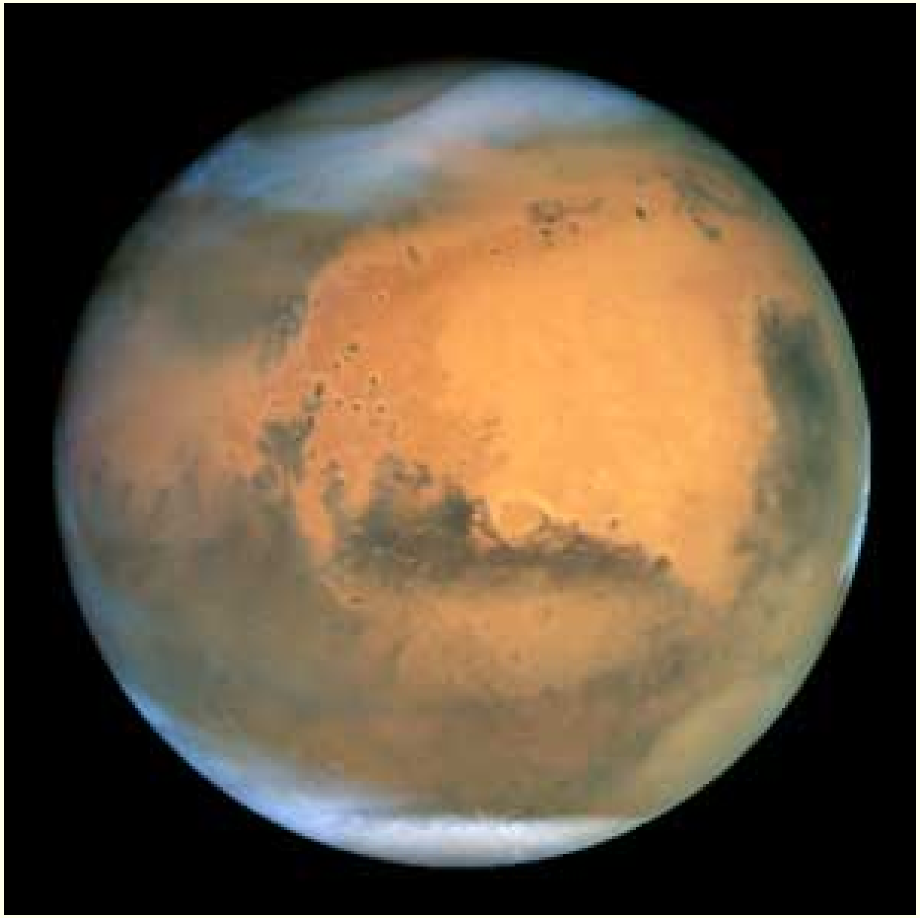


Photo from Hubble Space Telescope

- $r_M = 0,53\ r_E$
- $m_M = 0,11\ m_E$
- distance from sun : 1,52 AU
- very thin atmosphere
    - ~ 0.01 atm.
    - 95% CO_2
- very weak magnetic field

Jupiter

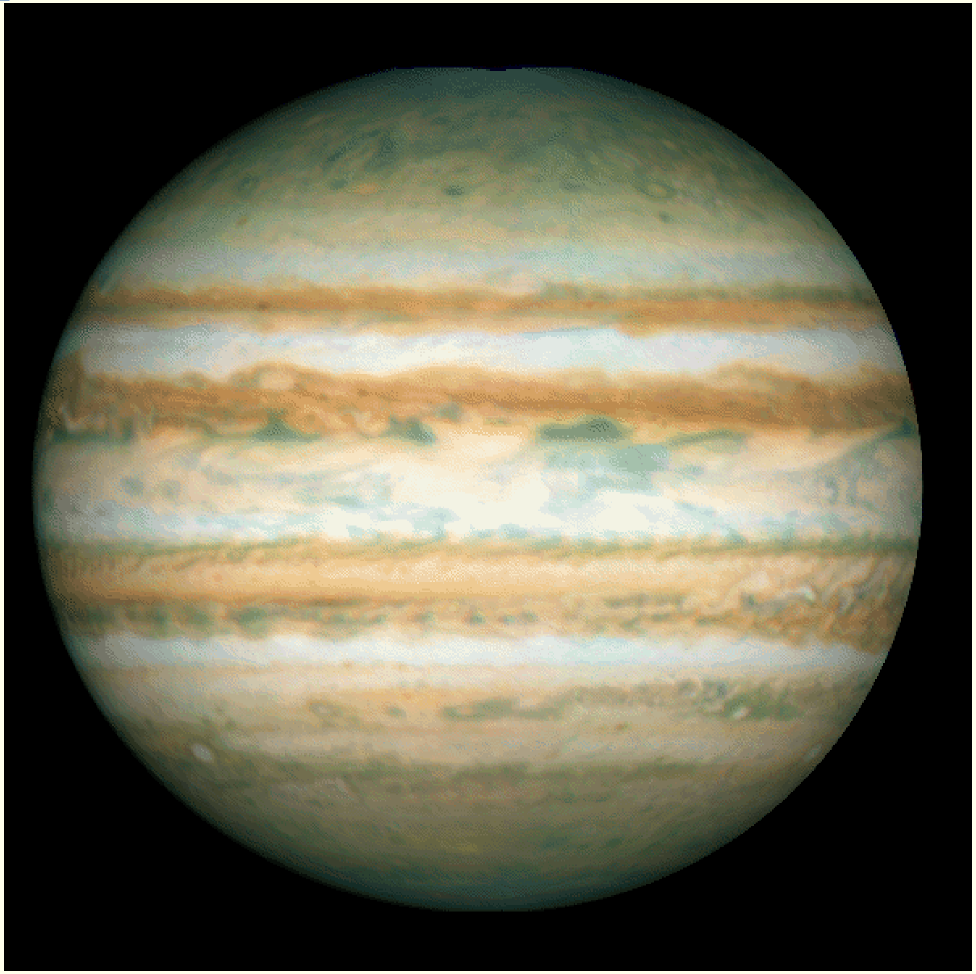
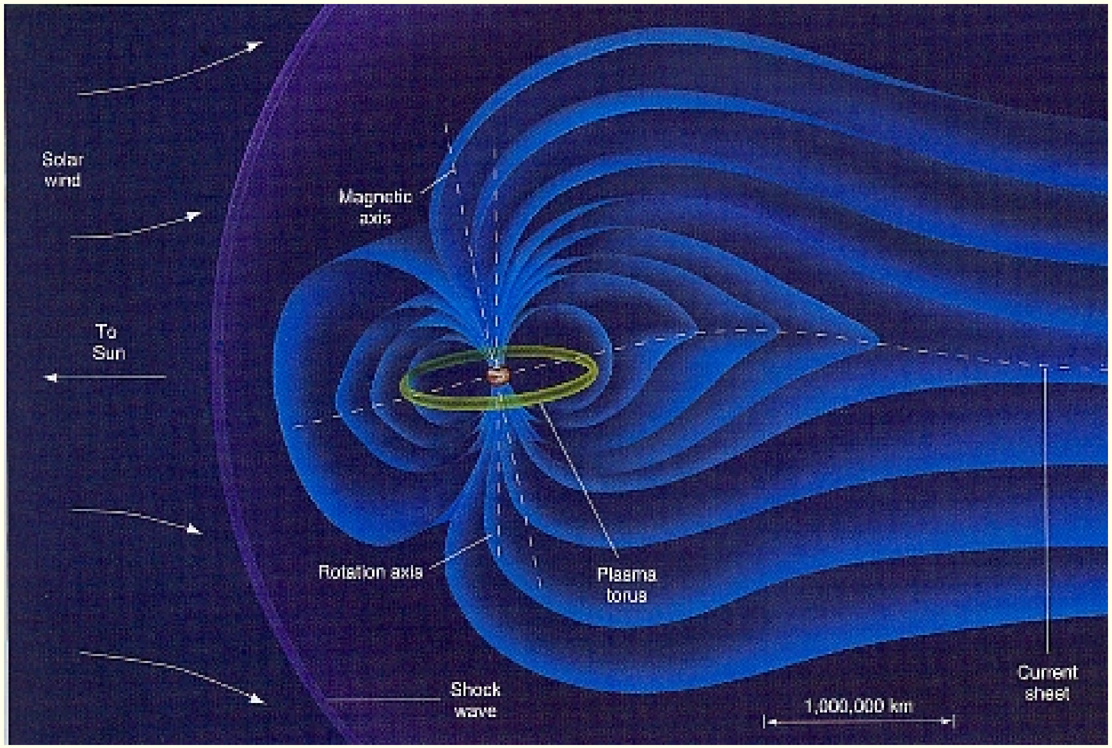


Photo from Hubble Space Telescope

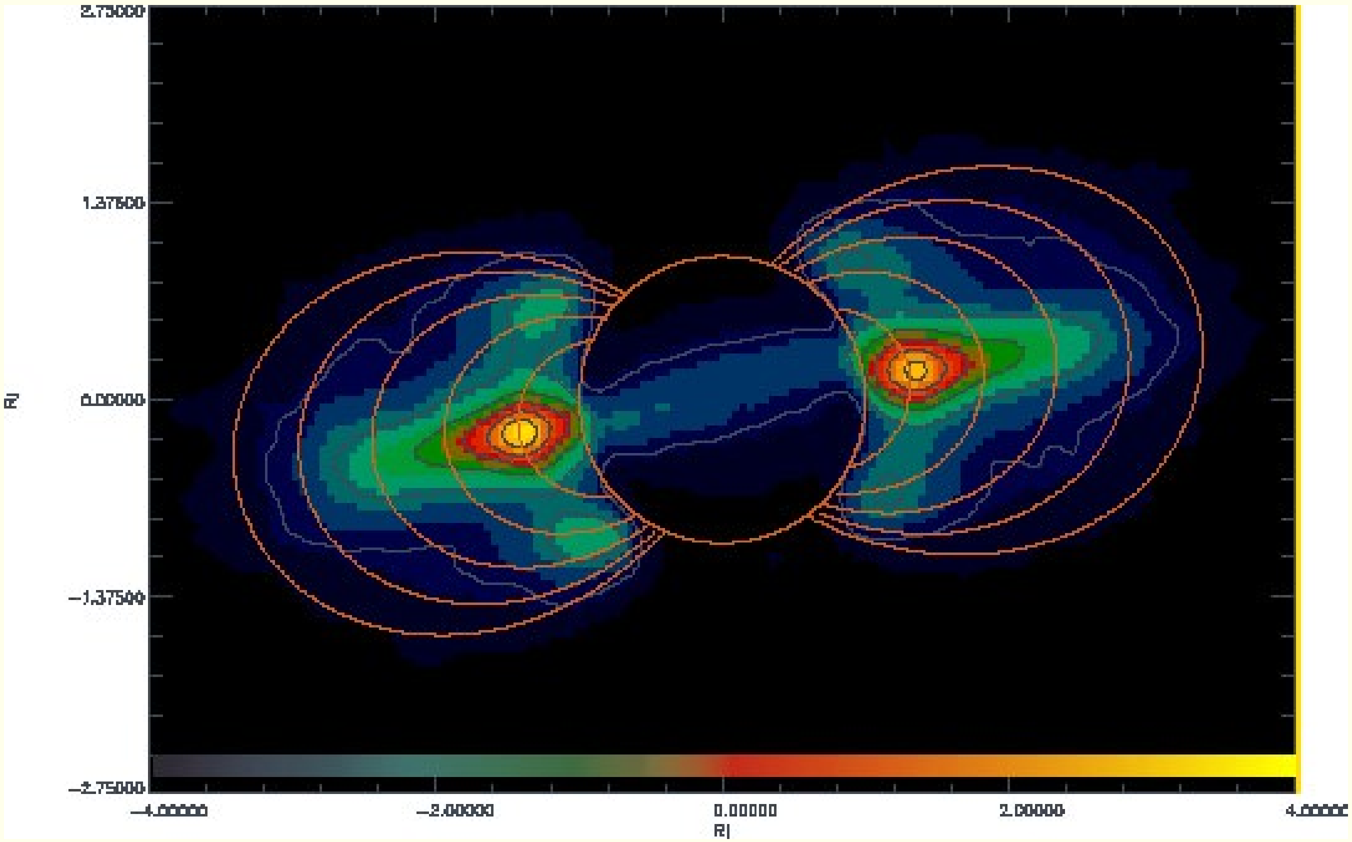
- $r_J = 11,2\ r_E$
- $m_J = 318\ m_E$
- distance from sun: 5,20 AU
- gas giant with very dense atmosphere containing hydrogen, helium, ammonium, methane, etc.
- ~ 60 moons (+ weak ring system)

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



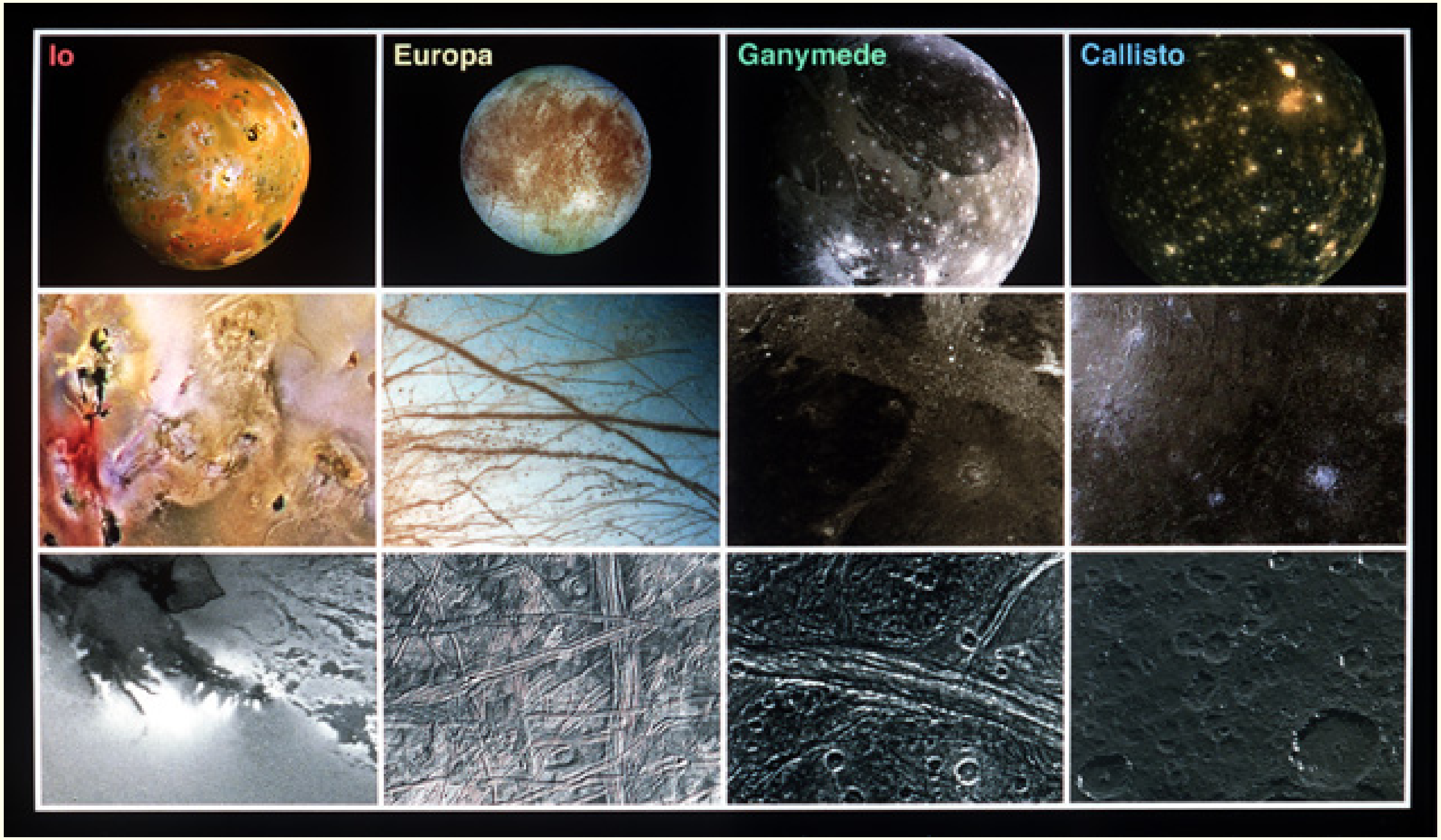
- Gyrating electrons emit "syncrotron radiation" with frequencies ~ $f_{ce} = eB/(2\pi m_e)$

- 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

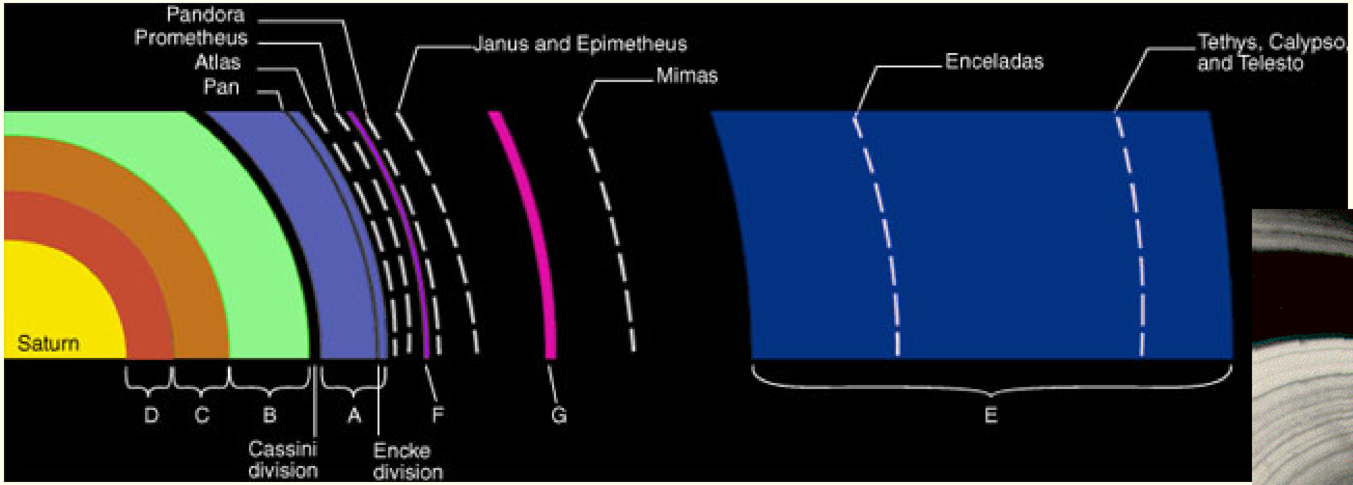
Weak magnetic field

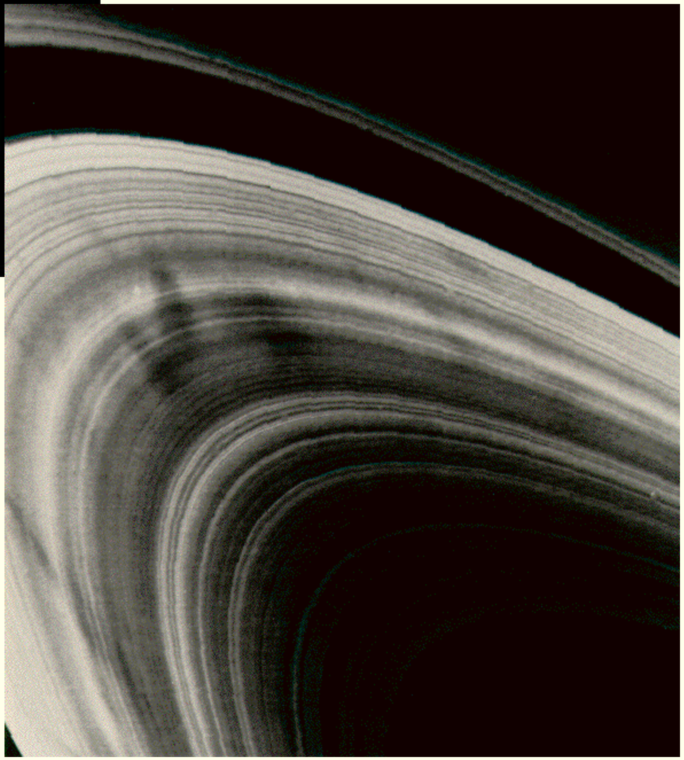
Saturn

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

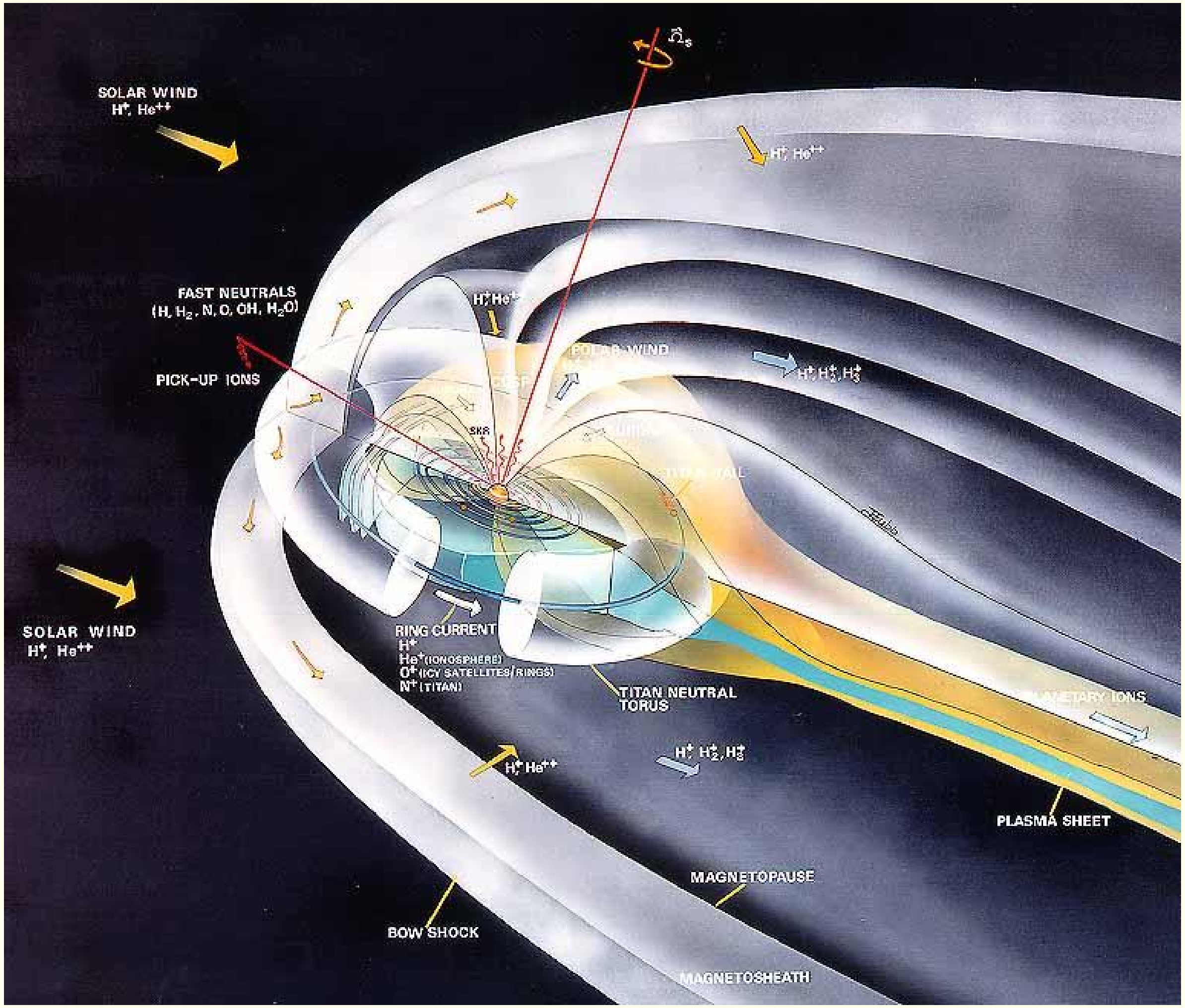
Saturn's rings



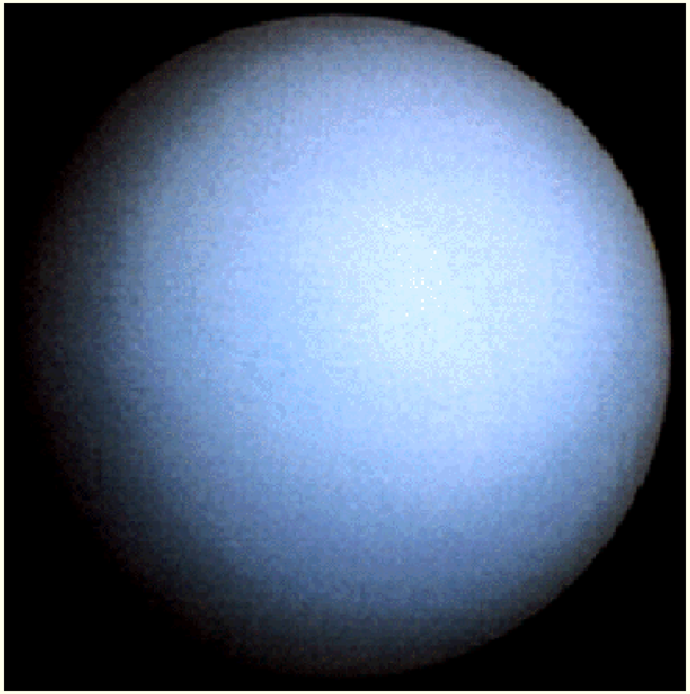


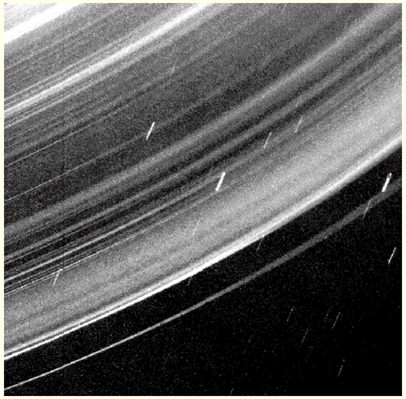
- ring systemet is made up of ice and mineral particles from ~ 1 cm to ~ 1 km
- rings are only 1.5 km thick

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

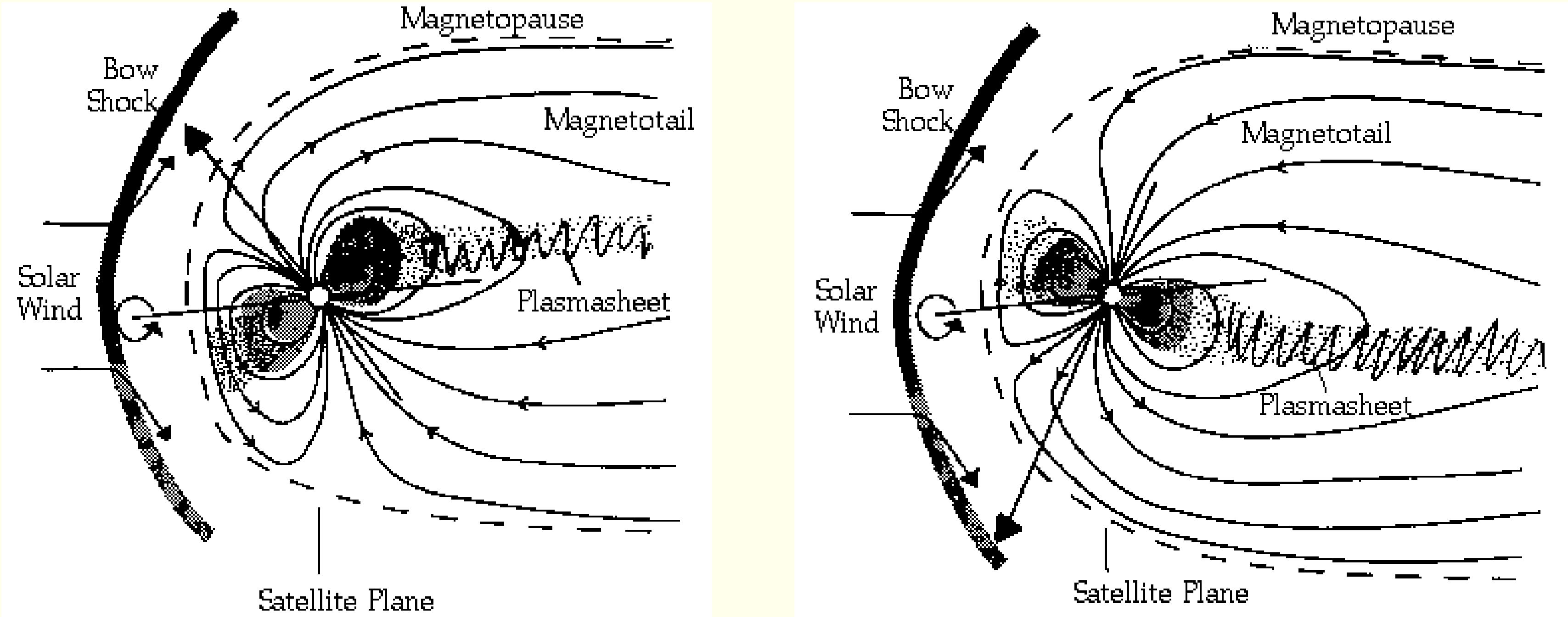




Uranus

- $r_U = 3{,}84\ r_E$
- $m_U = 14{,}5\ m_E$
- 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

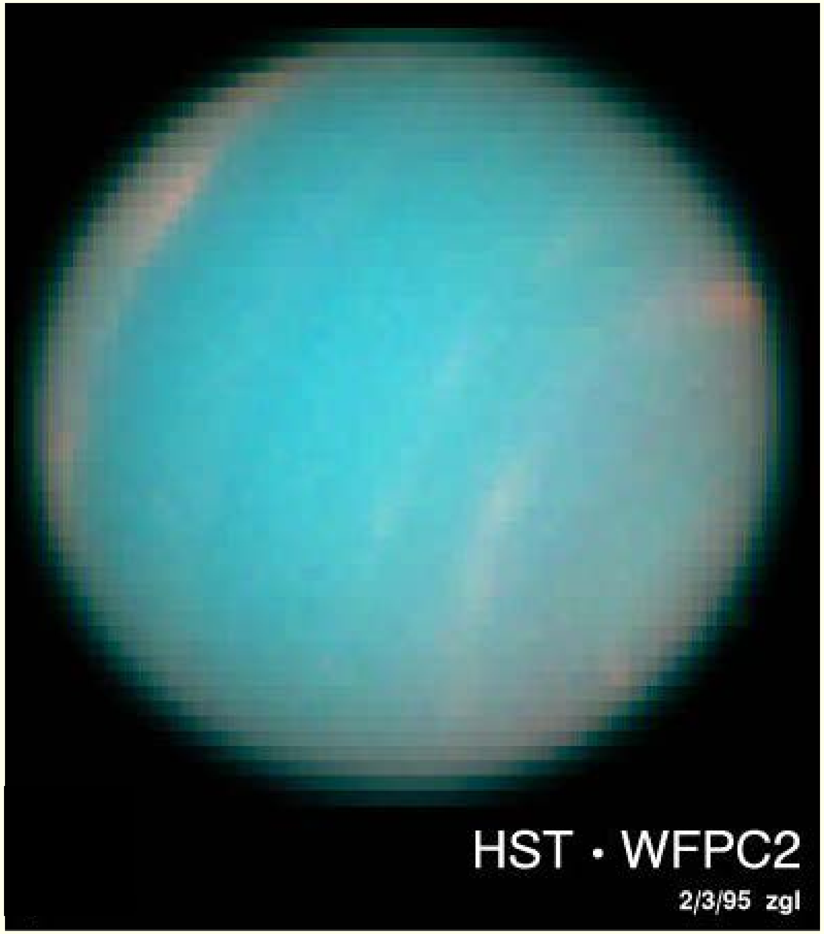
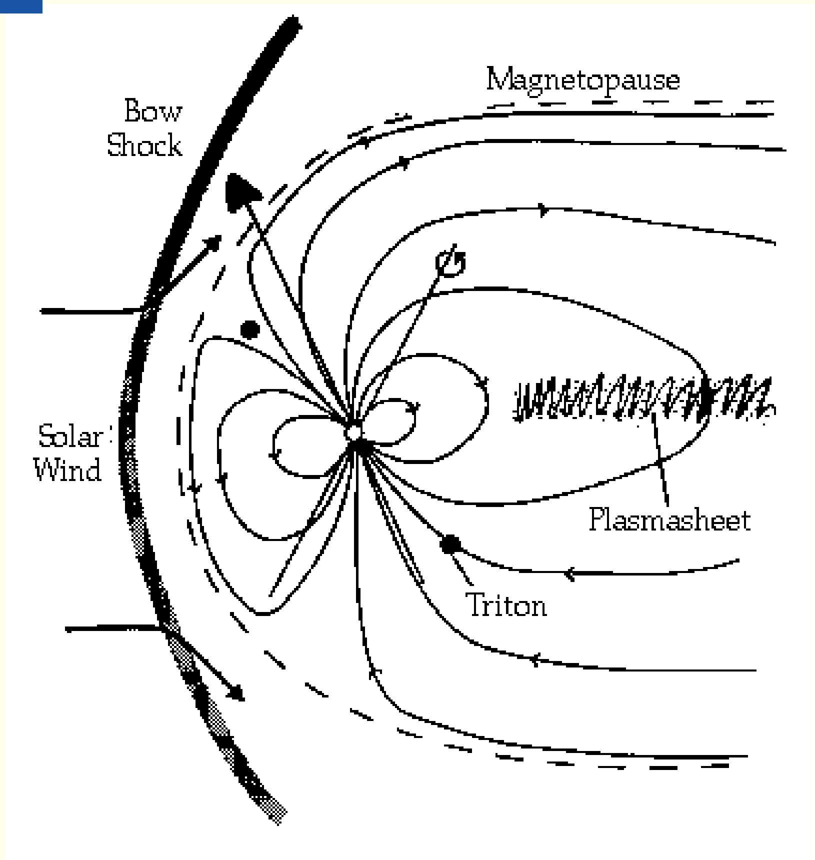
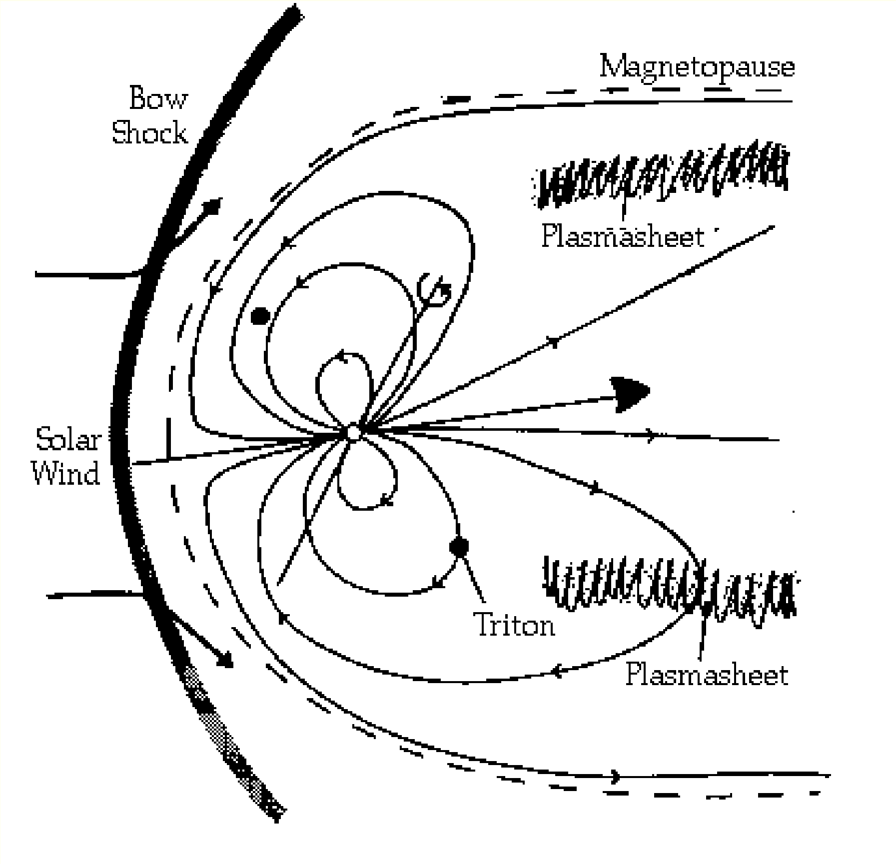


Photo from Hubble Space Telescope

- $r_N = 3{,}93\ r_E$
- $m_N = 17{,}2\ m_E$
- distance from sun : 30.1 AU
- gas giant with very dense atmosphere containing mainly methane
- 11 moons + ring system

Neptune



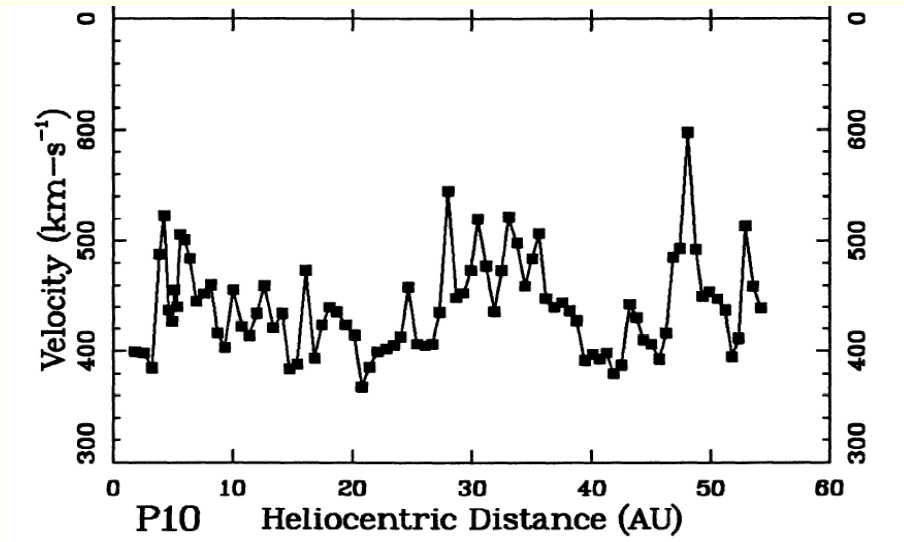


- magnetic field axis makes an angle of around 43° with rotational axis
- this gives enourmous daily variations of the structure of the magnetosphere also for Neptune

Comparative magnetospheres

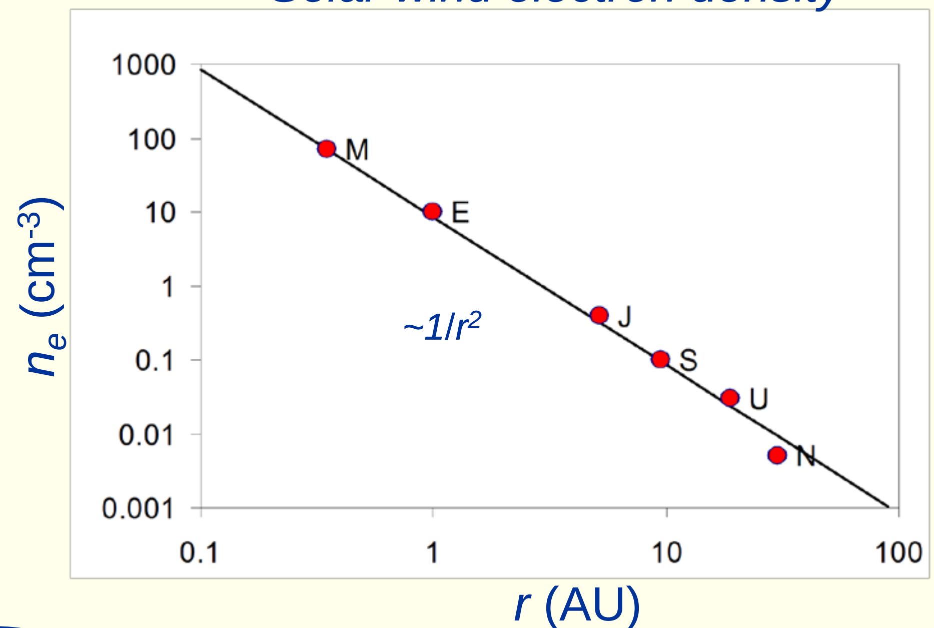
Solar wind properties

Solar wind velocity

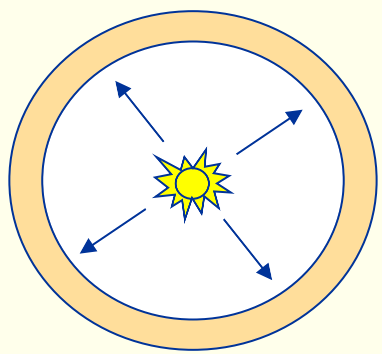


Pioneer 10, measurements
[Grazin et al., 1994]

Solar wind electron density



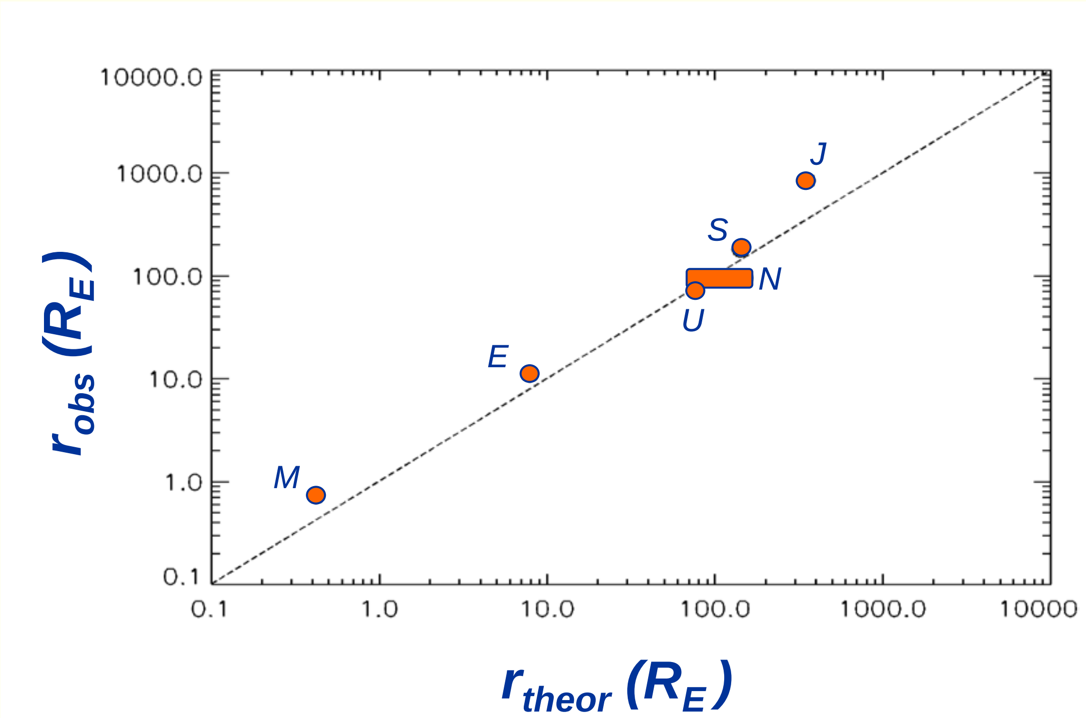
[Blanc et al., 2005]



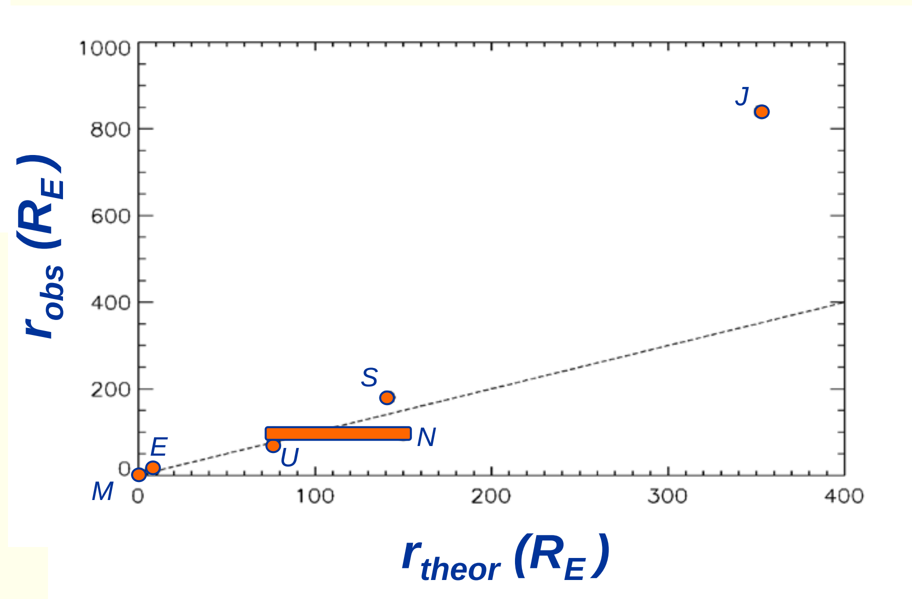
$$dV = 4\pi r^2 dr$$

Comparative magnetospheres

Observed vs. theoretical standoff-distance



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

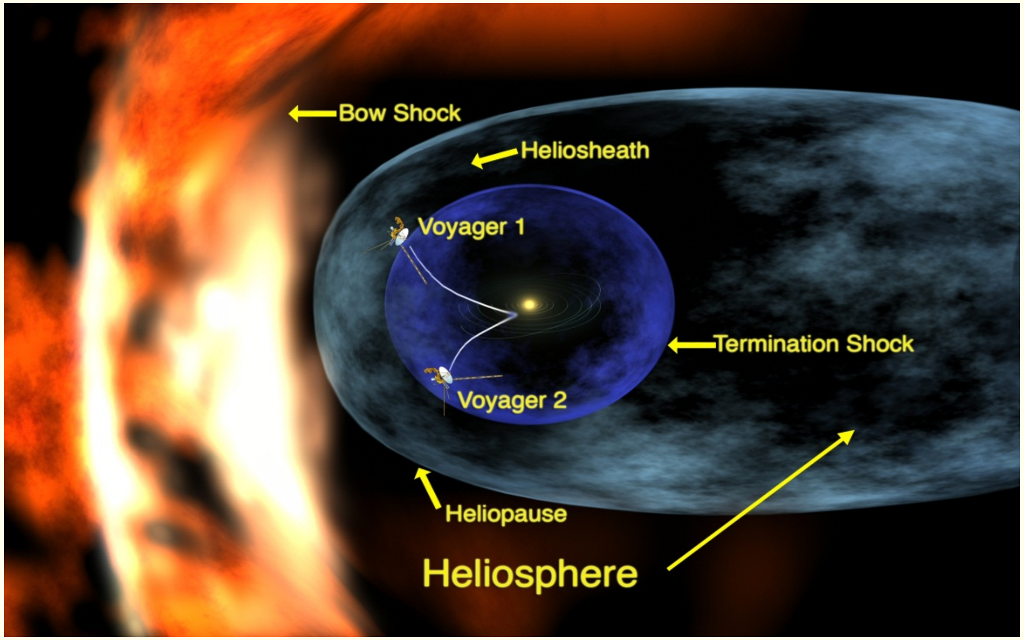


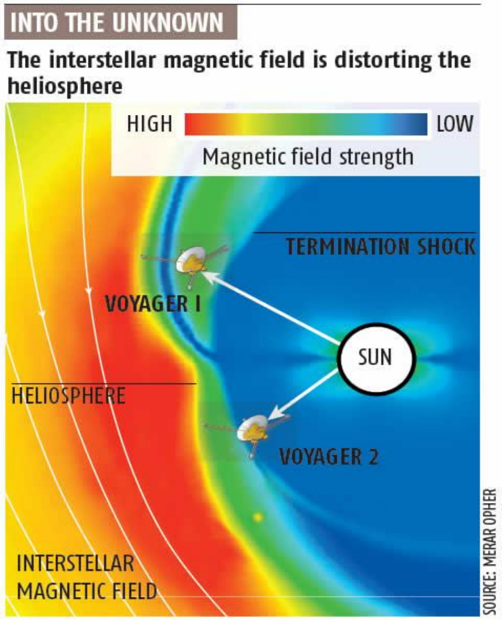
- *Model reasonably valid over three orders of magnitude*
- *Size of Jupiter's (and maybe Saturn's) magnetosphere underestimated*

Other other magnetospheres

Heliosphere

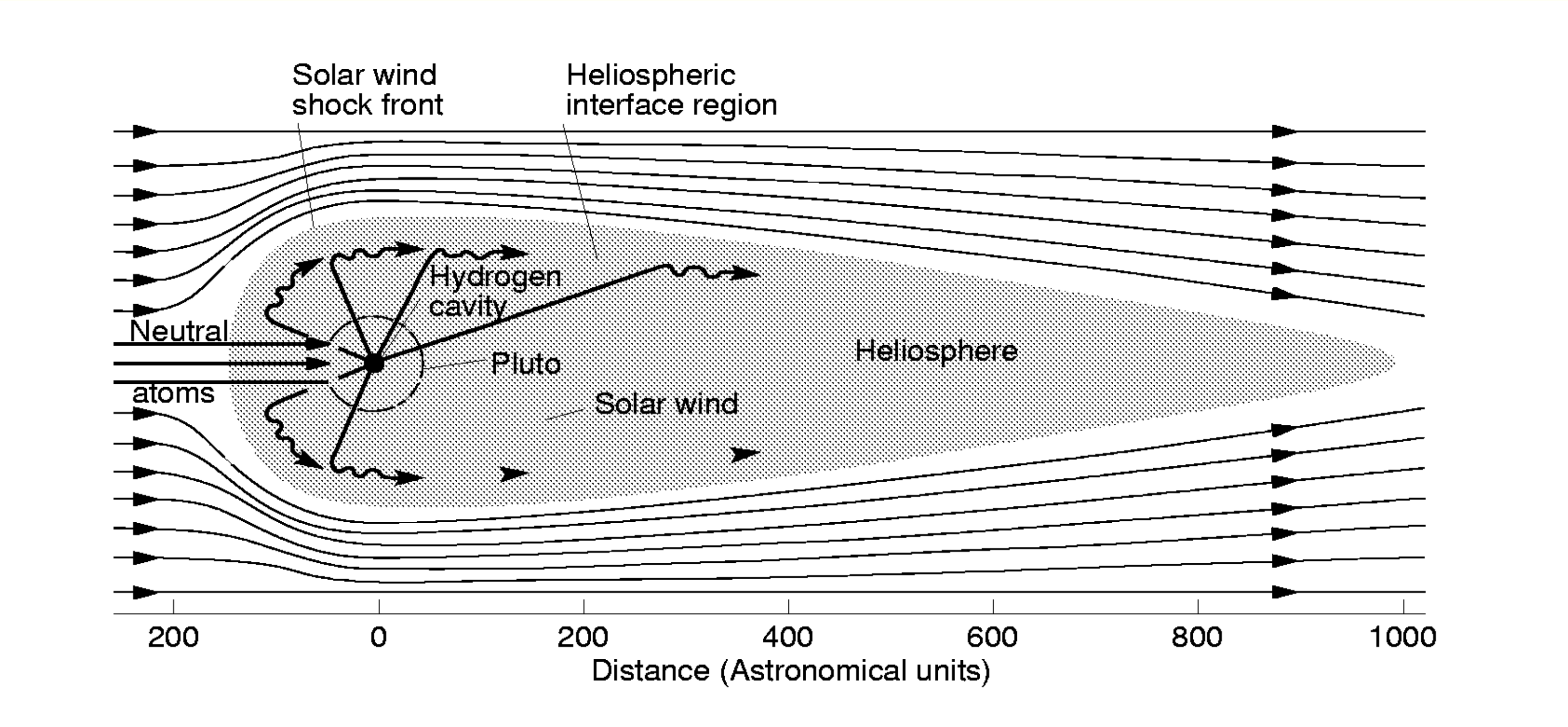
Interstellar wind





[Opher, 2007]

Heliosphere



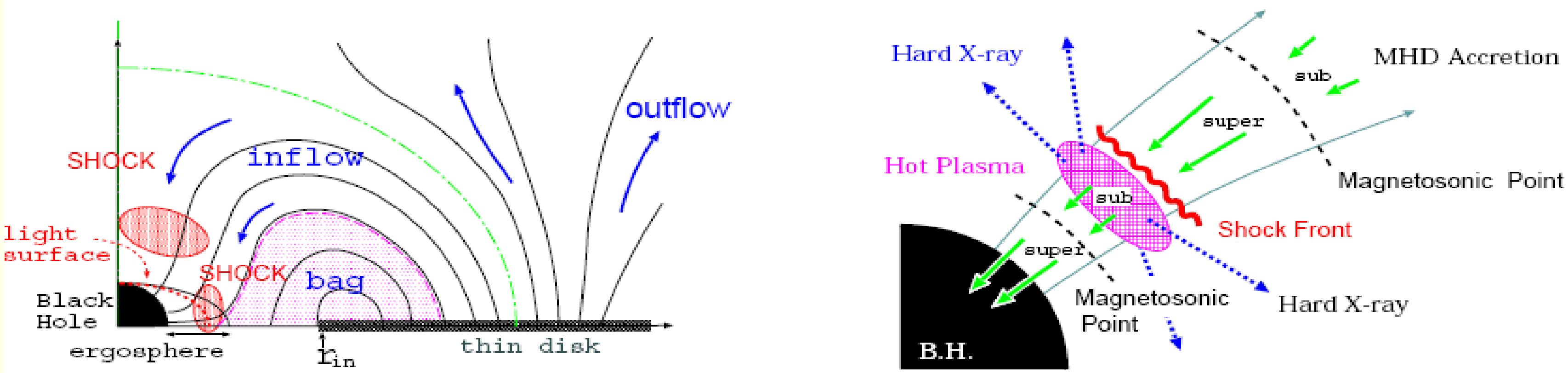
- Reaches approximately 100 AU into space (=1.5x10^{13} m)
- Voyager sonds are approaching/encountering the heliopause right now

Other other magnetospheres

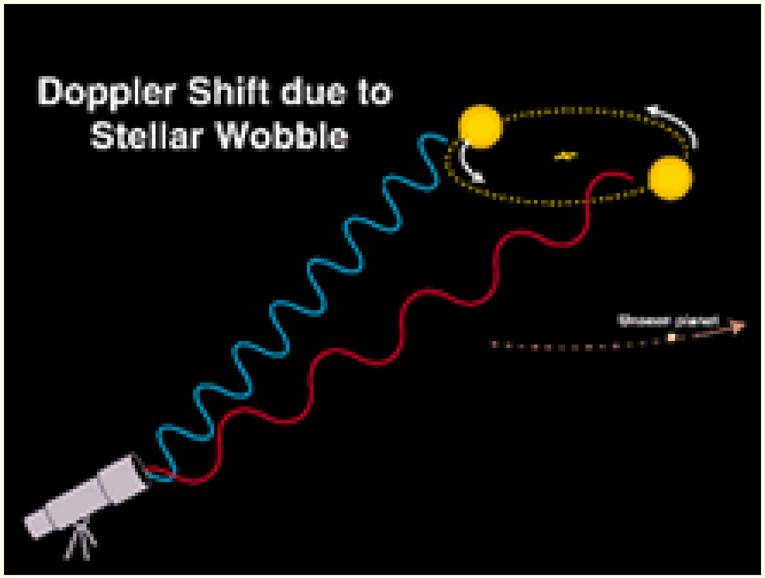
Exotic magnetospheres

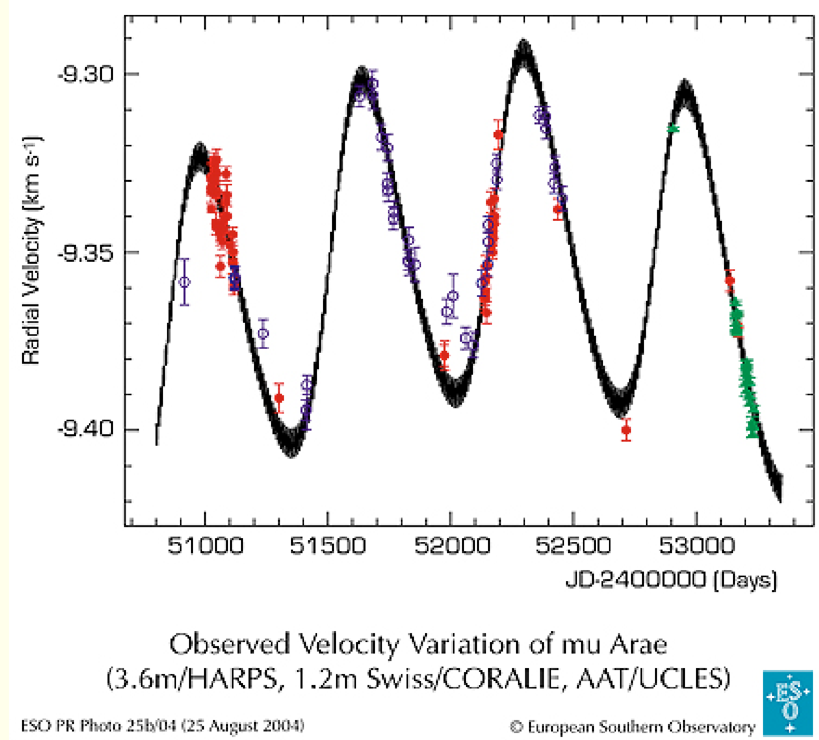
"Black Hole Magnetosphere" =

Loop (bag) + Disk–BH (inflow) + BH (Disk) − r_∞ (outflow)



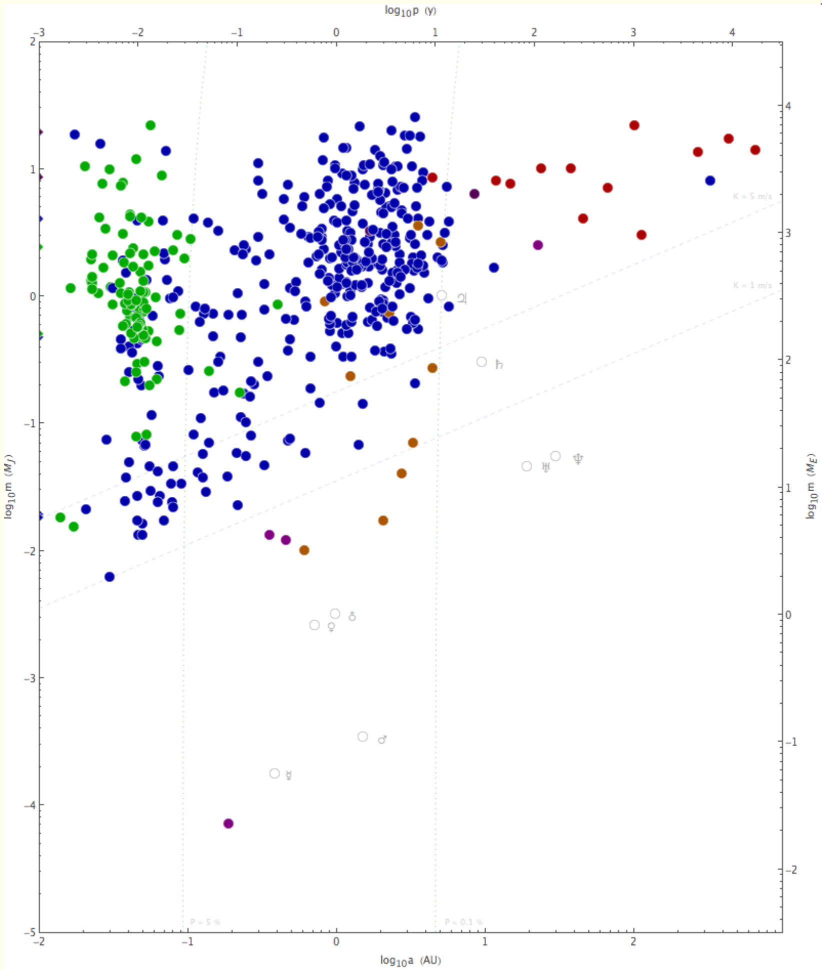
Exoplanets





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

Magnetospheres of exoplanets



log *m*

log *a*

- 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

Last Minute!

Last Minute!

- What was the most important thing of today's lecture? Why?
- What was the most unclear or difficult thing of today's lecture, and why?
- Other comments