Last lecture (5)

- Particle drift velocity in magnetized plasma
- Electrical conductivity in ionosphere

Today's lecture (6)

- Magnetosphere, introduction
- Magnetospheric size (standoff distance)
- Particle motion in the magnetosphere
- Other magnetospheres

Today

Activity	Date	Time	Room	Subject	Litterature
L1	28/8	15-17	Q21	Course description, Introduction, The Sun 1	**CGF** Ch 1.1,1.2, 1.4, 5, (p 110-113), 6.3
L2	29/8	13-15	Q2	The Sun 2, Plasma physics 1	**CGF** Ch 1.3, 5 (p 114-121)
L3	4/9	10-12	E2	Solar wind, The ionosphere and atmosphere 1, Plasma physics 2	**CGF** Ch 6.1, 2, 3.1-3.2, 3.5, **LL** Ch III, Extra material
T1	6/9	8-10	Q21	Mini-group work 1	
L4	6/9	15-17	Q2	The ionosphere 2, Plasma physics 3	**CGF** Ch 3.4, 3.7, 3.8
T2	10/9	15-17	Q21	Mini-group work 2	
L5	11/9	10-12	E3	The Earth's magnetosphere 1, Plasma physics 4	**CGF** 4-1-4.3, **LL** Ch I, II, IV.A
T3	17/9	8-10	Q21	Mini-group work 3	
L6	18/9	13-15	Q33	The Earth's magnetosphere 2, Other magnetospheres	**CGF** Ch 4.6-4.9, **LL** Ch V.
L7	19/9	13-15	Q2	Aurora, Measurement methods in space plasmas and data analysis 1	**CGF** Ch 4.5, 10**, LL** Ch VI, Extra material
T4	24/9	8-10	Q2	Mini-group work 4	
L8	24/9	15-17	V3	Space weather and geomagnetic storms	**CGF** Ch 4.4, **LL** Ch IV.B-C, VII.A-C
T5	2/10	8-10	Q31	Mini-group work 5	
L9	2/10	13-15	Q2	Alfvén waves, Interstellar and intergalactic plasma, Cosmic radiation	**CGF** Ch 7-9, Extra material
T6	8/10	15-17	Q21		
L10	9/10	10-12	Q2	Guest Lecture by Swedish astronaut Christer Fuglesang	
Written examination	16/10	14-19	L21, L22, L31		

EF22445 Space Physics II
7.5 ECTS credits, P2

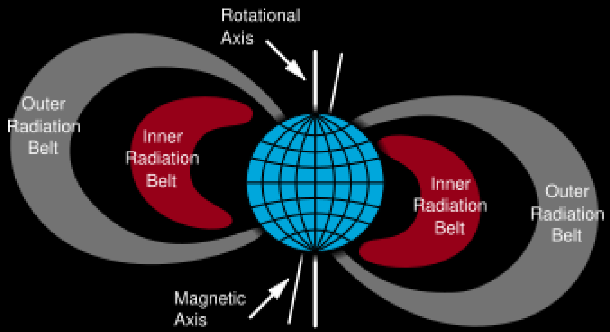
- shocks and boundaries in space
- solar wind interaction with magnetized and unmagnetized bodies
- reconnection
- sources of magnetospheric plasma
- magnetospheric and ionospheric convection
- auroral physics
- storms and substorms
- global oscillations of the magnetosphere

Courses at the Alfvén Laboratory

EF2260 SPACE ENVIRONMENT AND SPACECRAFT ENGINEERING , 6 ECTS credits, period 2

- environments spacecraft may encounter in various orbits around the Earth, and the constraints this places on spacecraft design
- basic operation principles underlying the thermal control system and the power systems in spacecraft
- measurements principles in space

The Astrid-2 satellite



Radiation environment in near-earth space

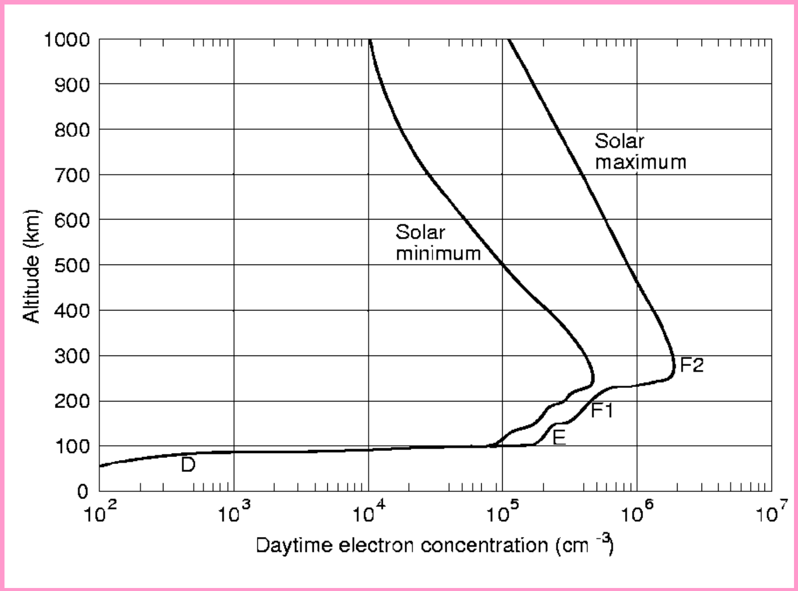
Projects:

- Design power supply for spacecraft
- Study of radiation effects on electronics

Mini-groupwork 3

a)

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



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

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

$q = 1.7 \cdot 10^4\ \mathrm{cm^{-3}s^{-1}} = 1.7 \cdot 10^{10}\ \mathrm{m^{-3}s^{-1}}$

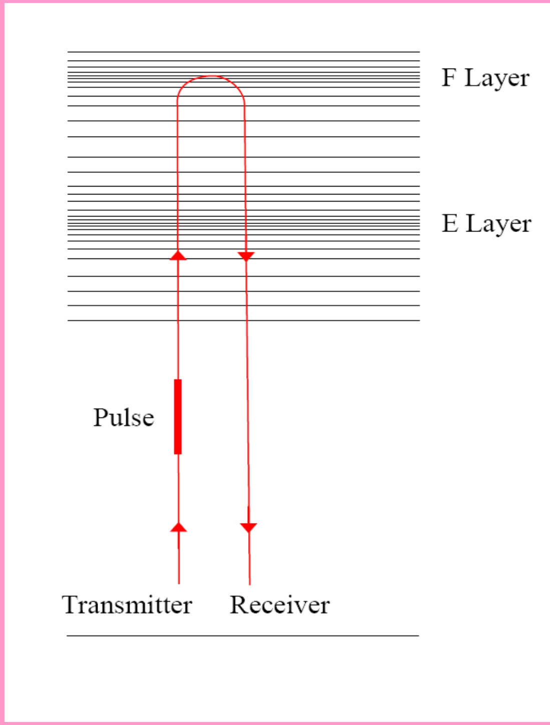
$n_e(150\ \mathrm{km}) = 2 \cdot 10^5\ \mathrm{cm^{-3}} = 2 \cdot 10^{11}\ \mathrm{m^{-3}}$

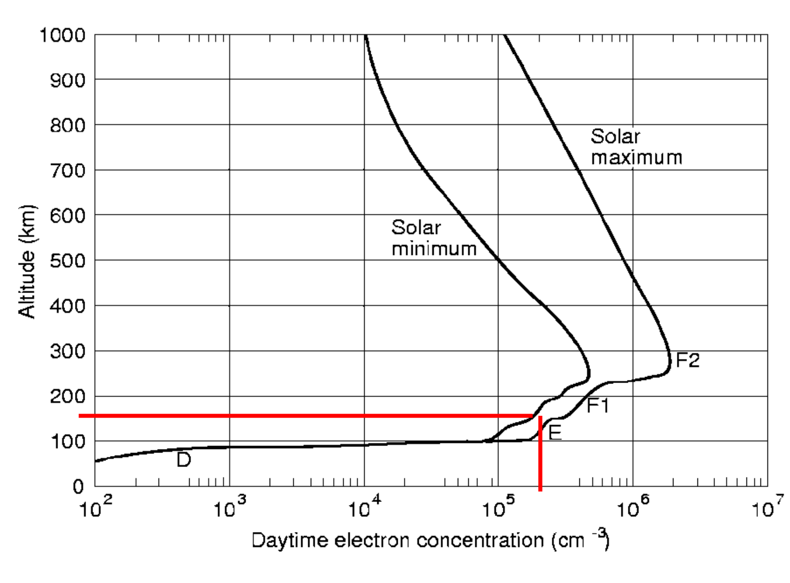
Thus

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

Mini-groupwork 3

b)





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

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

$$\Rightarrow$$

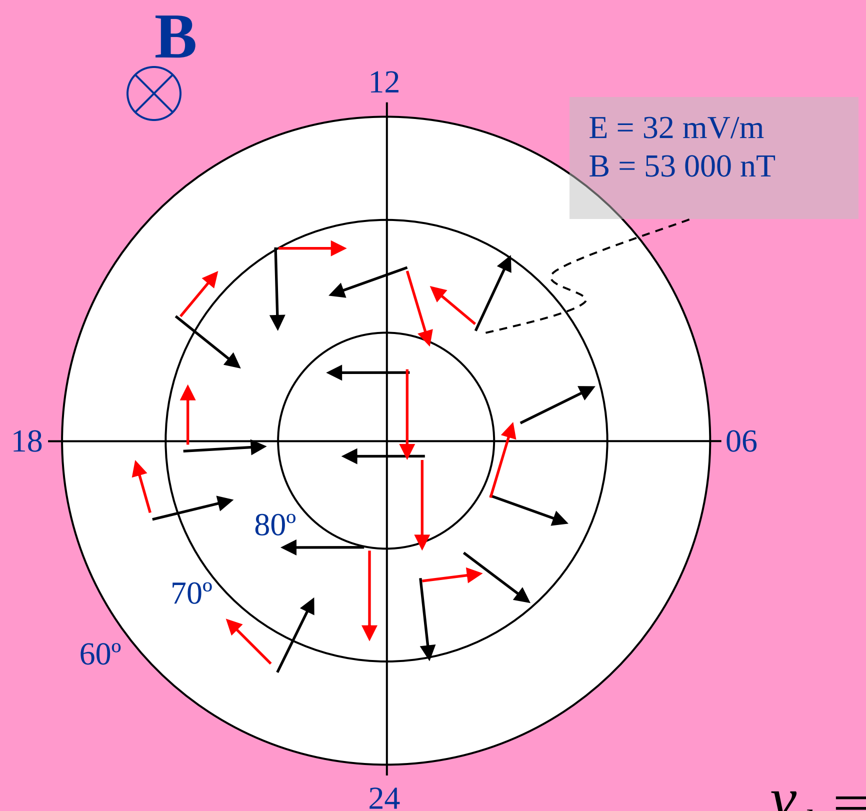
$$n_e = \left(\frac{5\cdot 10^6}{9}\right)^2 = 3\cdot 10^{11} m^{-3}$$

$$h = 150\ km$$

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

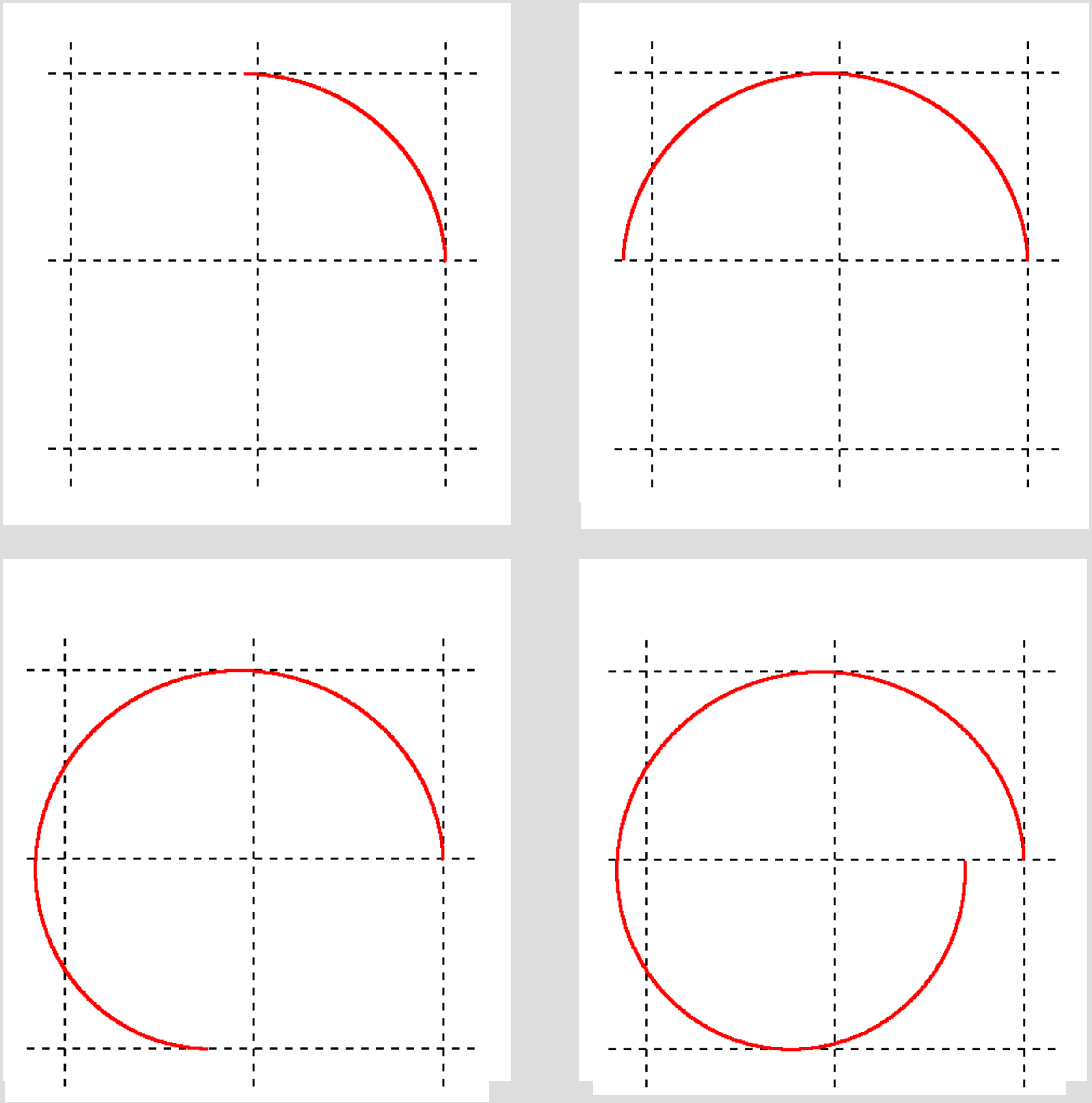
Mini-groupwork 3

c)



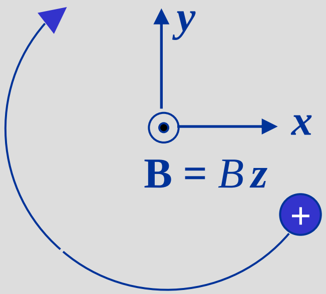
$$v_d = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = \frac{E}{B} = \frac{32\cdot 10^{-3}}{53000\cdot 10^{-9}} = 604\ ms^{-1}$$


E
B



Drift motion

Consider a charged particle in a magnetic field.



Assume an electric field in the x-z plane:

$$\mathbf{E} = \left(E_x, 0, E_z\right)$$

$$m\frac{d\mathbf{v}}{dt} = q\left(\mathbf{v}\times\mathbf{B}+\mathbf{E}\right) \Rightarrow$$

$$\begin{cases} m\dfrac{dv_x}{dt} = qv_yB + qE_x \\ m\dfrac{dv_y}{dt} = -qv_xB \\ m\dfrac{dv_z}{dt} = qE_z \end{cases}$$

Constant acceleration along z

$$\Rightarrow$$

$$\begin{cases} \dfrac{d^2v_x}{dt^2} = \dfrac{qB}{m}\dfrac{dv_y}{dt} = \omega_g\dfrac{dv_y}{dt} = -\omega_g^2 v_x \\ \dfrac{d^2v_y}{dt^2} = -\dfrac{qB}{m}\dfrac{dv_x}{dt} = -\omega_g\dfrac{dv_x}{dt} = -\omega_g^2 v_y - \dfrac{q^2B}{m^2}E_x \end{cases}$$

$$\Rightarrow$$

Drift motion

$$\begin{cases} \dfrac{d^2 v_x}{dt^2} = \dfrac{qB}{m}\dfrac{dv_y}{dt} = \omega_g \dfrac{dv_y}{dt} = -\omega_g^2 v_x \\ \dfrac{d^2 v_y}{dt^2} = -\dfrac{qB}{m}\dfrac{dv_x}{dt} = -\omega_g \dfrac{dv_x}{dt} = -\omega_g^2 v_y - \dfrac{q^2 B}{m^2} E_x \end{cases}$$

$$\therefore$$

$$\begin{cases} \dfrac{d^2 v_x}{dt^2} - \omega_g^2 v_x \\ \dfrac{d^2\left(v_y + \dfrac{E_x}{B}\right)}{dt^2} = -\omega_g^2 \left(v_y + \dfrac{E_x}{B}\right) \end{cases}$$

$\Rightarrow$

$$\begin{cases} v_x = v_\perp e^{i\omega_g t + \delta_x} \\ v_y = -\dfrac{E_x}{B} + v_\perp e^{i\omega_g t + \delta_y} \end{cases}$$

Average over a gyro period:

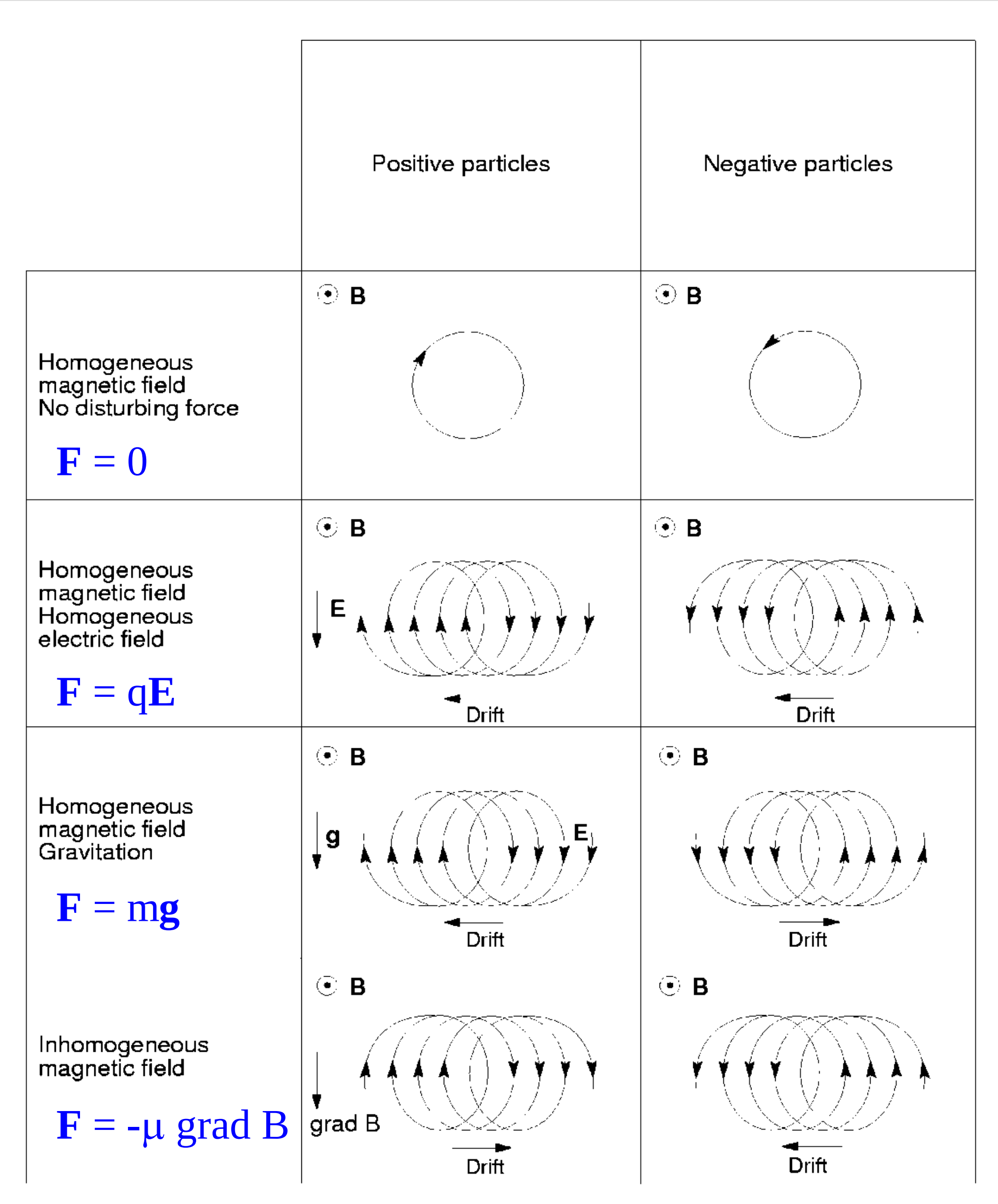
$$v_{drift,y} = -\frac{E_x}{B} = -\frac{E_x B_z}{B^2} = \frac{(\mathbf{E}\times\mathbf{B})_y}{B^2}$$

In general:

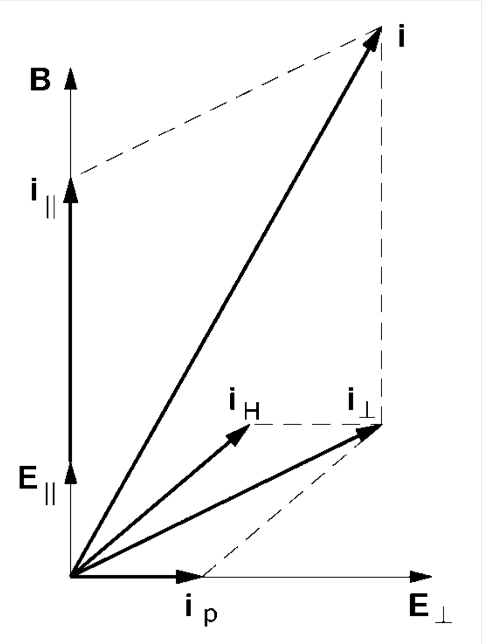
$$\mathbf{v}_{drift} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = \frac{q\mathbf{E}\times\mathbf{B}}{qB^2} = \frac{\mathbf{F}\times\mathbf{B}}{qB^2}$$

Drift motion

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



Possible to get current in opposite direction to E?



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

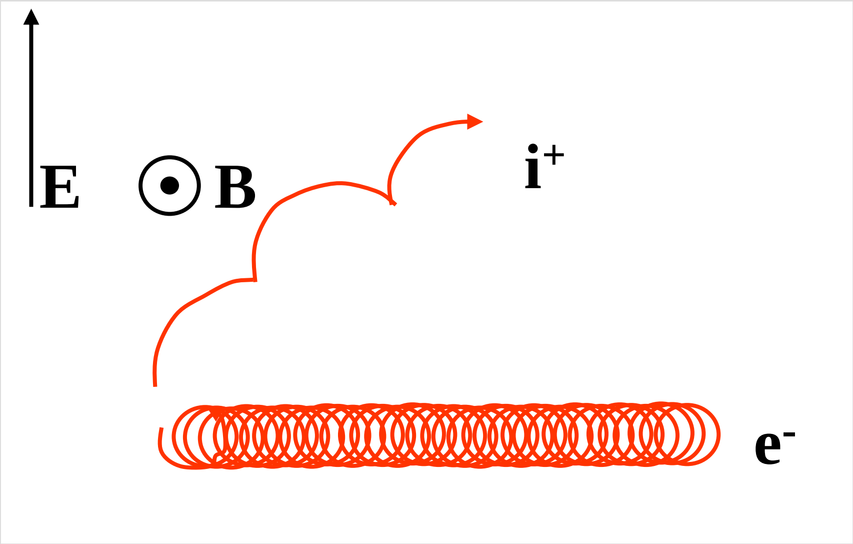
$$\sigma_H = \sigma_e \frac{\omega_{ge}\tau_e}{1+\omega_{ge}^2\tau_e^2} - \sigma_i \frac{\omega_{gi}\tau_i}{1+\omega_{gi}^2\tau_i^2}$$

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

$$\sigma_e = e^2 n \tau_e / m_e$$

$$\sigma_i = e^2 n \tau_i / m_i$$

With collisions



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

$$\left.\begin{aligned} i_P &= \sigma_P E_\perp \\ i_H &= \sigma_H E_\perp \end{aligned}\right\}$$

Geomagnetic field

Approximated by a dipole close to Earth.

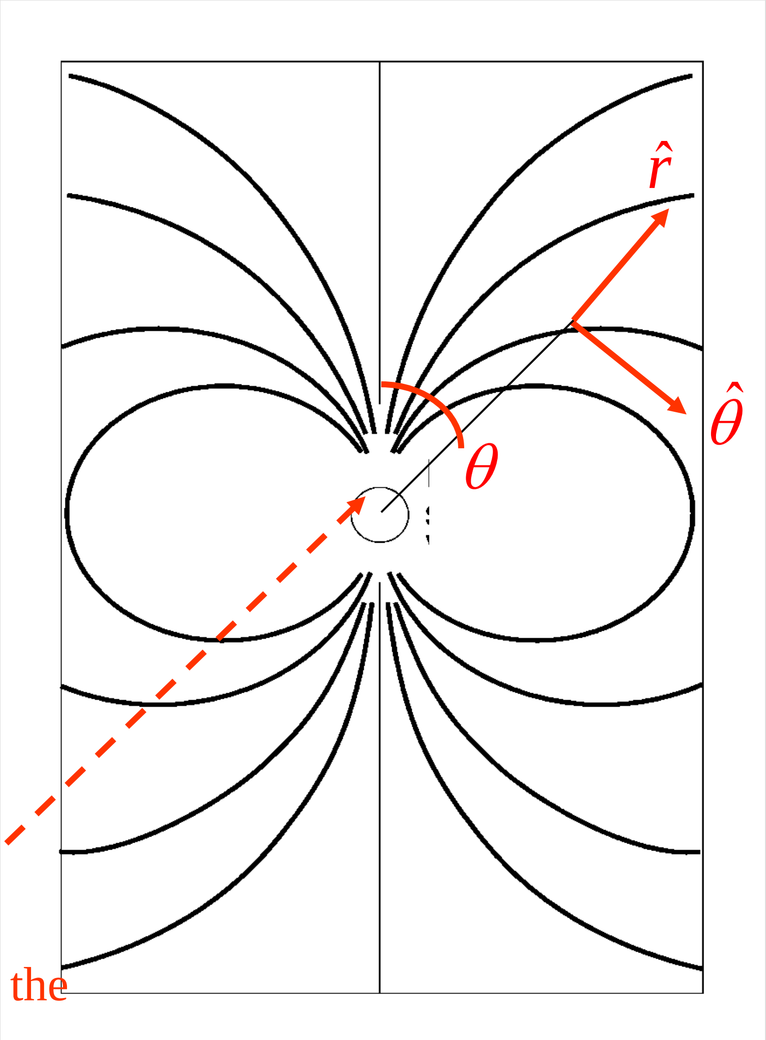
$$B_r = B_p \left(\frac{R_E}{r}\right)^3 \cos\theta$$

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

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

magnetic dipole moment

Magnetic field at the "north pole"



Geomagnetic field

Alternative formulation of dipole field

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

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

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

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

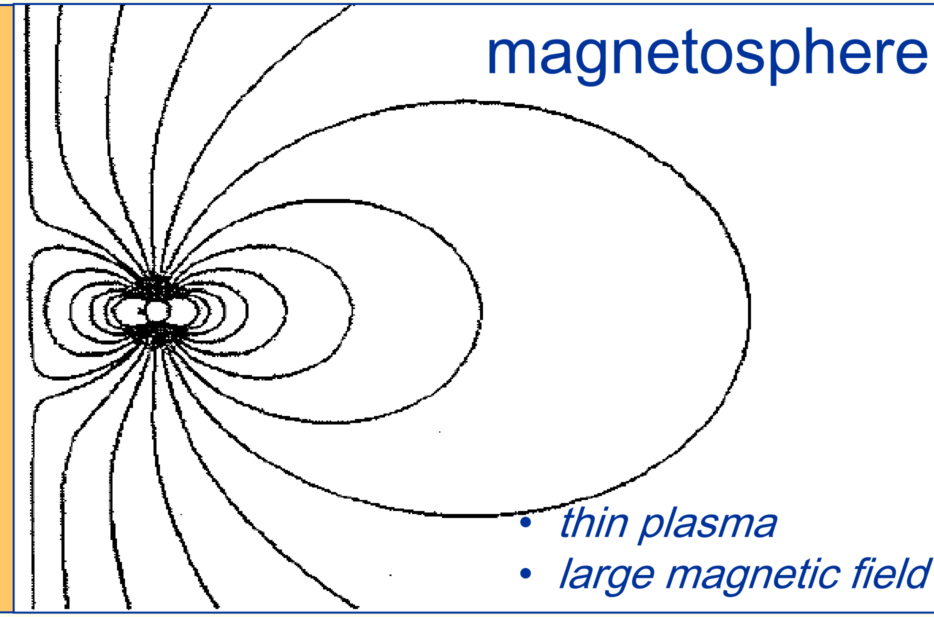
$$a = \frac{2\pi R_E^3 B_p}{\mu_0}$$

magnetic dipole moment

Stand-off distance from pressure balance

solar wind

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



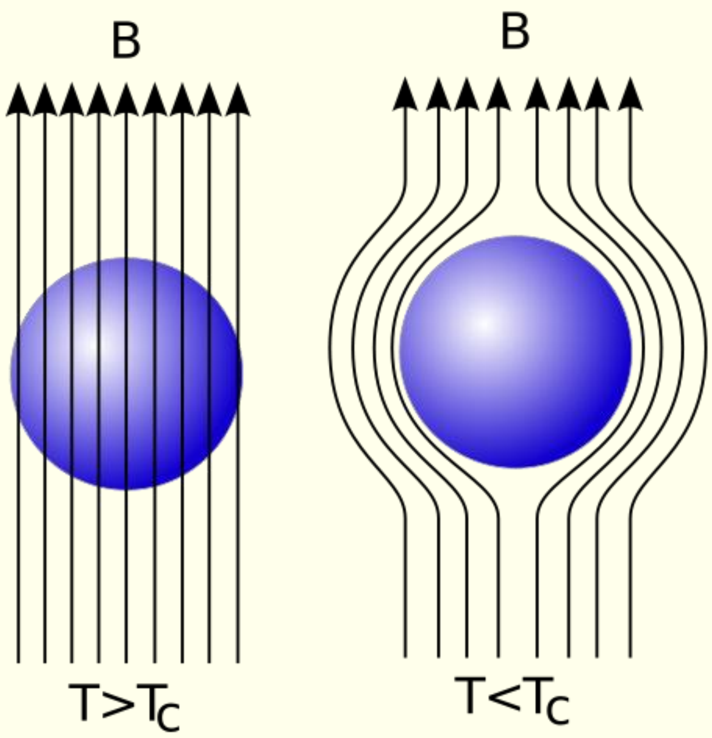
Dynamic pressure:

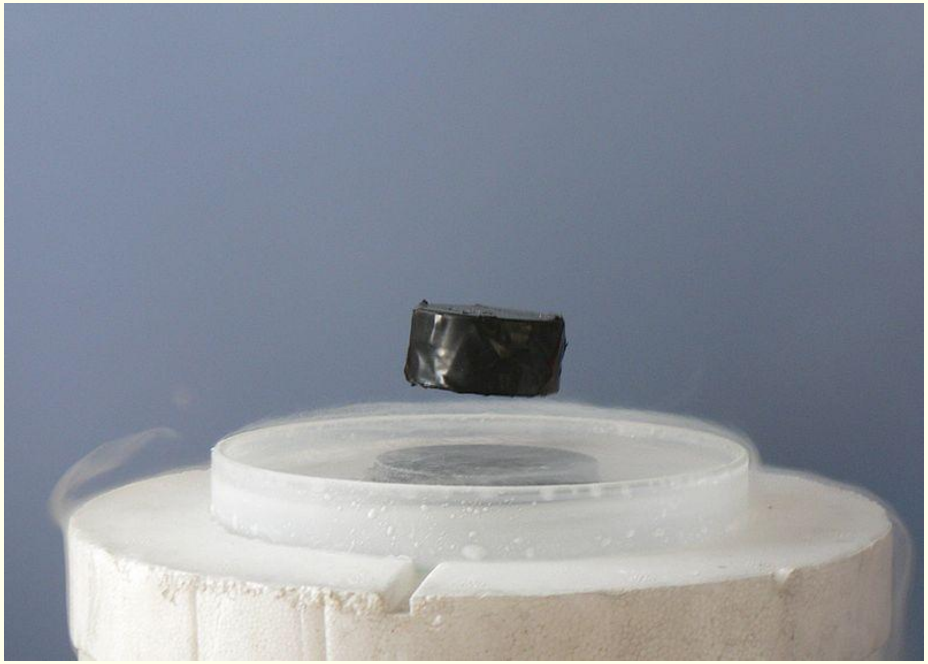
$$p_d = \rho_{SW} v_{SW}^2$$

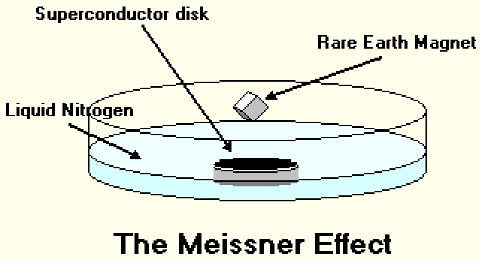
Magnetic pressure:

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

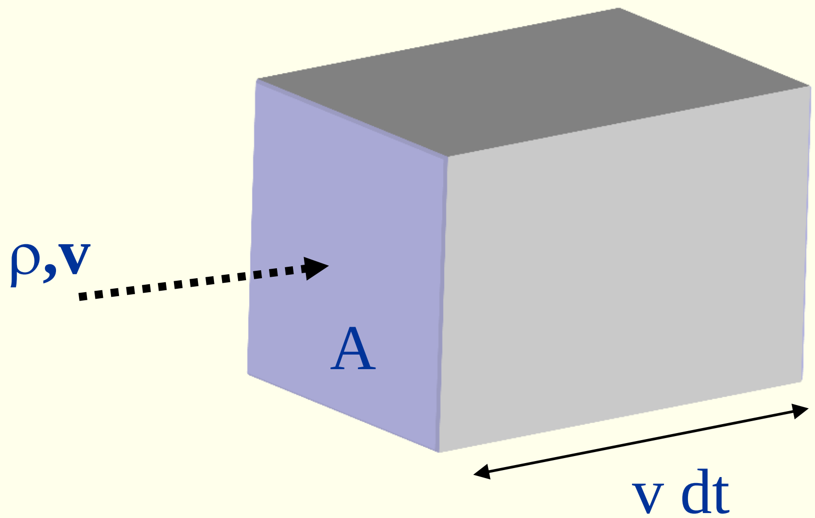
Meissner effect in super-conductors





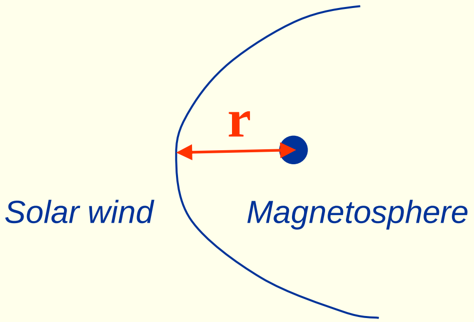


Dynamic (kinetic) pressure



$$p_d = \frac{F}{A} = \frac{d(mv)}{dt}\frac{1}{A} \approx \frac{\Delta(mv)}{\Delta t}\frac{1}{A} = \frac{\rho \cdot Av\Delta t \cdot v}{\Delta t A} = \rho v^2$$

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): $B = \dfrac{\mu_0 a}{4\pi} \dfrac{1}{r^3}$

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

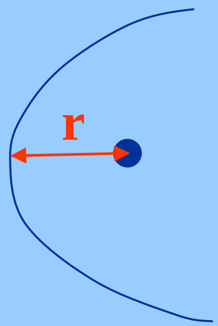
$$r = \left(\frac{\mu_0 a}{4\pi} \right)^{1/3} \left(2\mu_0 \rho_{SW} v_{SW}^2 \right)^{-1/6}$$

$a = 8 \times 10^{22}$ 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)

Standoff distance

v=500 km/s, $\rho_{SW}=10^7 x 1.7 x 10^{-27}$ kg/m^3: **r = 7 R_e**



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

How will the standoff distance change if the magnetosphere is hit by a coronal mass ejection (CME)? ($\rho = 10\rho_{SW}$, $v = 1000$ km/s)

Blue	r = 1.8 R_e	Yellow	r = 5.8 R_e
Green	r = 3.8 R_e	Red	r = 9.8 R_e

Standoff distance

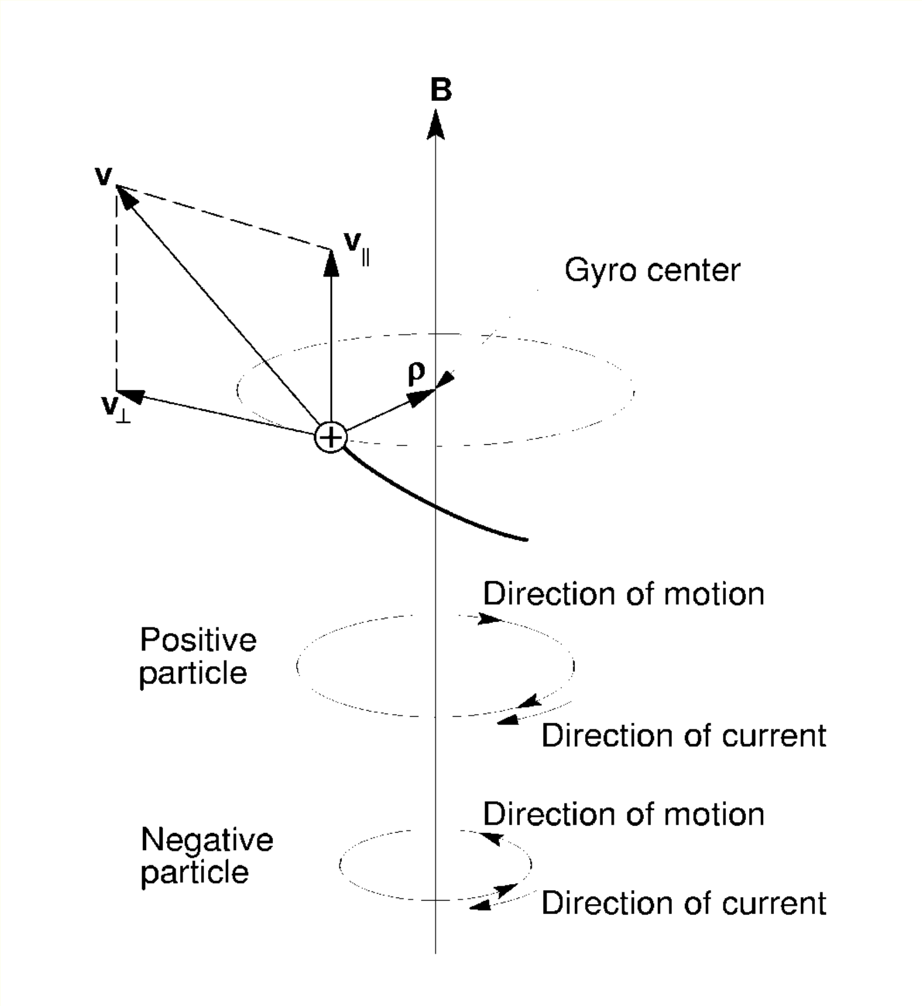
$$r = \left(\frac{\mu_0 a}{4\pi}\right)^{1/3} \left(2\mu_0 10 \rho_{SW} (2v)^2_{SW}\right)^{-1/6} = \left(\frac{\mu_0 a}{4\pi}\right)^{1/3} \left(2\mu_0 \rho_{SW} v^2_{SW}\right)^{-1/6} 40^{-1/6}$$

$$40^{-1/6} \cdot 7 = 0.54 \cdot 7 = 3.8$$

Green

$r = 3.8\ R_e$

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:

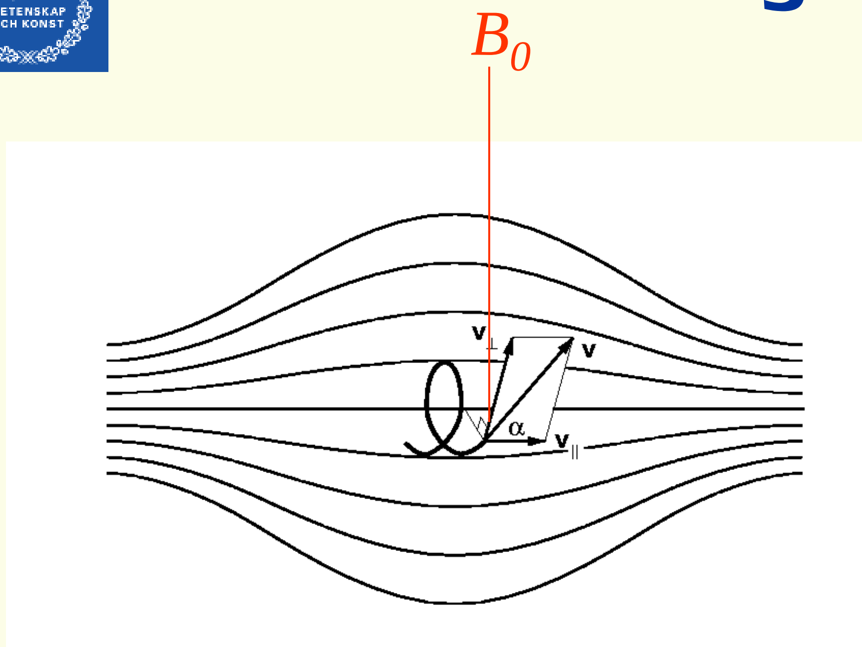
An **adiabatic invariant** is a property of a physical system which stays constant when changes are made slowly.

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) ➡

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

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

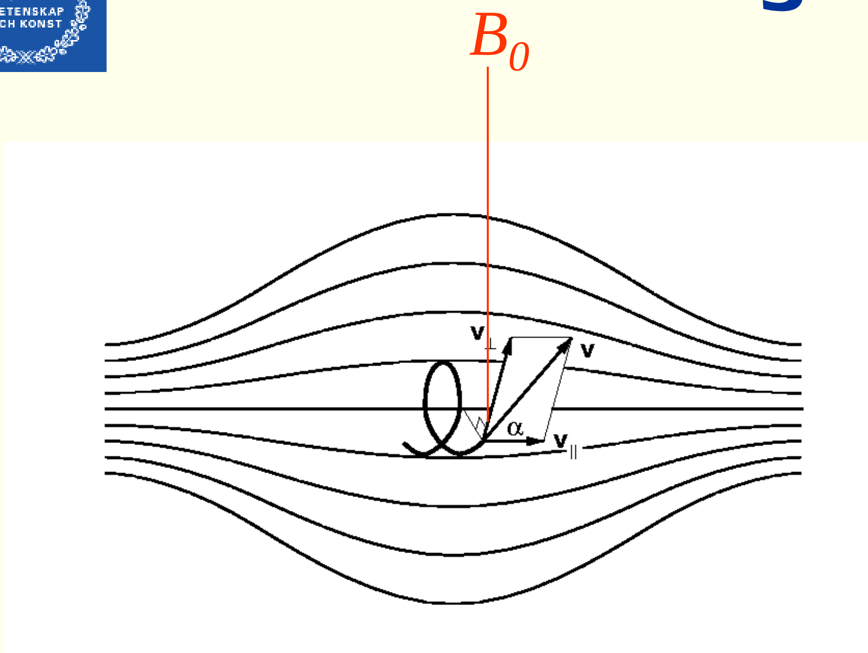
Red — α increases

Yellow — α decreases

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

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

Magnetic mirror



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

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

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

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

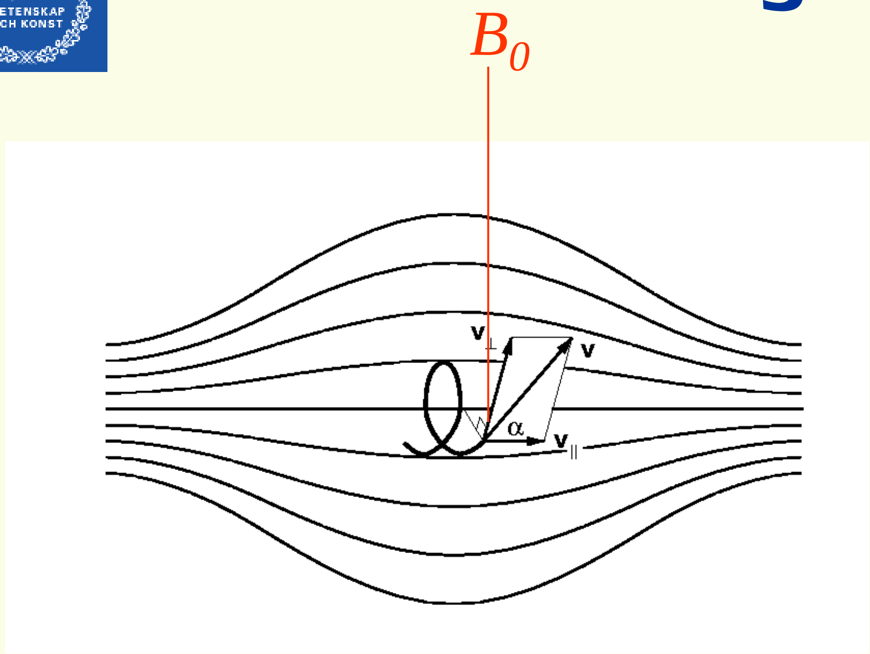
Red

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



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

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

particle turns when α = 90° ➡

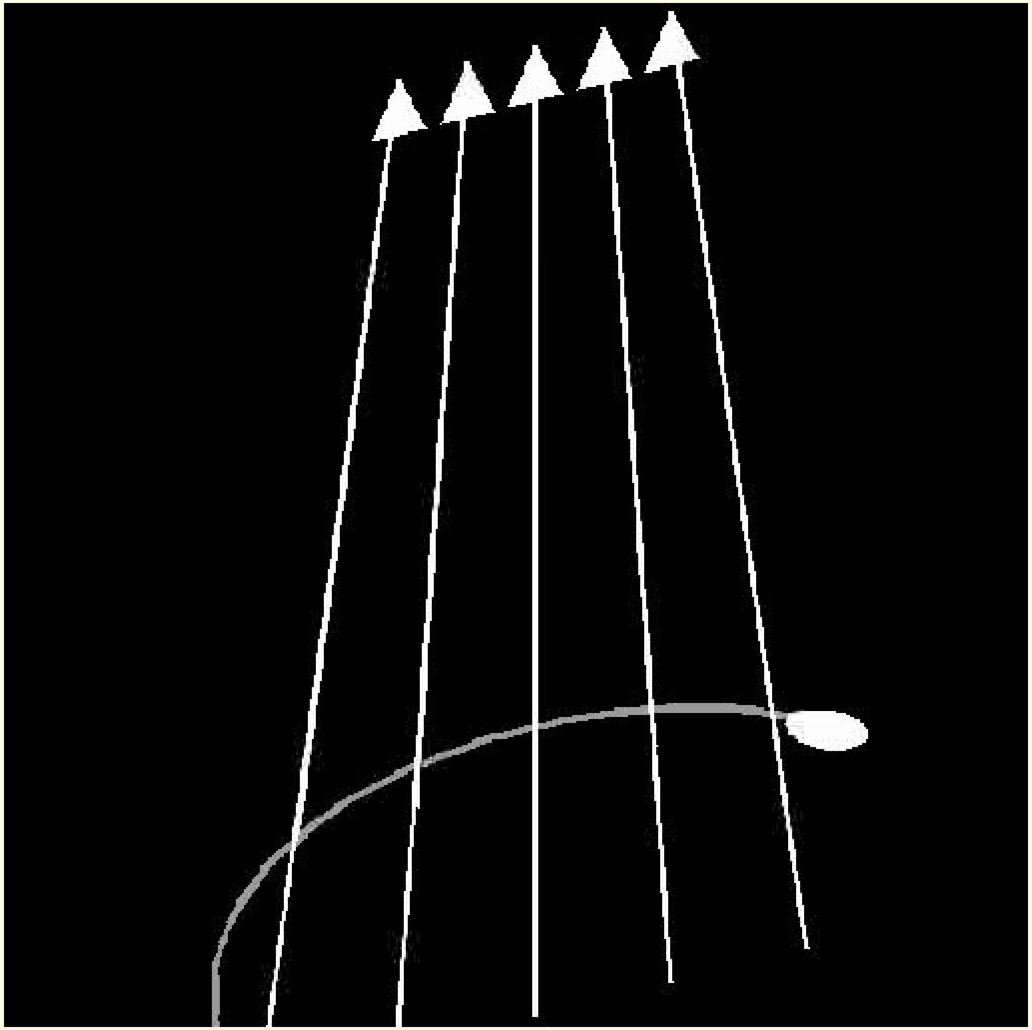
$$\frac{B_{turn}}{\sin^2 90^\circ} = \frac{B_0}{\sin^2\alpha}$$ ➡

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

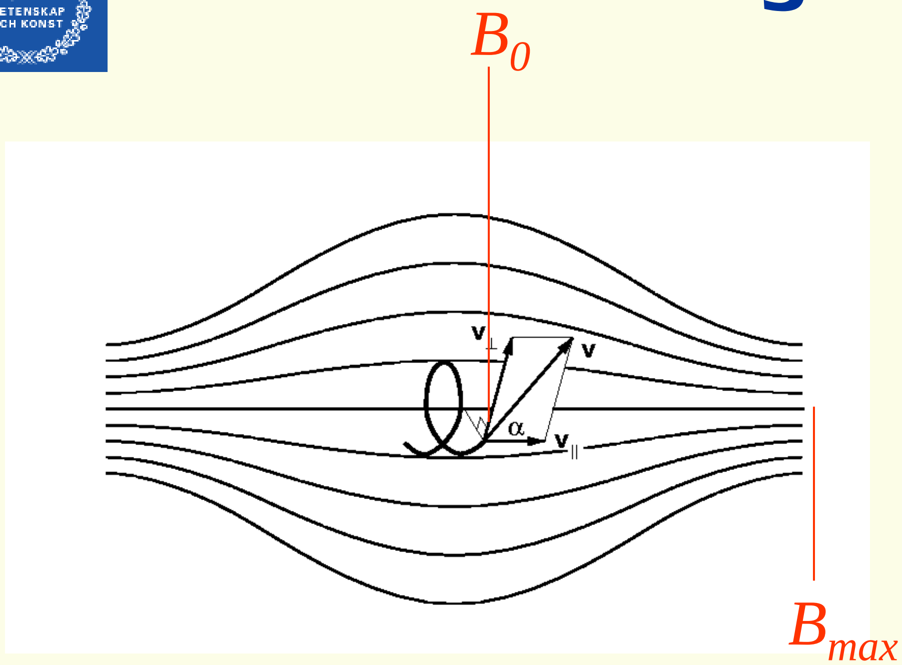
The magnetic moment μ is an ***adiabatic invariant***.

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

Magnetic mirror



Magnetic mirror



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

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

particle turns when $\alpha = 90°$ ➡

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

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

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

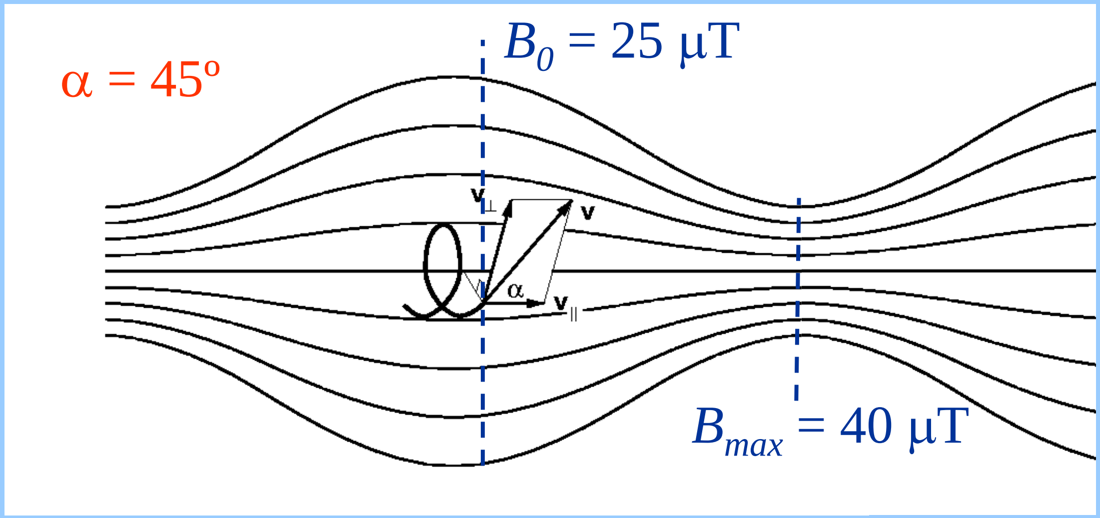
$$\alpha > \alpha_{lc} = \arcsin\sqrt{B_0 / B_{\max}}$$

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

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

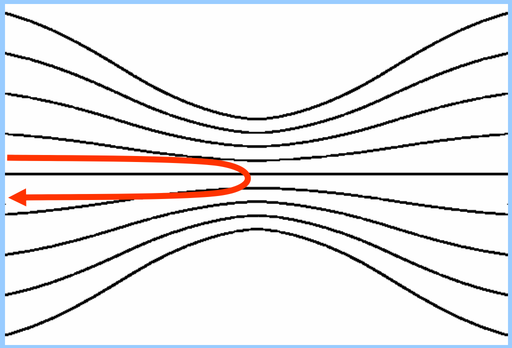
Particles in ***loss cone*** : $\alpha < \alpha_{lc}$

What will happen to the particle?

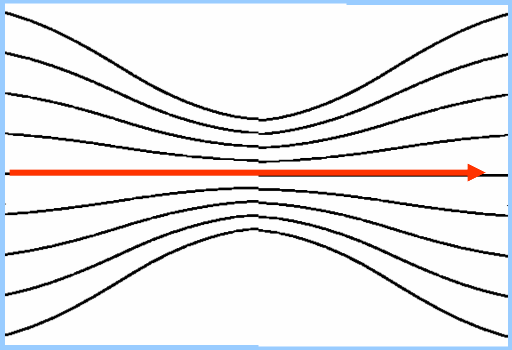


$$\alpha_{lc} = \arcsin \sqrt{B_0 / B_{\max}}$$

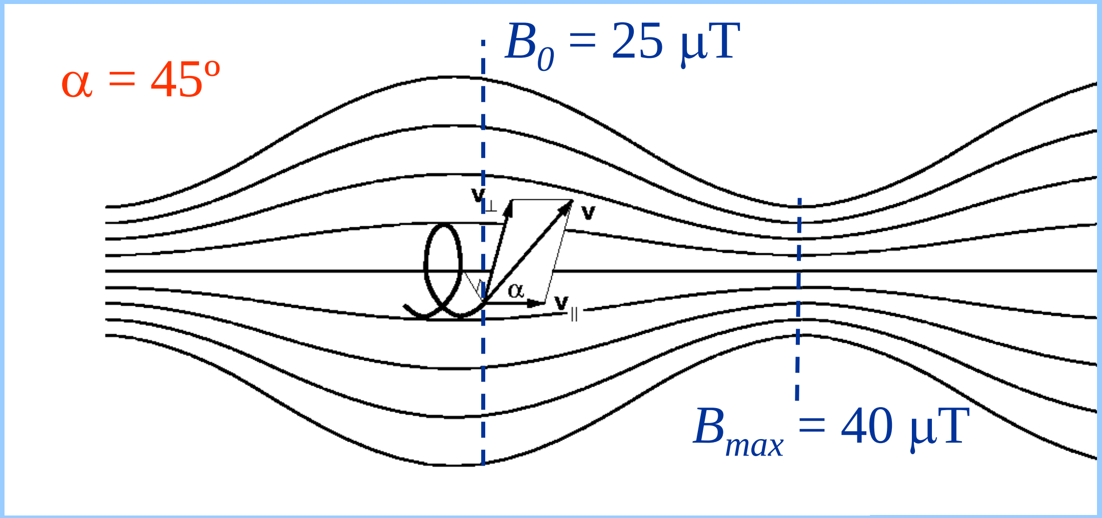
Blue It will mirror



Yellow It will escape

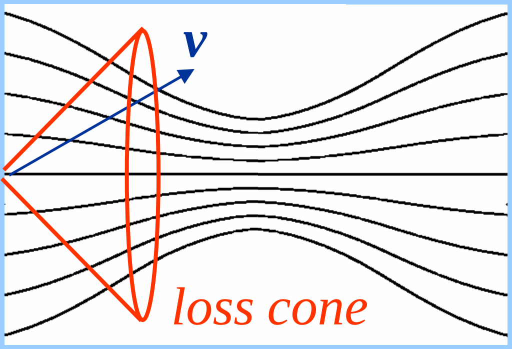


What will happen to the particle?



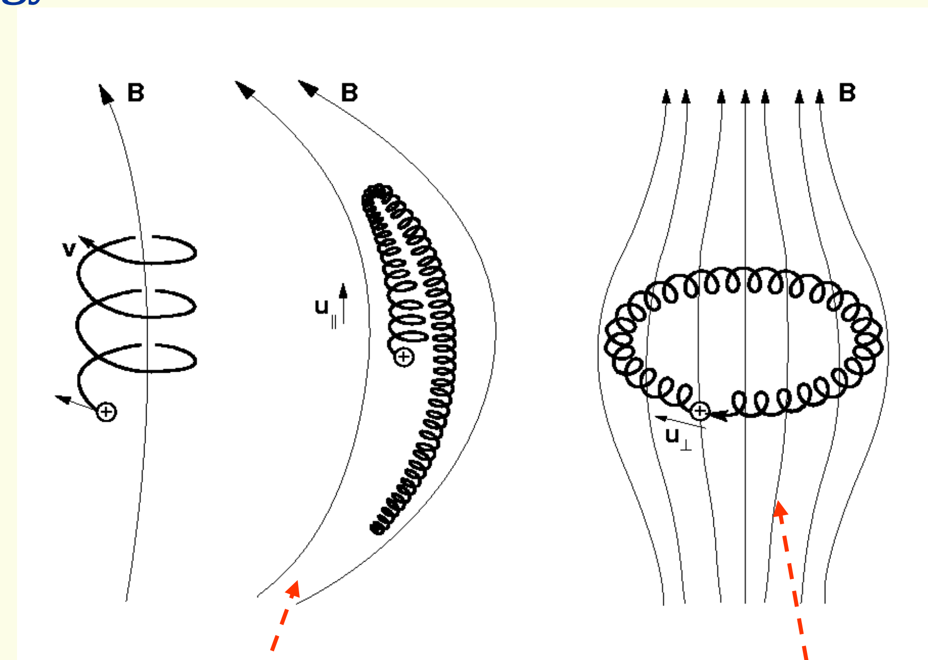
$$\alpha_{lc} = \arcsin\sqrt{B_0 / B_{\max}} =$$
$$\arcsin\sqrt{25/40} = 52°$$

Yellow   It will escape



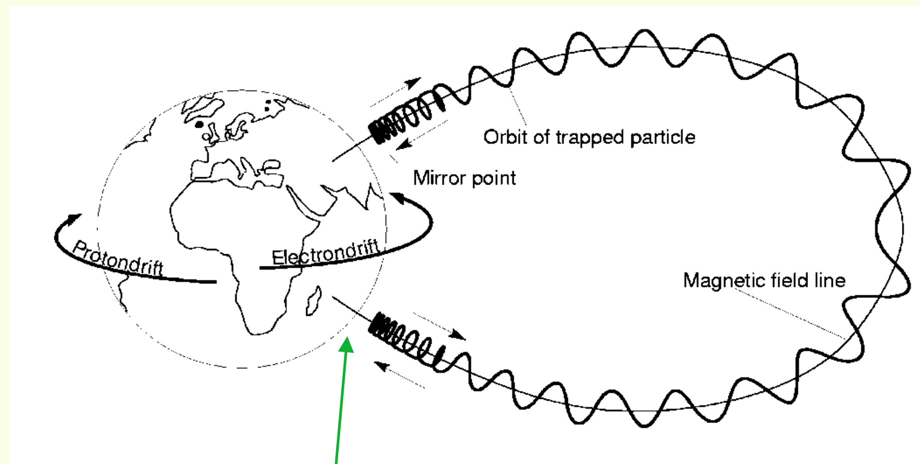
Particle motion in geomagnetic field

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



Magnetic mirror

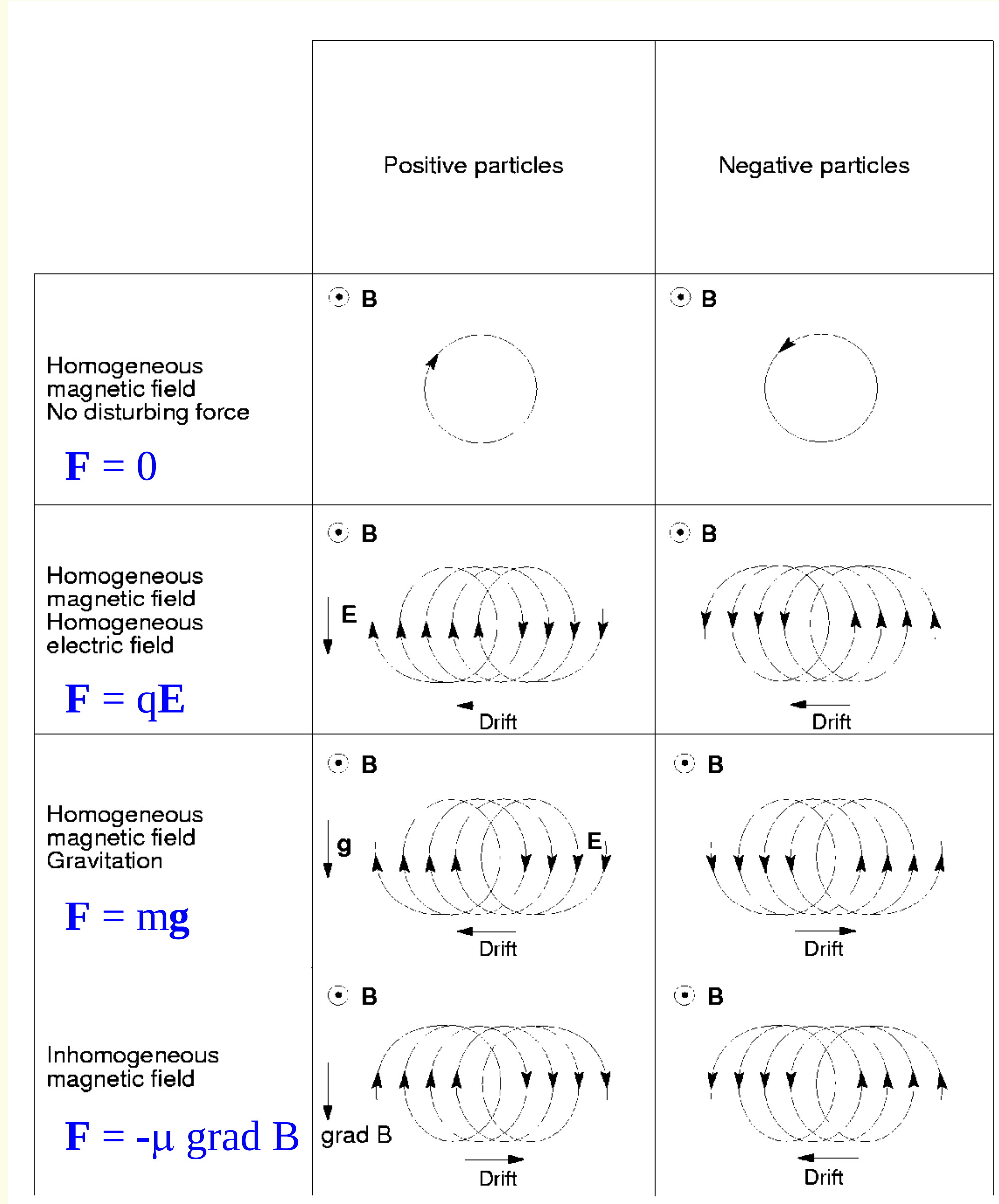
grad B drift



Particles in the loss cone create the aurora!

Drift motion

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

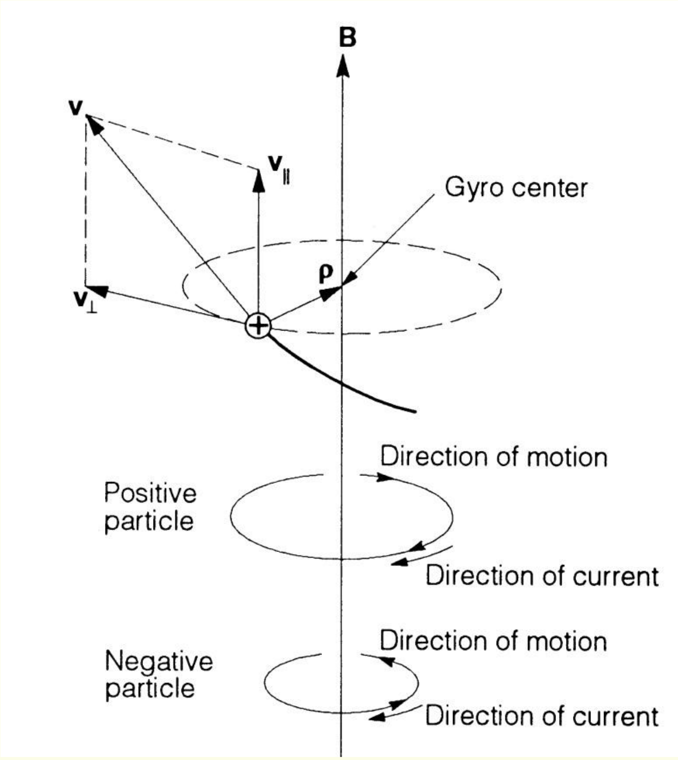


Force on magnetic dipole

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

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

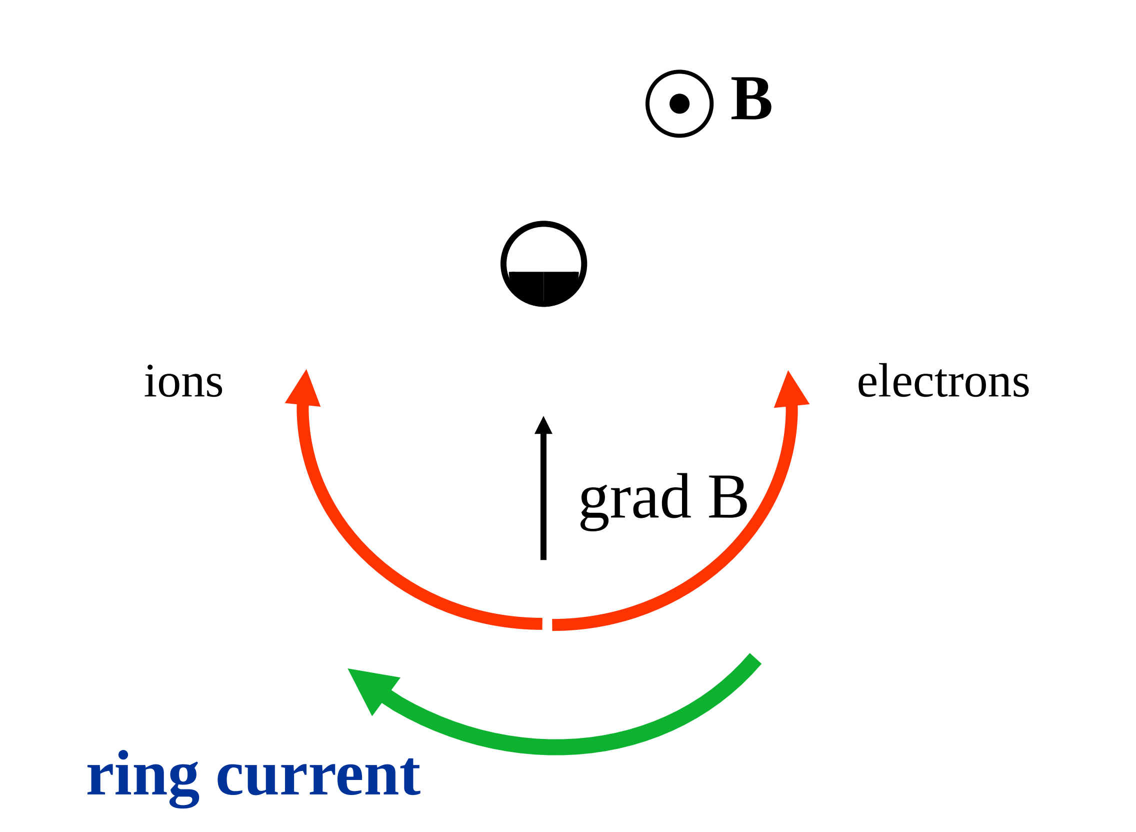
$$= -\mu \nabla \left(\frac{B^2}{B} \right) = -\mu \nabla B$$



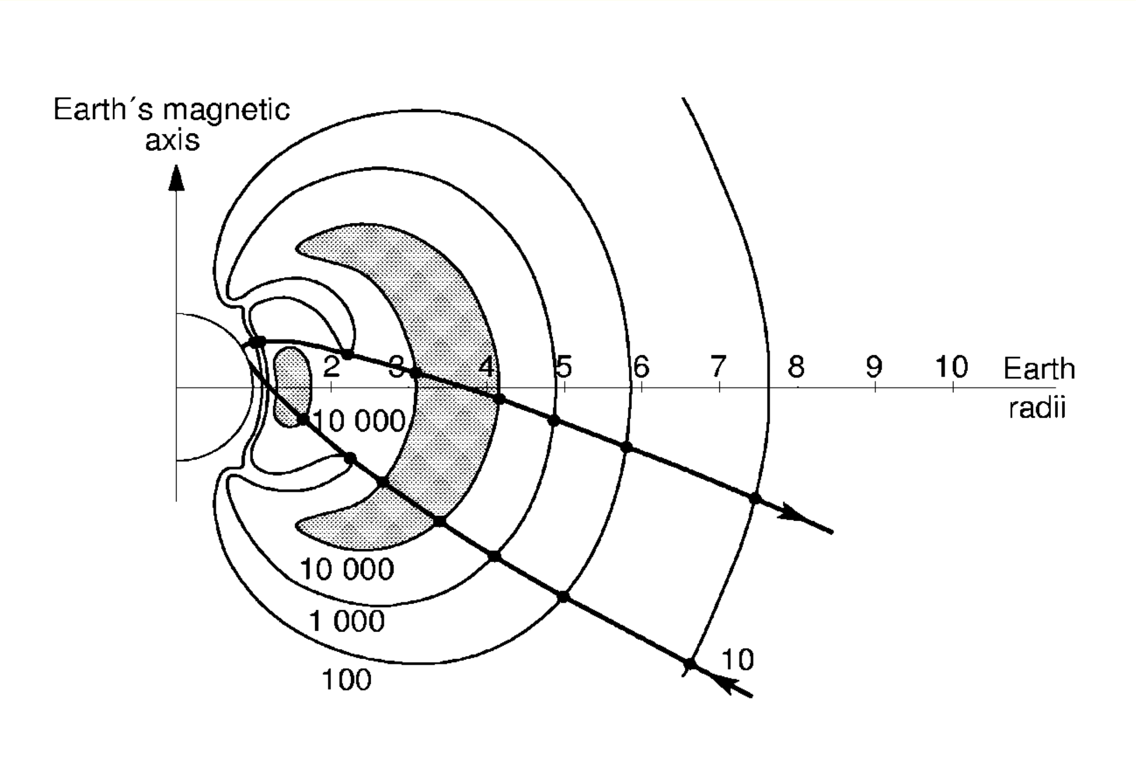
Ring current and particle motion

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

$$\mu = \frac{m v_\perp^2}{2B}$$



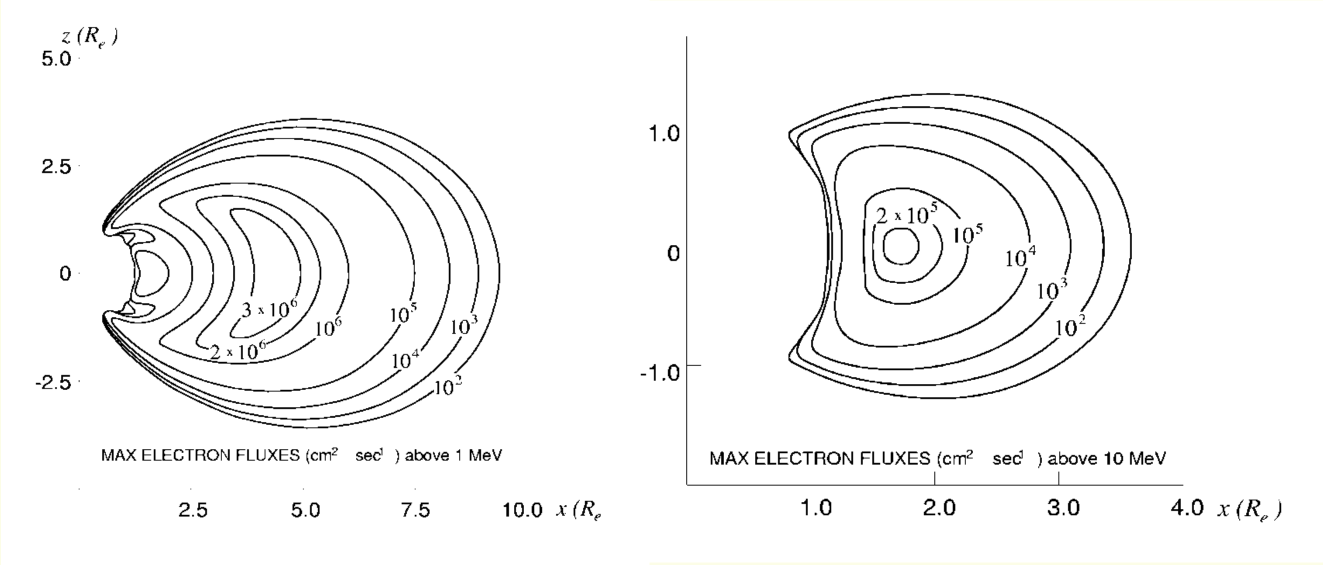
Radiation belts



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

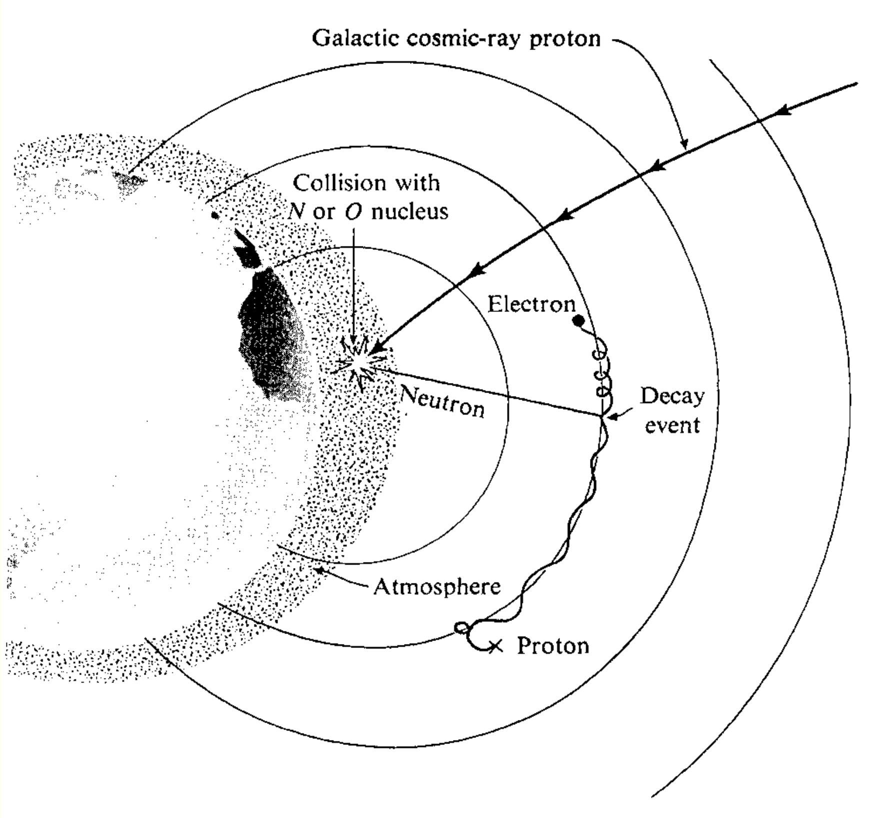
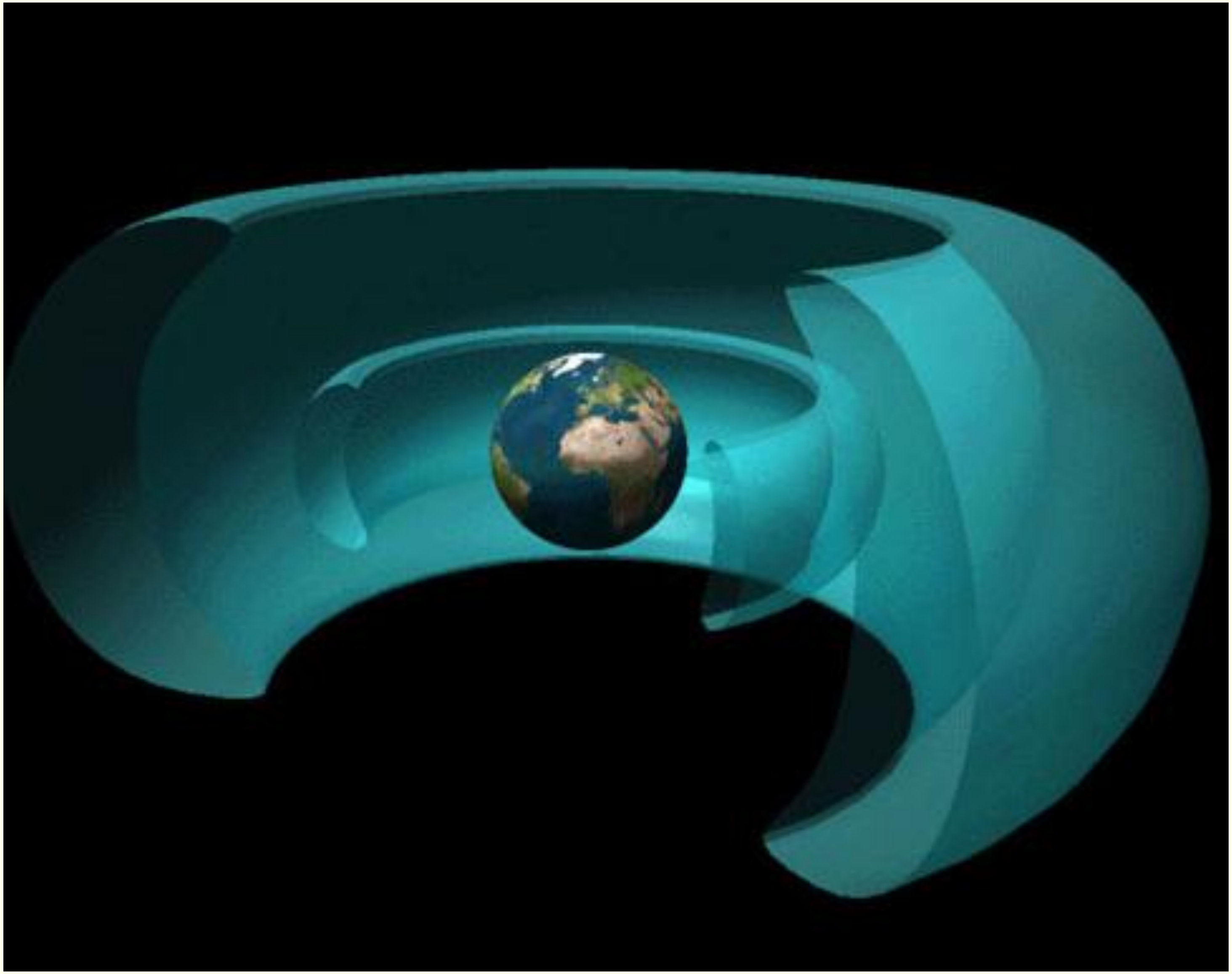


Figure 8. An illustration of the CRAND process for populating the inner radiation belts [Hess, 1968].

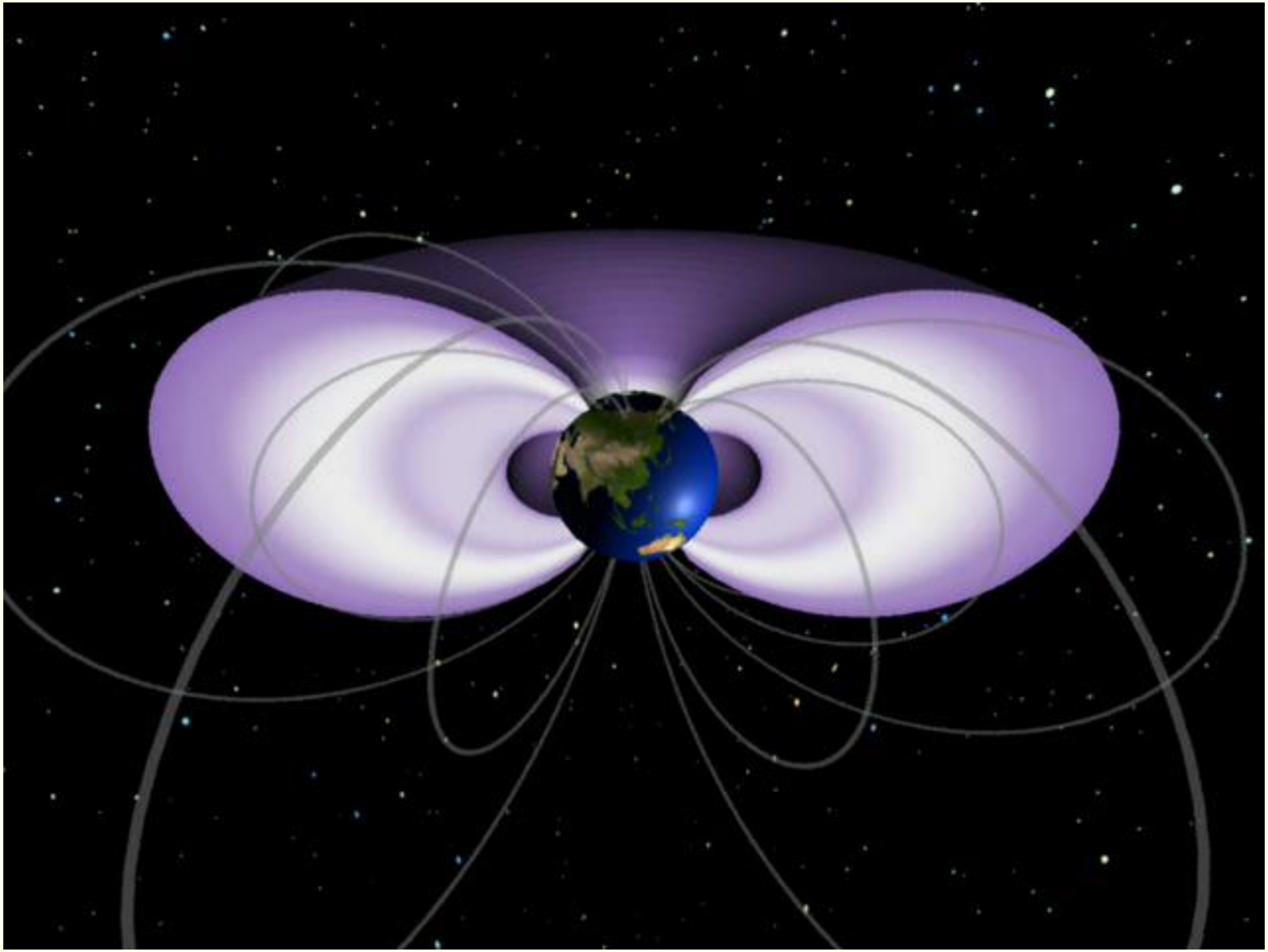
Collisions between cosmic ray particles and the Earth create new particles. Among these are neutrons, that are not affected by the magnetic field. They decay, soom eof them when they happen to be in the radiation belts. The resulting protons and electrons are trapped in the radiation belts.

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

Radiation belts



Radiation belts

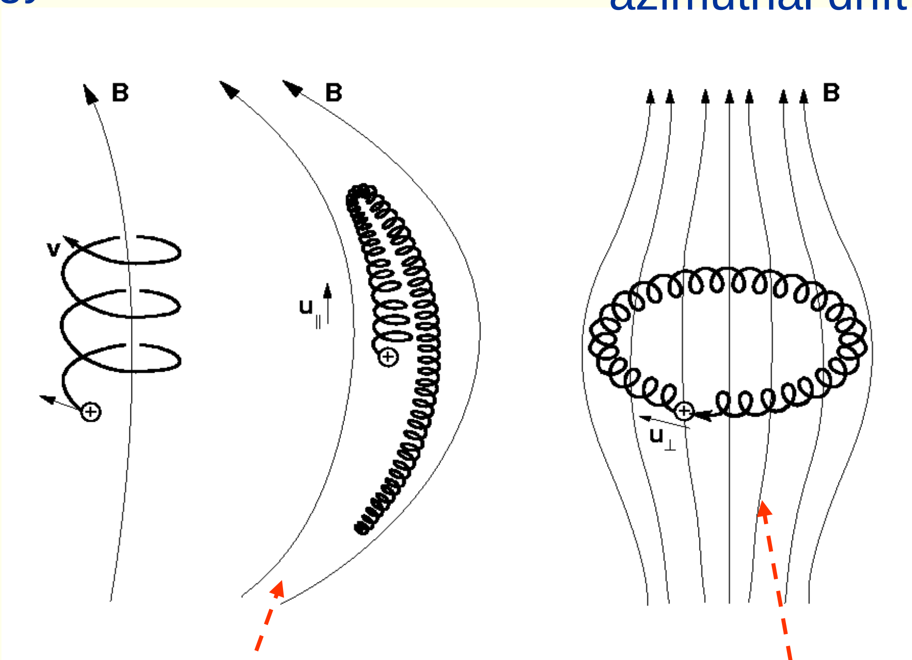


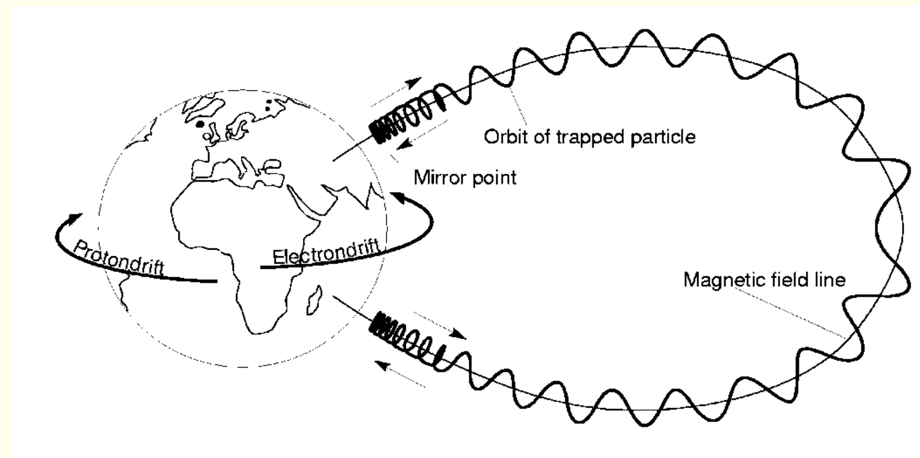
Particle motion in geomagnetic field

longitudinal oscillation

gyration

azimuthal drift

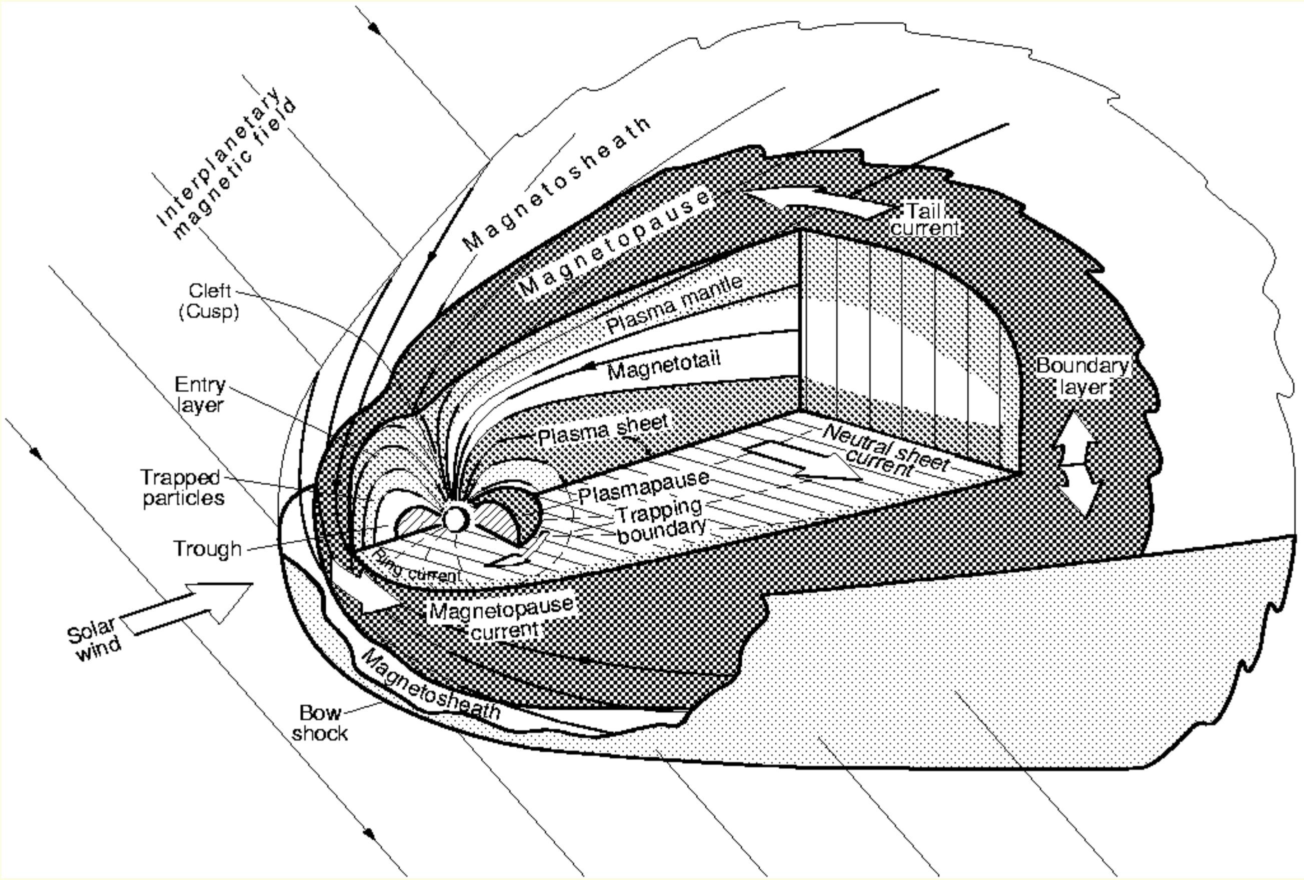




Magnetic mirror

grad B drift

Structure of magnetosphere

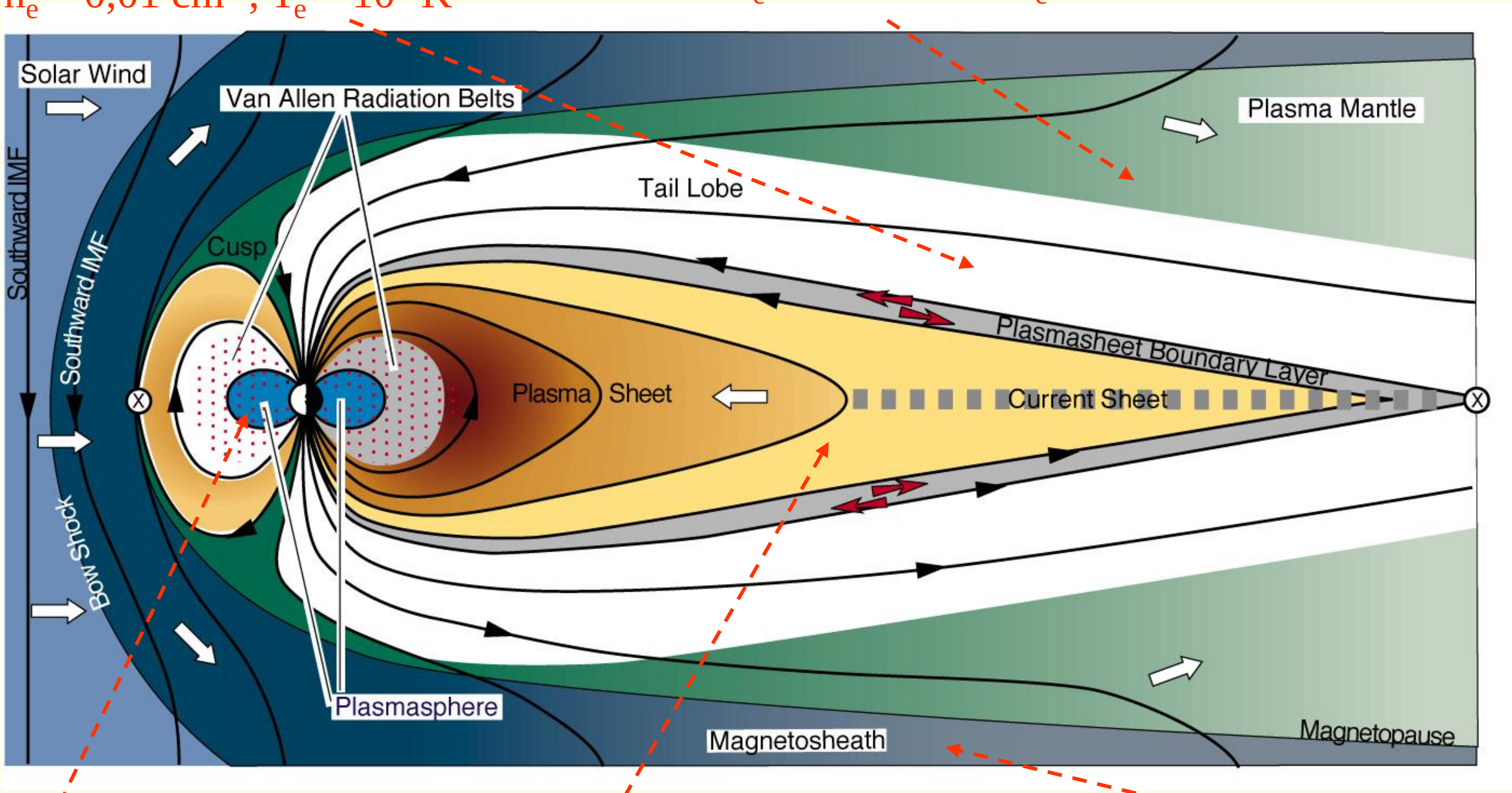


- The plasma in the is made up of approximately equal parts of H^+ and O^+.
- Plasma populations organized by geomagnetic field.
- Particles will mirror between northern and southern hemispheres on closed field lines

Magnetospheric structure

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

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

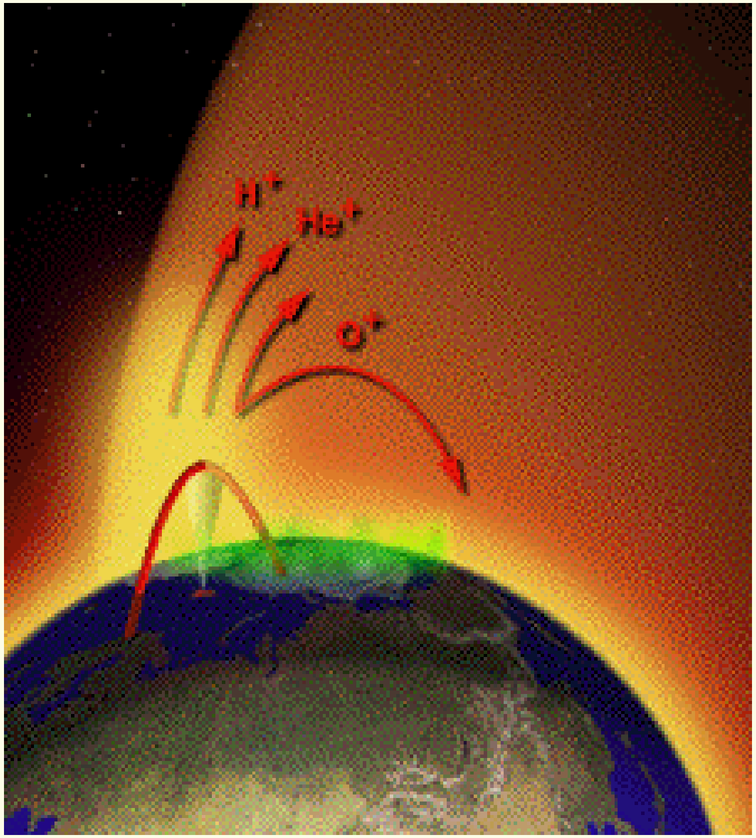


plasmasphere:
$n_e \sim 10\text{-}100\ cm^{-3}$, $T_e \sim 1000$ K

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

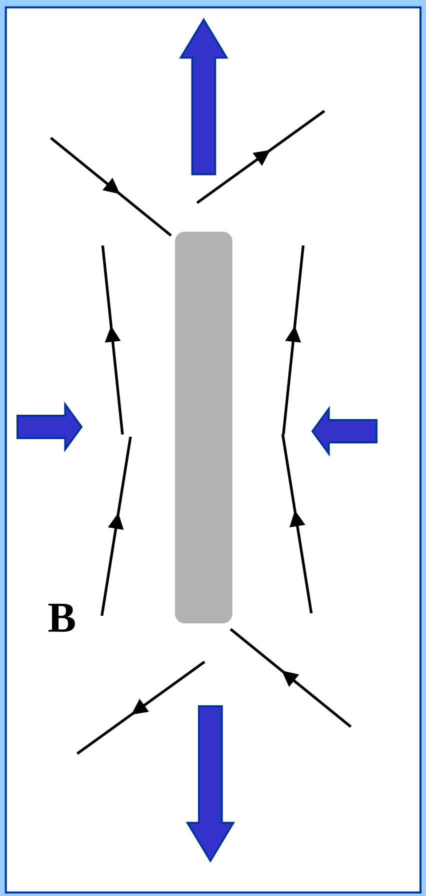


An important source for the magnetospheric plasma. Research is ongoing.

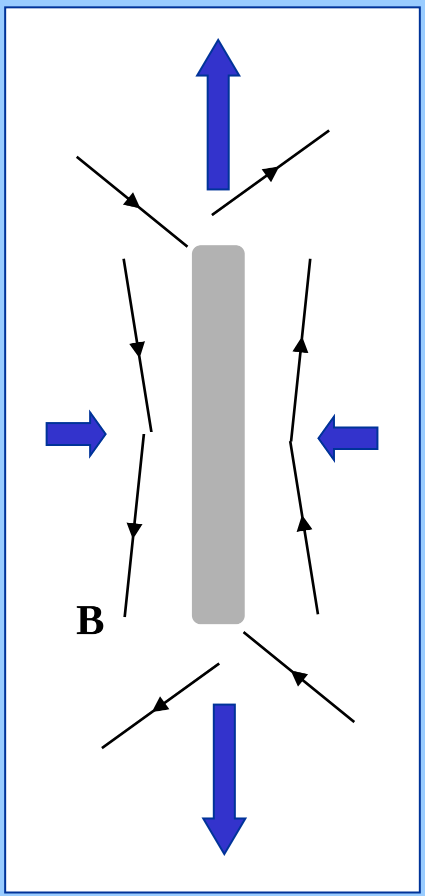
Magnetic reconnection

Which figure is correct?

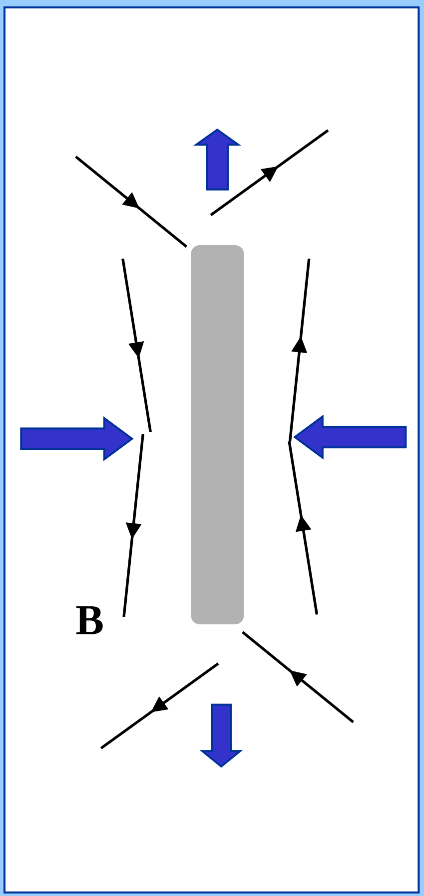
Size of arrows represents plasma flow velocity



Green



Yellow

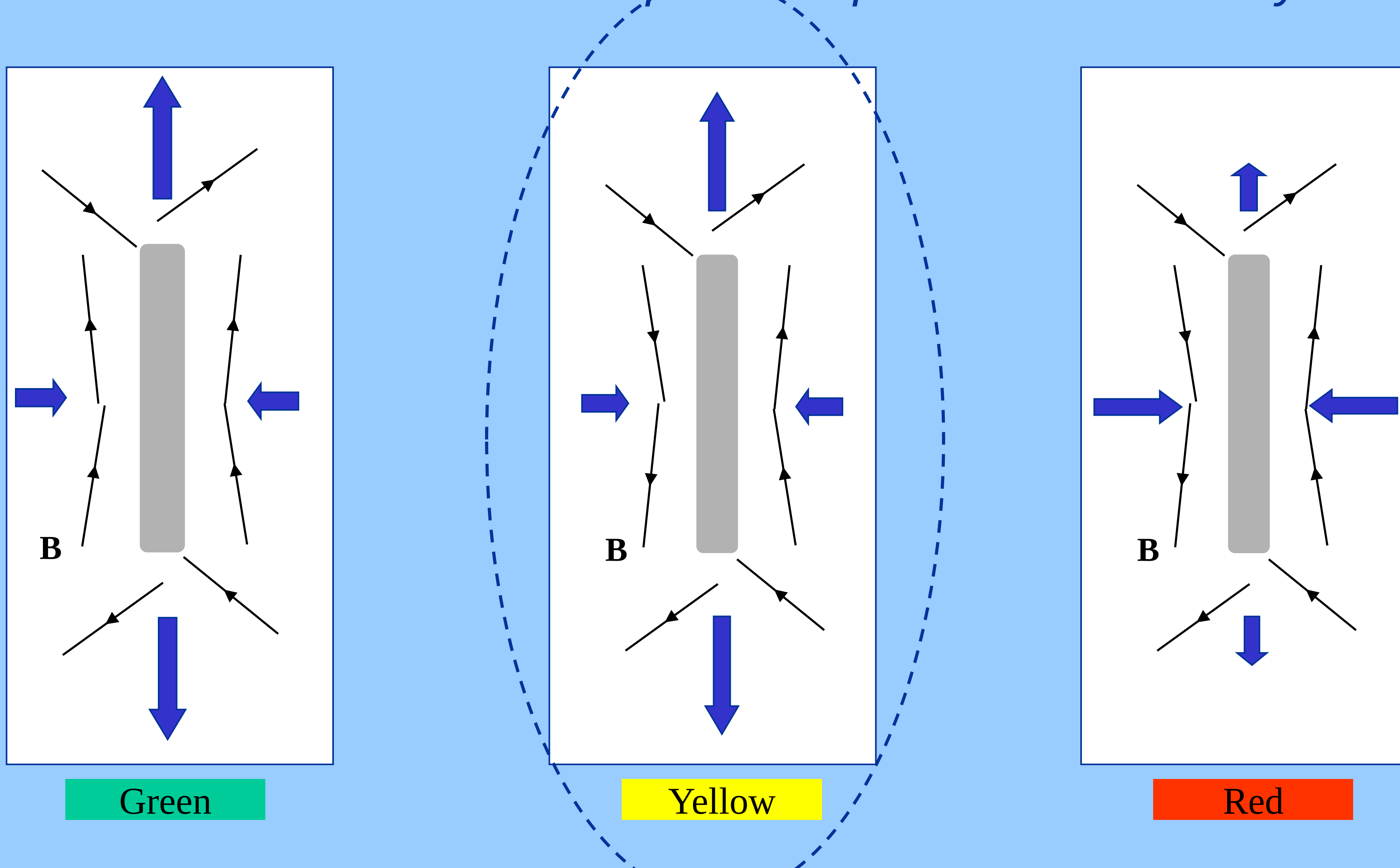


Red

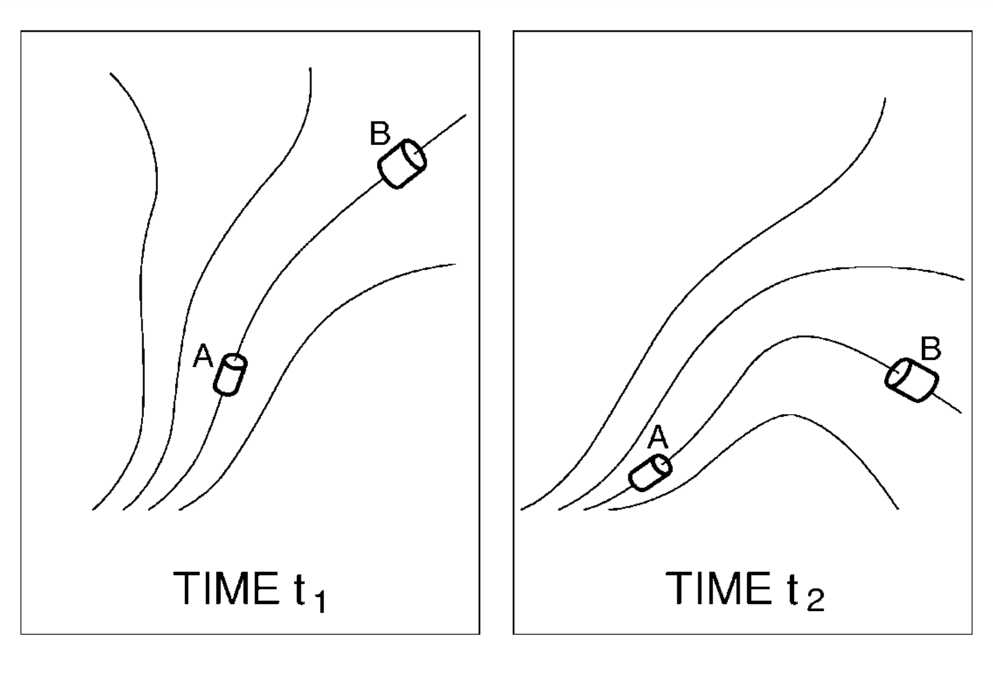
Magnetic reconnection

Which figure is correct?

Size of arrows represents plasma flow velocity



Frozen in magnetic field lines



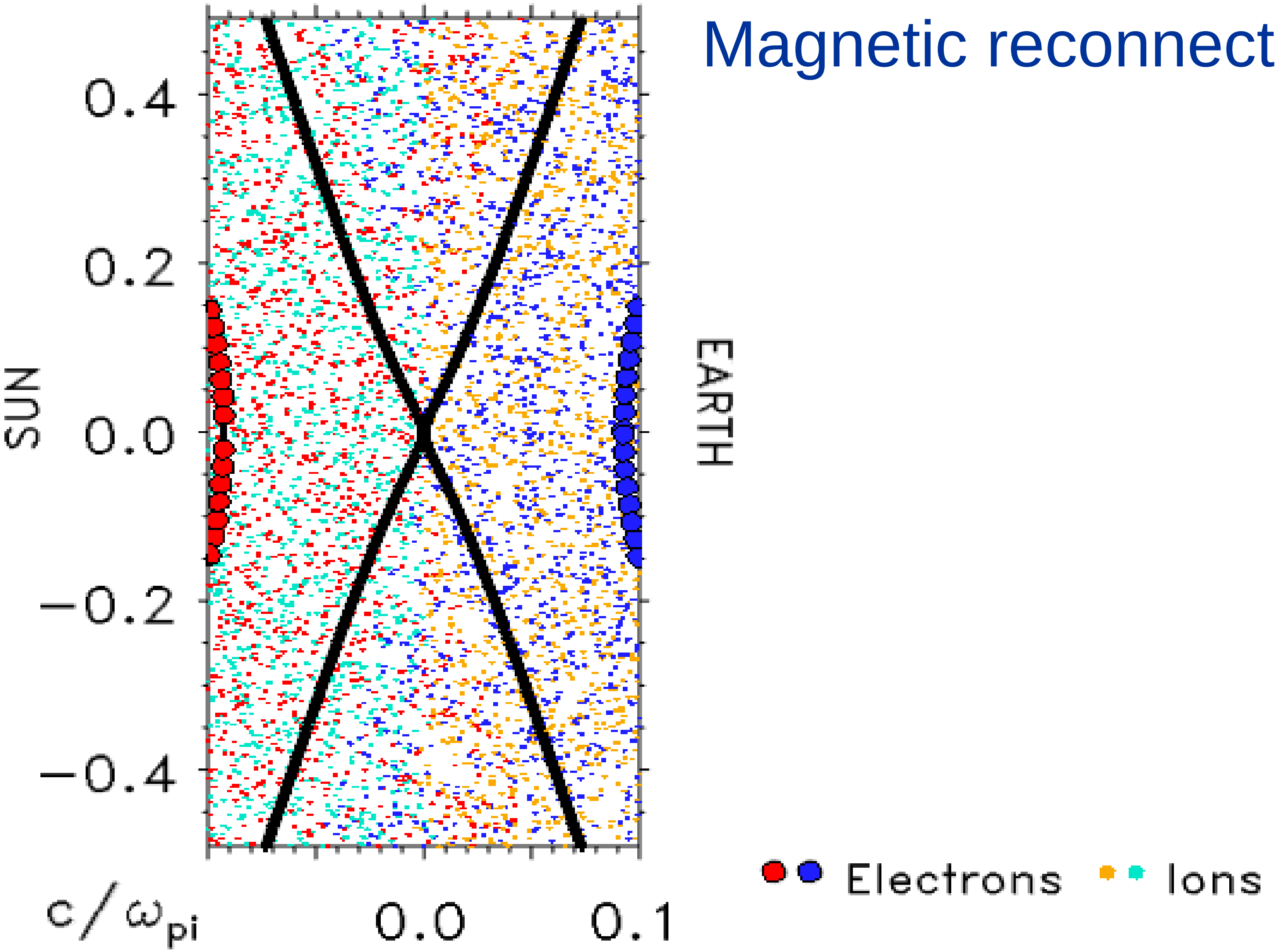
In fluid description of plasma two plasma elements that are connected by a common magnetic field line at time t_1 will be so at any other time t_2.

This applies if the magnetic Reynolds number is large:

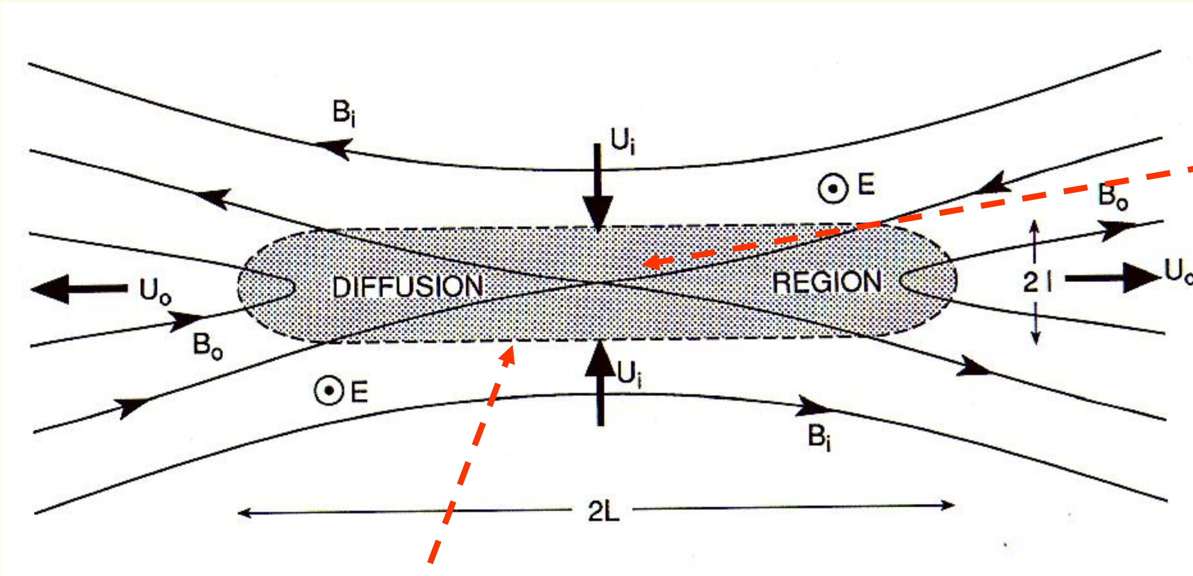
$$R_m = \mu_0 \sigma l_c v_c >> 1$$

An example of the collective behaviour of plasmas.

Magnetic reconnection



Reconnection



In 'diffusion region':

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

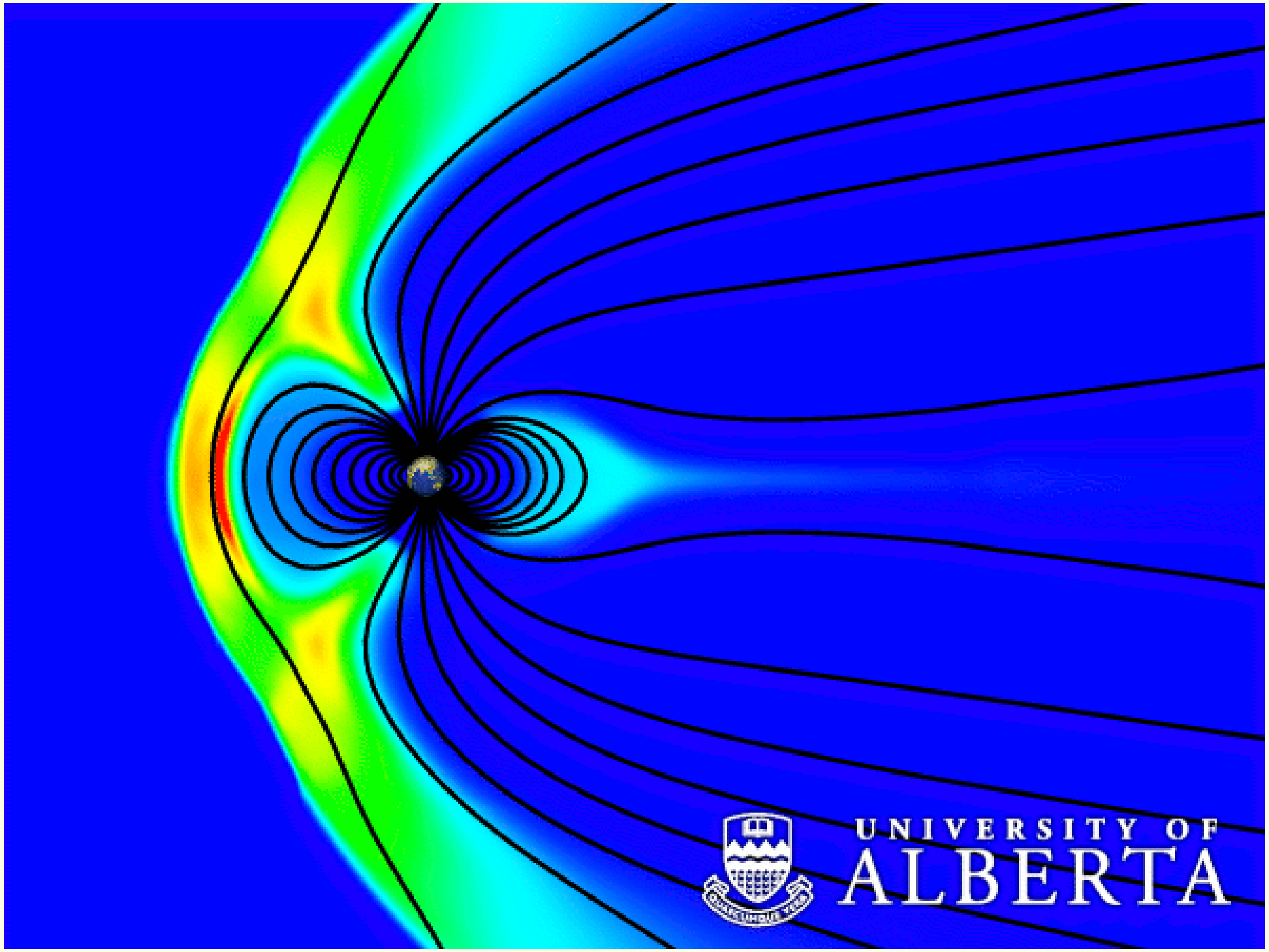
Thus: condition for frozen-in magnetic field breaks down.

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**

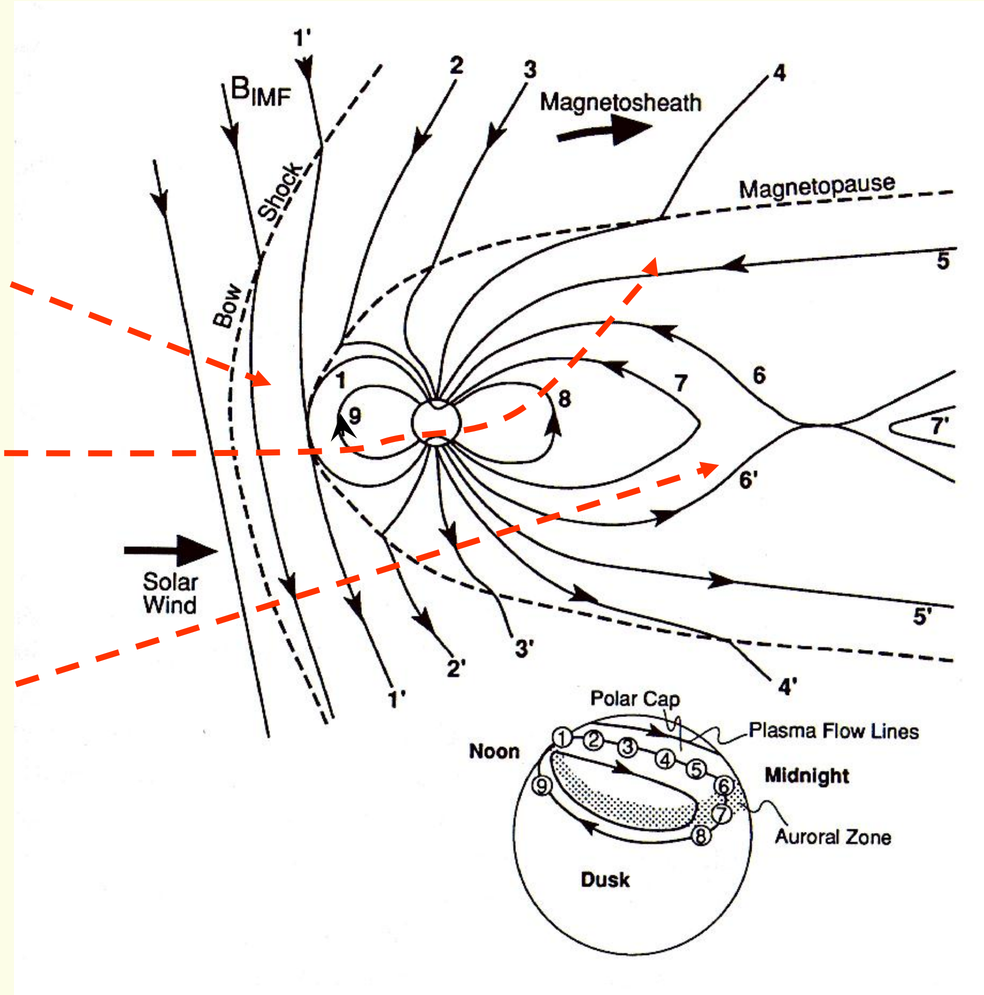
Reconnection and plasma convection

Solar wind

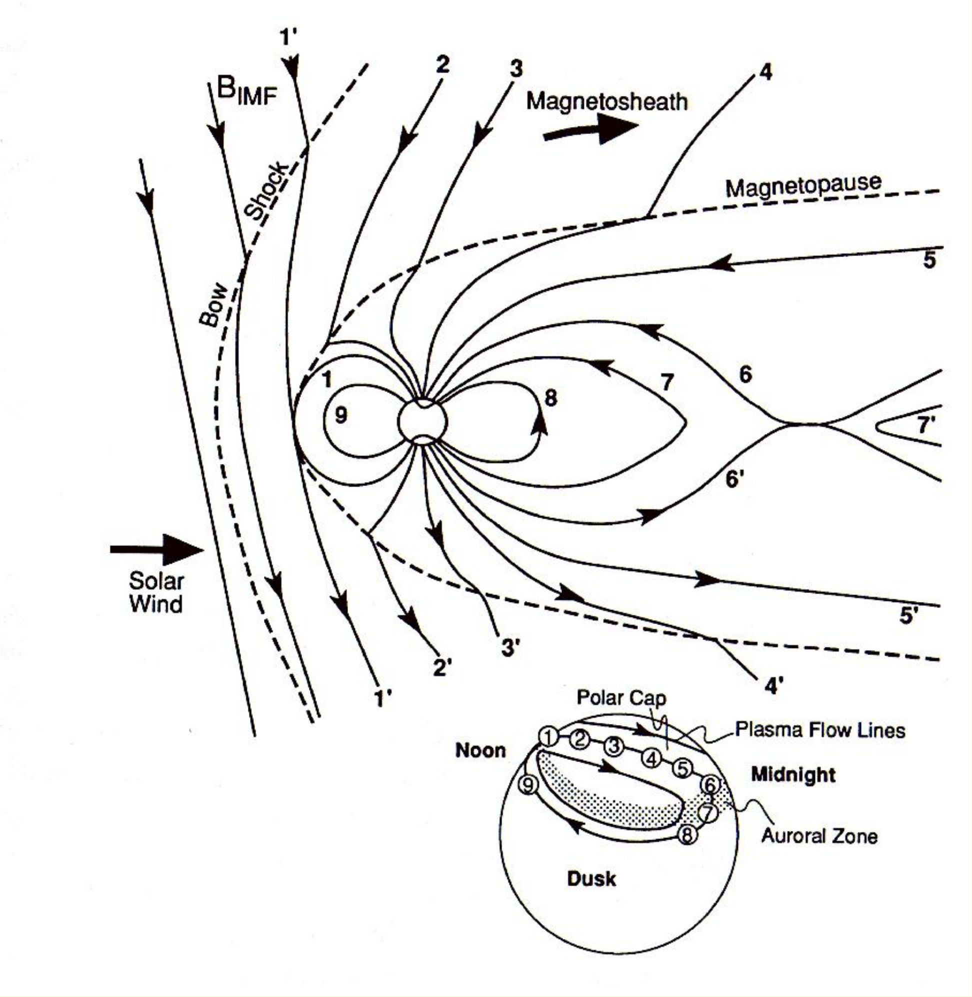


Reconnection och plasma convection

- 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.

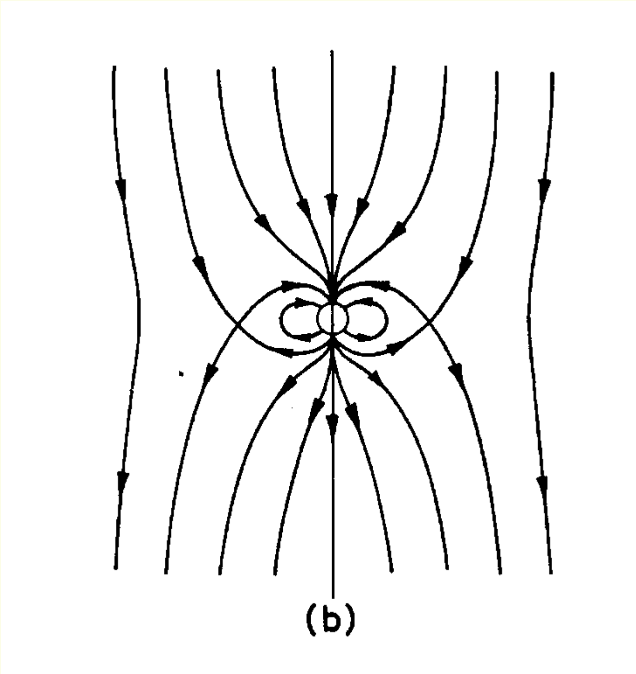


What happens if IMF is northward instead?

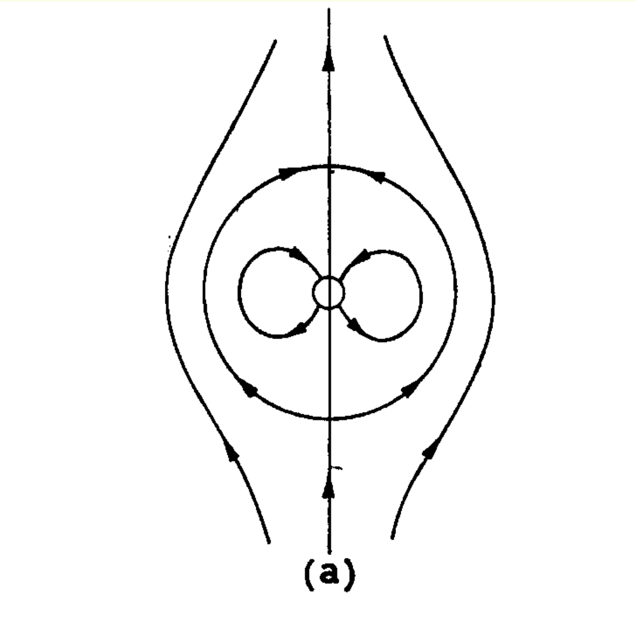


Magnetospheric dynamics

open magnetosphere



closed magnetosphere



southward

Interplanetary magnetic field (IMF)

northward

What do the magnetospheres of the other planets look like?