Last lecture (5)

- Solar wind
  - magnetic structure
- Ionosphere
  - index of refraction
  - reflection of radio waves
  - particle drift motion in magnetized plasma

Today's lecture (6)

- Electrical conductivity in ionosphere
- Magnetosphere, introduction
- Magnetospheric size (standoff distance)
- Particle motion in the magnetosphere

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

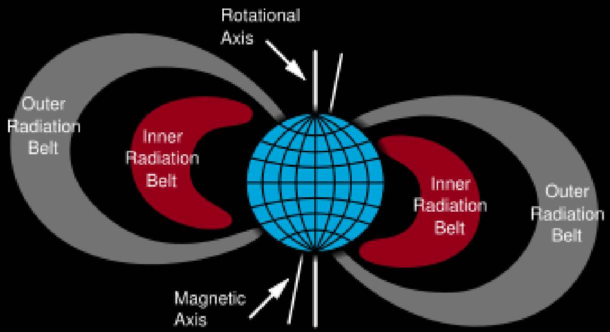
- shocks and boundaries in space
- solar wind interaction with magnetized and unmagnetized bodies
- reconnection
- sources of magnetospheric plasma
- magnetospheric and ionospheric convection
- auroral physics
- storms and substorms
- global oscillations of the magnetosphere

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



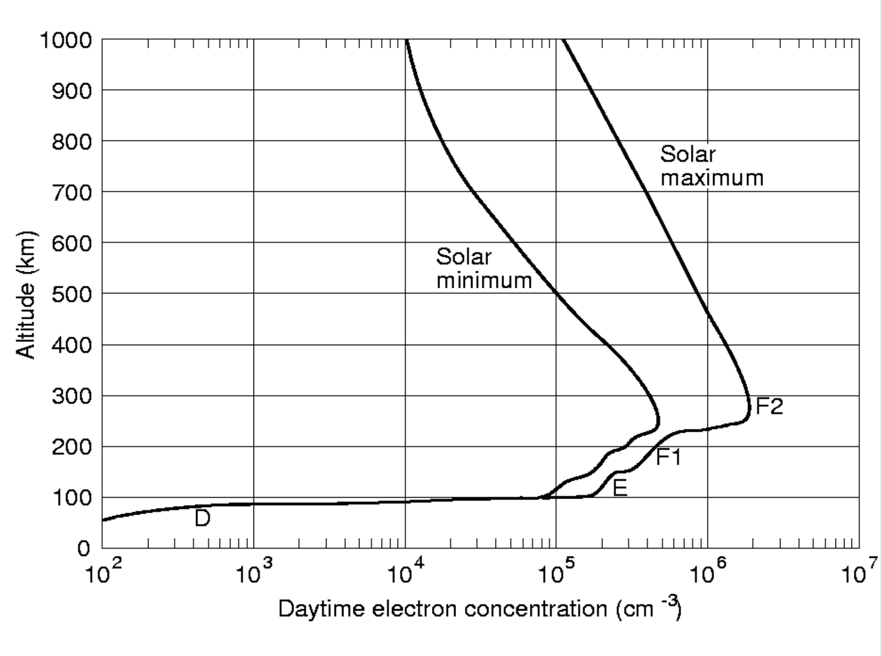
Radiation environment in near-earth space

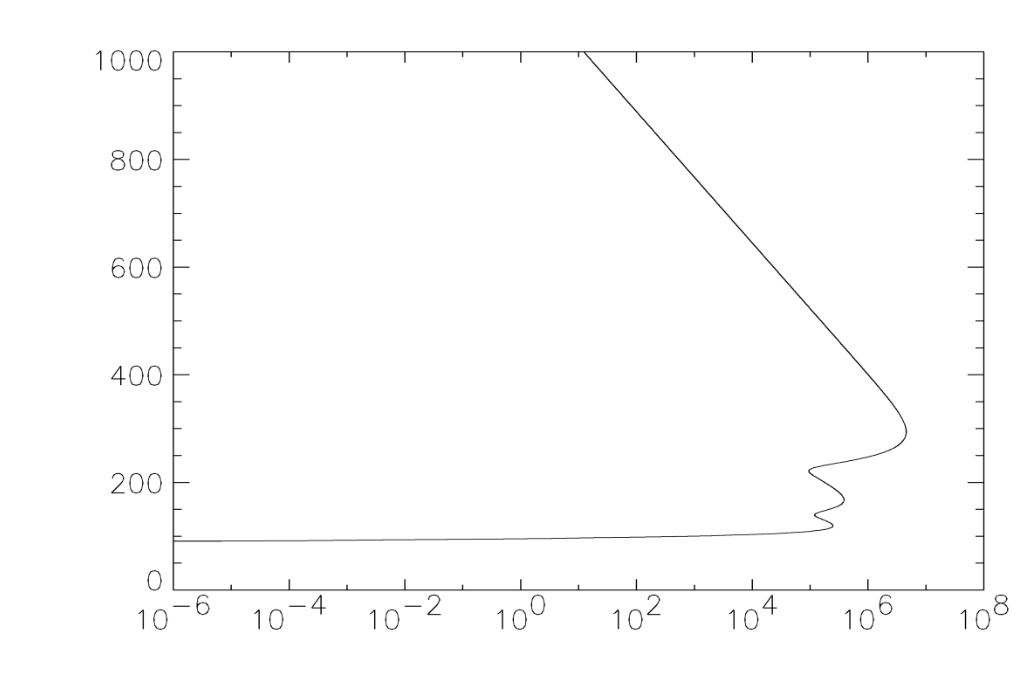
Projects:

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

Measurements

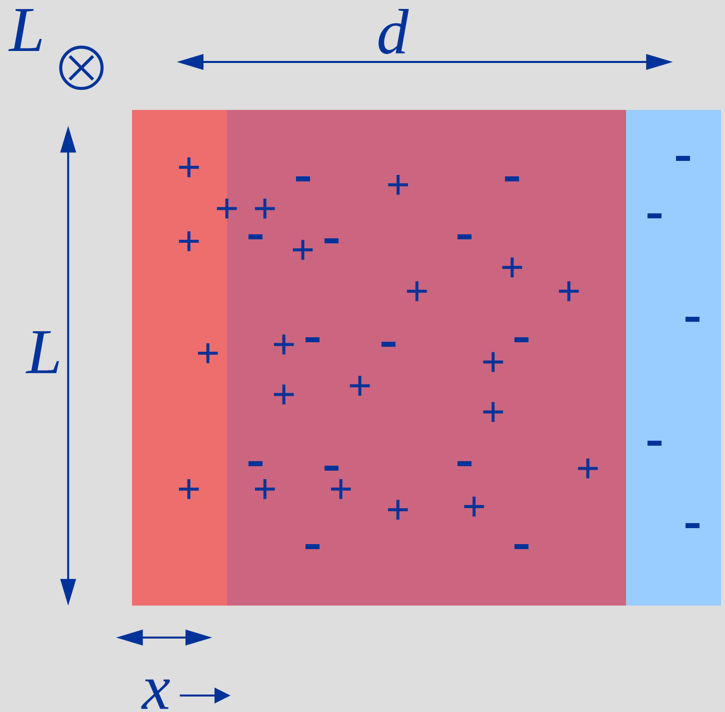
”E” + ”F1” + ”F2”





Ionospheric layers

Layer	D	E	F_1	F_2
Altitude (km)	60-85	85-140	140-200	200 - ca 1500
Nighttime electron density (cm^{-3})	$<10^2$	$2 \cdot 10^3$	—	$2 - 5 \cdot 10^5$
Daytime electron density (cm^{-3})	10^3	$1 - 2 \cdot 10^5$	$2 - 5 \cdot 10^5$	$0.5 - 2 \cdot 10^6$
Ion species	NO^+ O_2^+	NO^+ O_2^+	NO^+ O_2^+ O^+	O^+ He^+ H^+
Cause of ionization	Lyman α (1215 Å) + cosmic radiation	Lyman β (1025 Å) X-rays	UV	UV



$$F = m_e a \qquad E = \frac{\sigma}{\varepsilon_0}$$

$$F = -eE \qquad \sigma = e n_e x$$

$$\Rightarrow$$

$$-\frac{n_e e^2 x}{\varepsilon_0 m_e} = \frac{d^2 x}{dt^2}$$

$$x = \sin(\omega_{pe} t)$$

$$\omega_{pe} \equiv \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$$

Index of refraction for electromagnetic waves in a plasma (corrected)

(1) $$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

(2) $$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

(3) $$\mathbf{j} = -e n_e \mathbf{v}_e$$

(4) $$m_e \frac{\partial \mathbf{v}_e}{\partial t} = -e\mathbf{E}$$

Assume all quantities vary sinusoidally, with frequency ω, *e.g.*:

$$\mathbf{E} = \mathbf{E}_0 e^{i(\mathbf{k}\cdot\mathbf{r} - \omega t)}$$

(1) $$\Rightarrow \quad \nabla \times (\nabla \times \mathbf{E}) = -\nabla \times \frac{\partial \mathbf{B}}{\partial t}$$

(2) $$\Rightarrow \quad \nabla \times \frac{\partial \mathbf{B}}{\partial t} = \mu_0 \frac{\partial \mathbf{j}}{\partial t} + \frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

$$\therefore \quad \nabla \times (\nabla \times \mathbf{E}) = +\mu_0 \frac{\partial}{\partial t}(e n_e \mathbf{v}_e) - \frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

$$\Rightarrow$$

$$\nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} = +\mu_0 e n_e \frac{\partial \mathbf{v}_e}{\partial t} - \frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

$$\Rightarrow$$

Index of refraction for electromagnetic waves in a plasma (corrected)

$$\cancel{i\mathbf{k}\left(i\mathbf{k}\cdot\mathbf{E}\right)} - k^2\mathbf{E} = \mu_0\left(-i\omega\right)en_e\mathbf{v}_e - \frac{1}{c^2}\left(-i\omega\right)^2\mathbf{E}$$

Does not represent E.M. wave

(4) $\Rightarrow$

$$k^2\mathbf{E} = -\mu_0 en_e\frac{e\mathbf{E}}{m_e} + \frac{1}{c^2}\omega^2\mathbf{E}$$

$\Rightarrow$

$$c^2k^2 = -c^2\frac{\mu_0 n_e e^2}{m_e} + \omega^2 = \frac{-1}{\cancel{\mu_0}\varepsilon_0}\frac{\cancel{\mu_0}n_e e^2}{m_e} + \omega^2$$

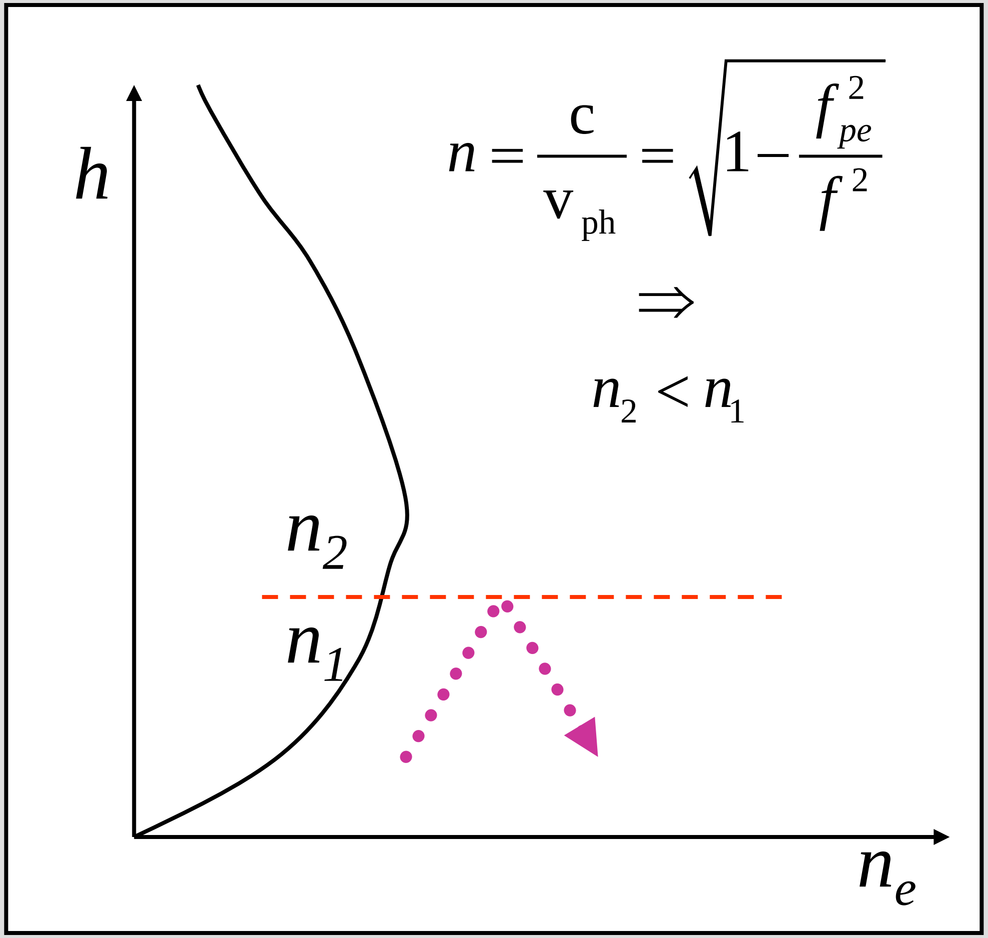
$$\therefore \quad \omega^2 = c^2k^2 + \omega_p^2$$

$$n^2 = \frac{c^2}{v_{ph}^2} = \frac{c^2k^2}{\omega^2} = \frac{\omega^2 - \omega_p^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}$$

$\therefore$

$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} = \sqrt{1 - \frac{f_p^2}{f^2}}$$

Where does the total reflection take place?

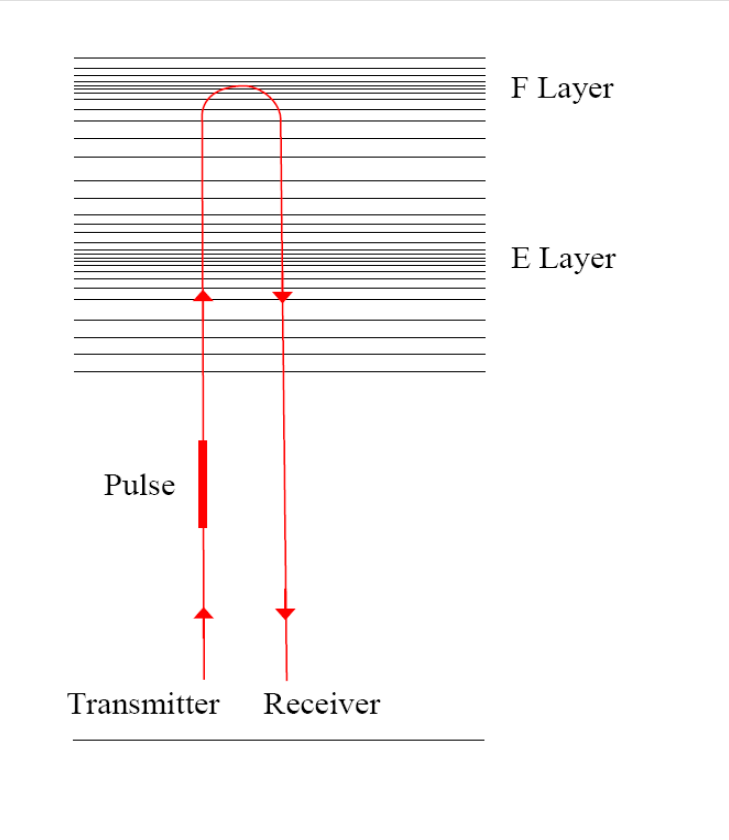


Large gradient when

$$f \approx f_{pe}$$

Higher frequencies $\rightarrow$ higher $f_{pe}\,(n_e)$

Ionosonde



The pulse will be reflected where

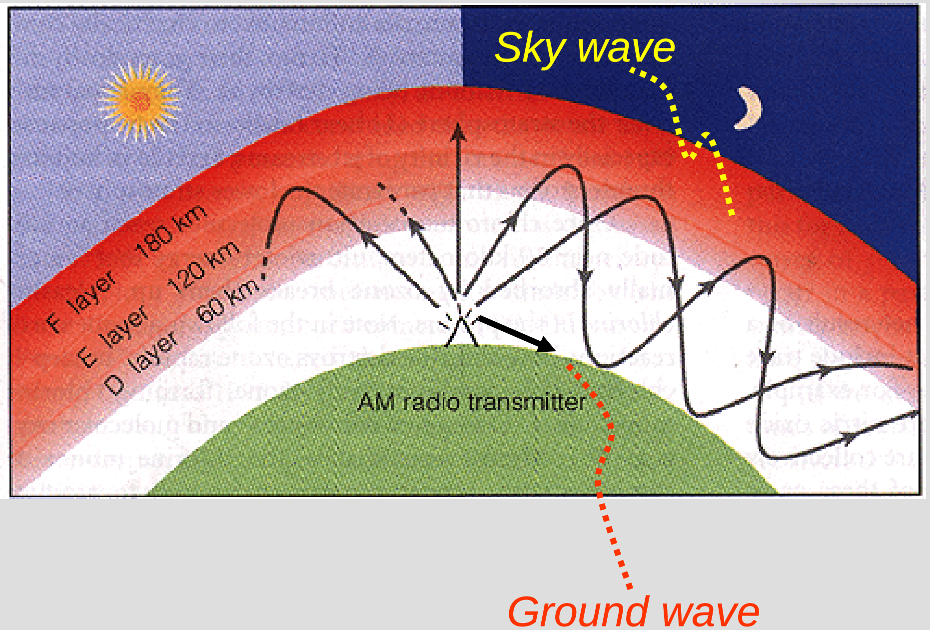
$$f = f_{pe}$$

The altitude will be determined by

$$2h = ct$$

Where t is the time between when the pulse is sent out and the registered again.

Reflection of radio waves



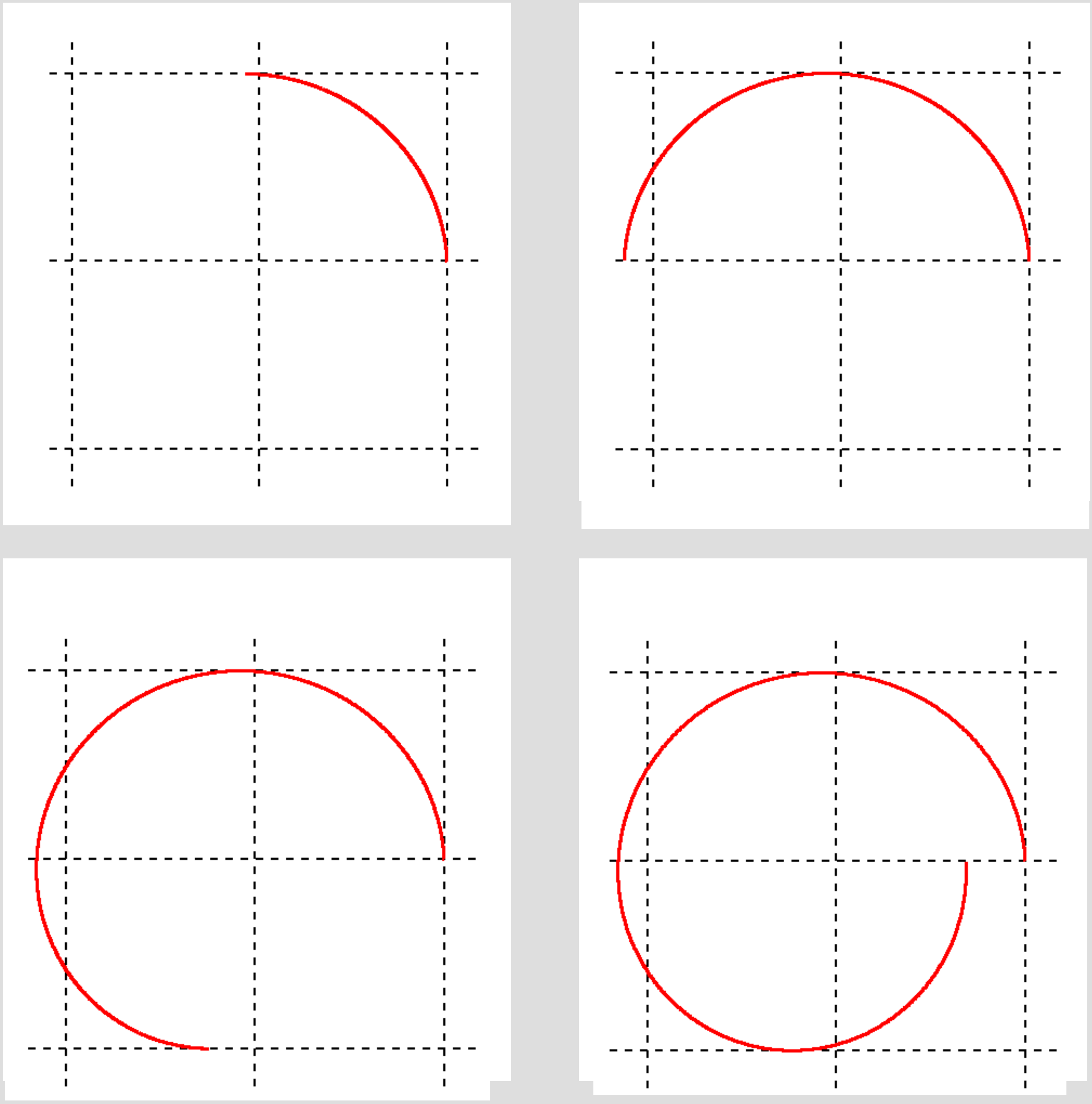
F2-layer during night:

$$n_e = 5 \cdot 10^{11}\ \mathrm{m}^{-3} \quad \Rightarrow$$

$$f_{pe} = 10^7\ \mathrm{Hz} = 10\ \mathrm{MHz}$$

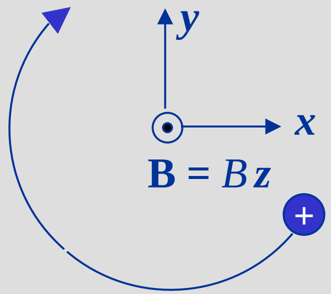
= HF/short wave

E
B



Drift motion

Consider a charged particle in a magnetic field.



Assume an electric field in the x-z plane:

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

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

$$\begin{cases} m\dfrac{dv_x}{dt} = qv_y B + qE_x \\ m\dfrac{dv_y}{dt} = -qv_x B \\ m\dfrac{dv_z}{dt} = qE_z \end{cases}$$

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:

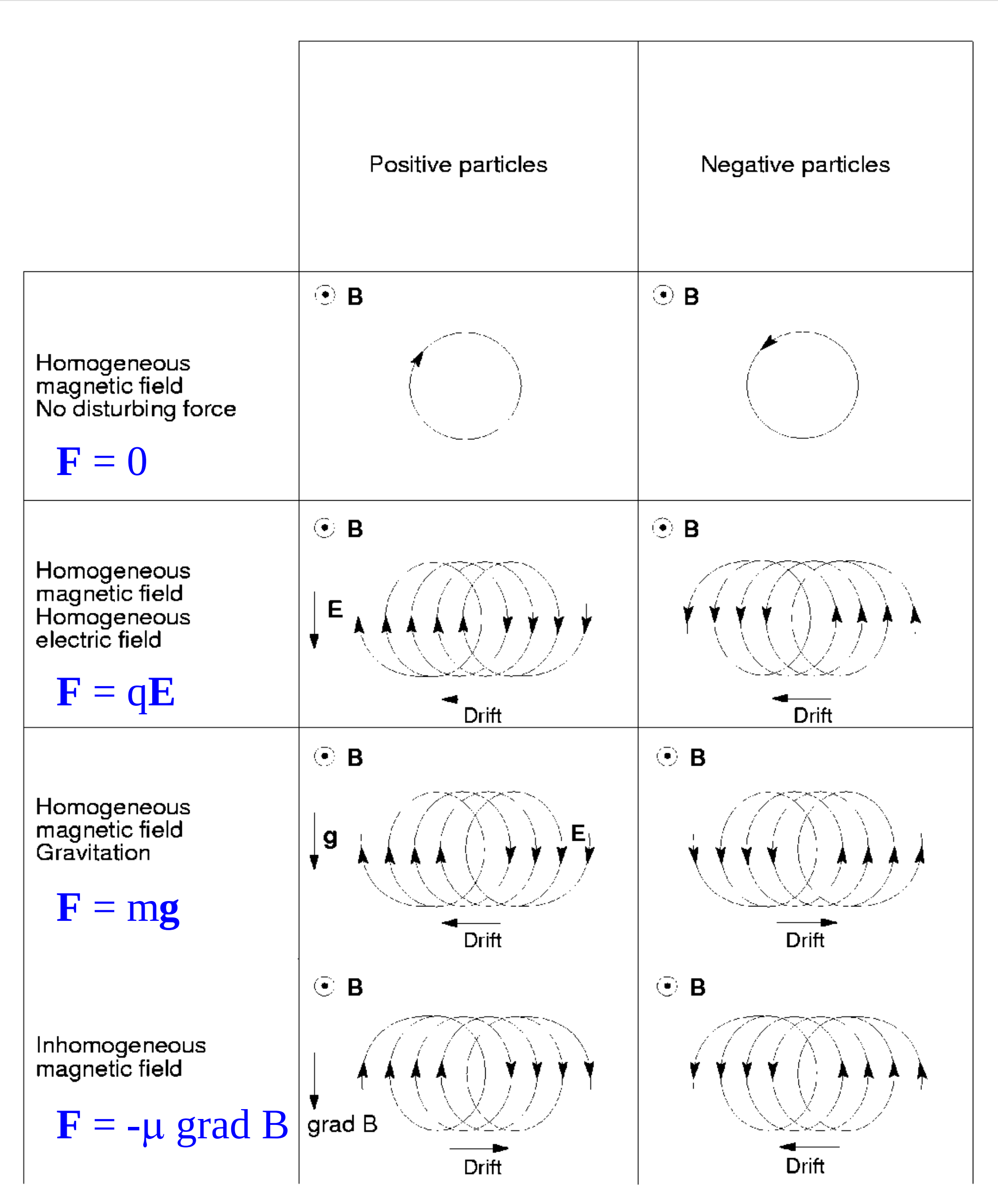
$$v_{drift,y} = -\frac{E_x}{B} = -\frac{E_x B_z}{B^2} = \frac{(\mathbf{E}\times\mathbf{B})_y}{B^2}$$

In general:

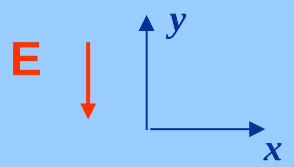
$$\mathbf{v}_{drift} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = \frac{q\mathbf{E}\times\mathbf{B}}{qB^2} = \frac{\mathbf{F}\times\mathbf{B}}{qB^2}$$

Drift motion

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



Suppose you apply an electric field **E** in the direction showed in the figure, and that one electron and one ion (charge –*e* and *e*) is present. What will the resulting current be?



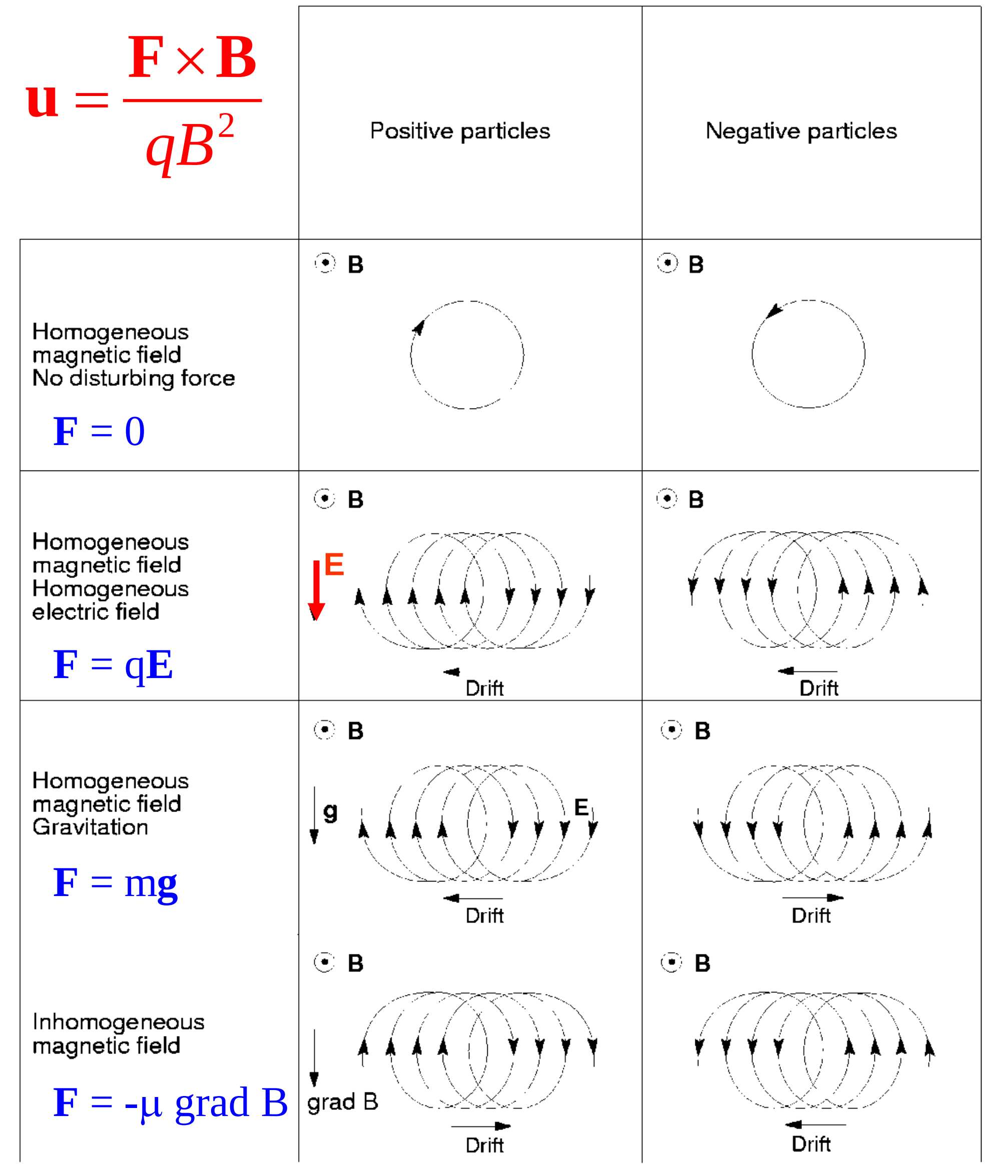
$$\mathbf{I} \equiv e\mathbf{u}_\mathrm{i} - e\mathbf{u}_\mathrm{e}$$

Yellow $\quad \mathbf{I} = -e\frac{E}{B}\hat{\mathbf{x}}$

Blue $\quad \mathbf{I} = 0$

Red $\quad \mathbf{I} = \frac{1}{2}e\frac{E}{B}\hat{\mathbf{x}} - \frac{1}{2}e\frac{E}{B}\hat{\mathbf{y}}$

Green $\quad \mathbf{I} = e\frac{E}{B}\hat{\mathbf{y}}$

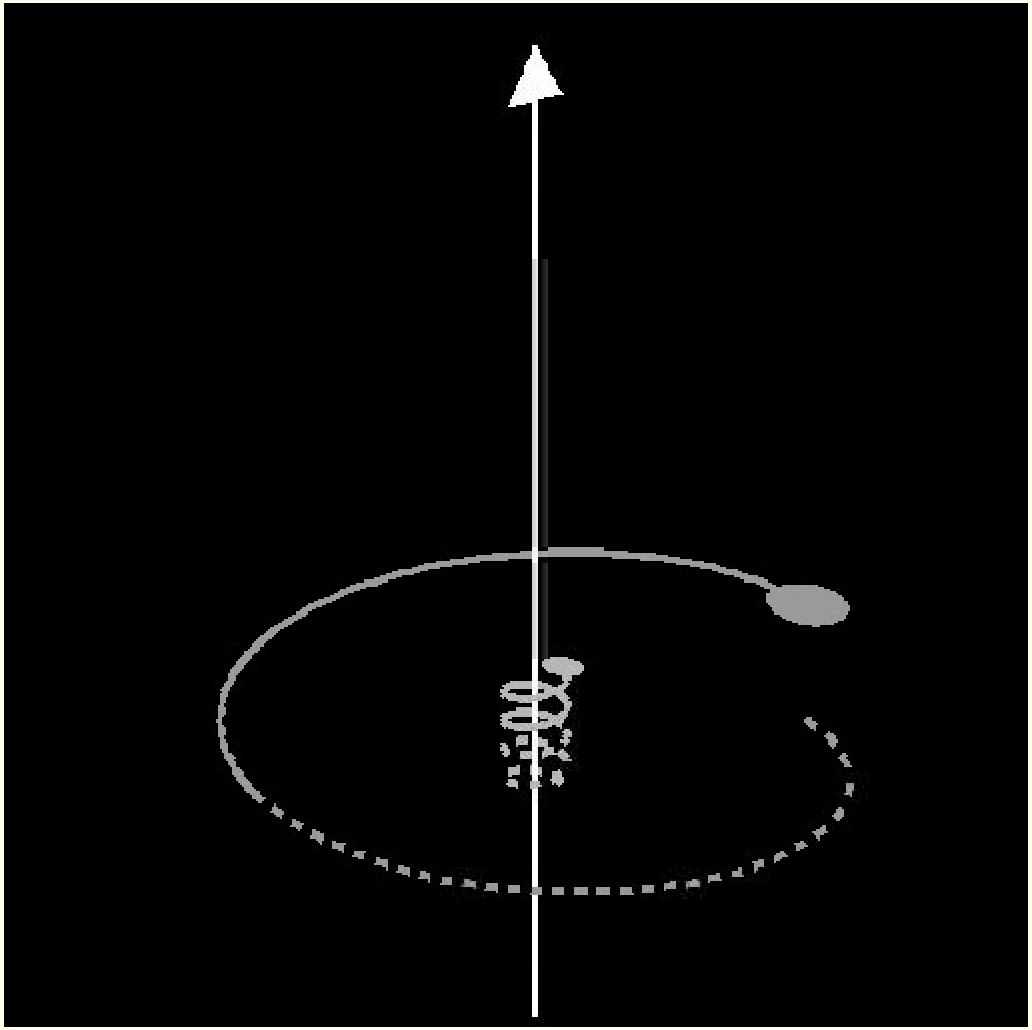


So, if there is no current when you apply an electric field, is the conductivity of the ionospheric plasma zero ?

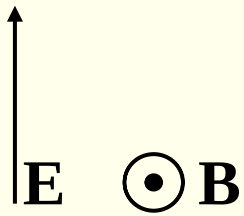
What is the electron density at 100 km?

What is the neutral density at 100 km?

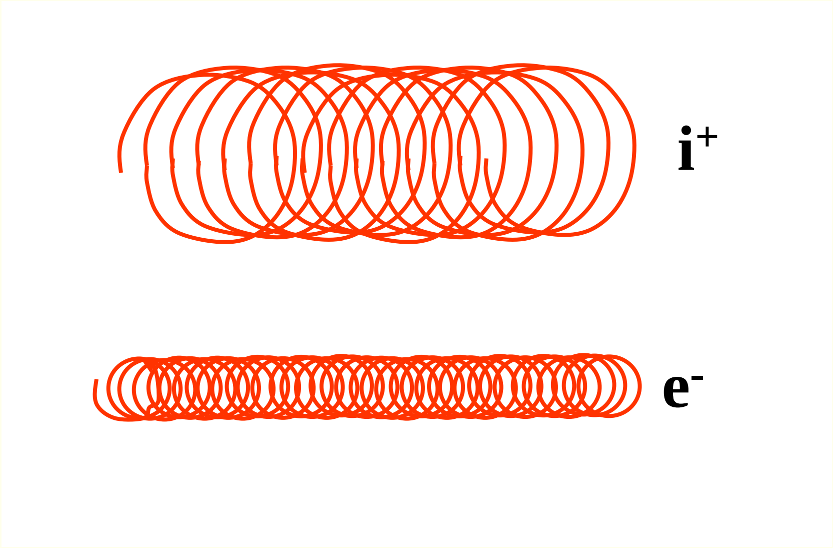
Gyro motion



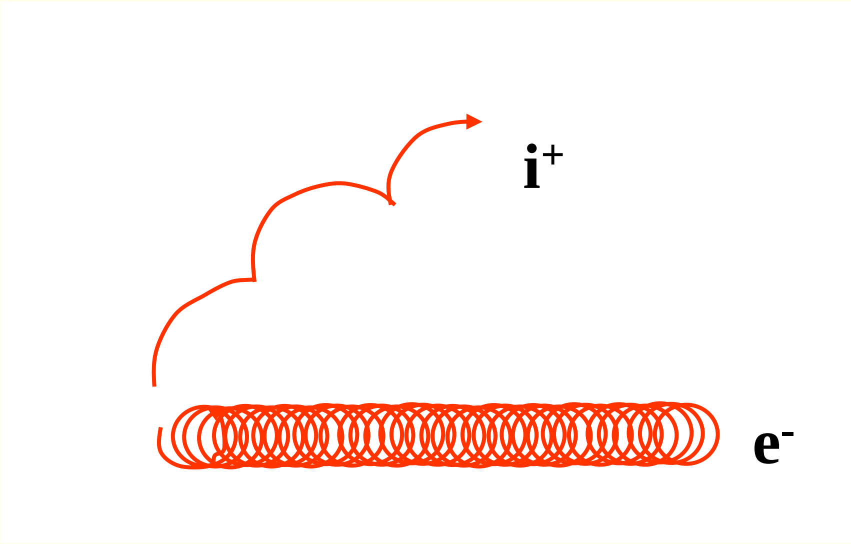
ExB-drift



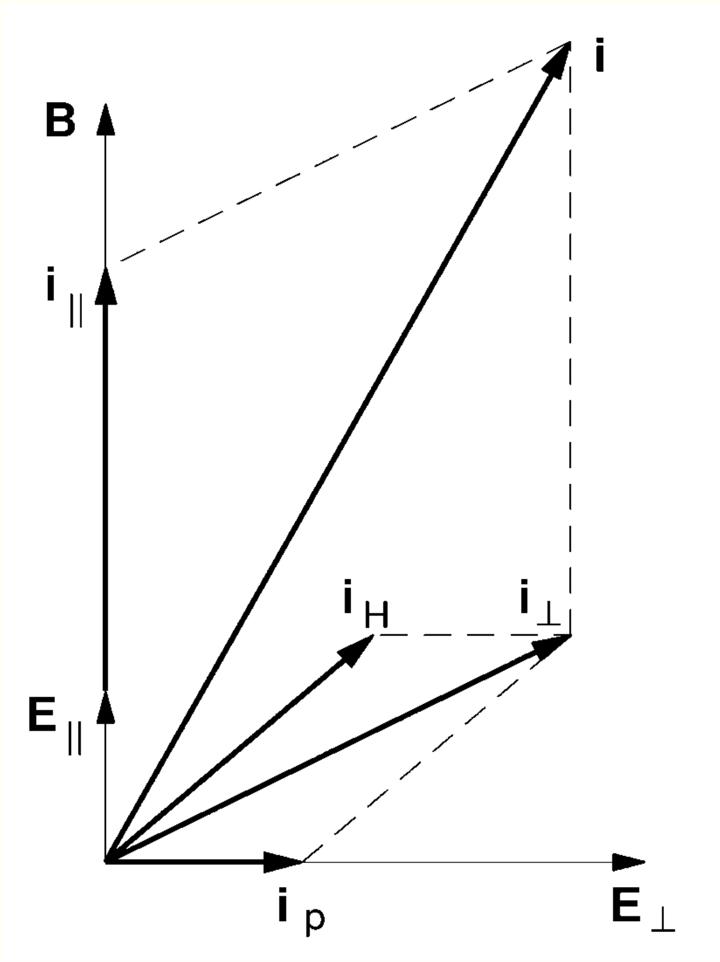
Without collisions



With collisions

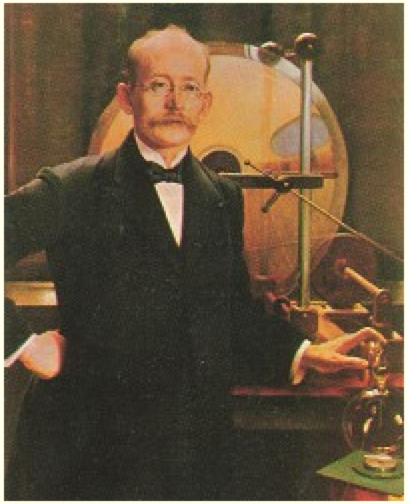


Electric conductivity in a magnetized plasma



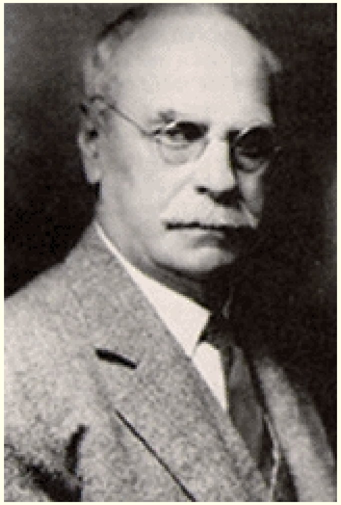
- $i_{//}$ = parallel current
- i_P = Pedersen current
- i_H = Hall current

Birkeland, Hall, Pedersen



Kristian Birkeland
1867-1917

Norwegian
scientist



Edwin Hall
1855-1938

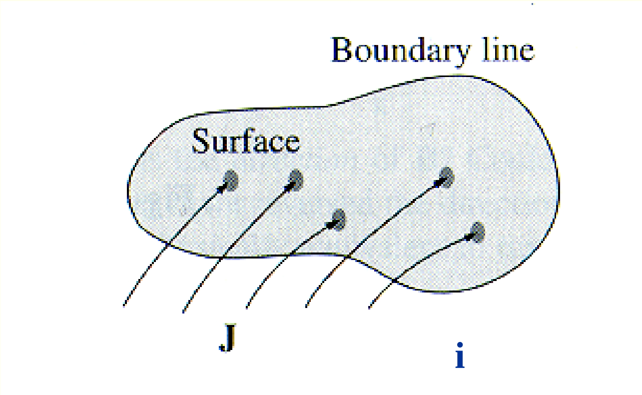
American
physicist

Peder Oluf Pedersen
1874-1941

Danish engineer
and physicist

Current density

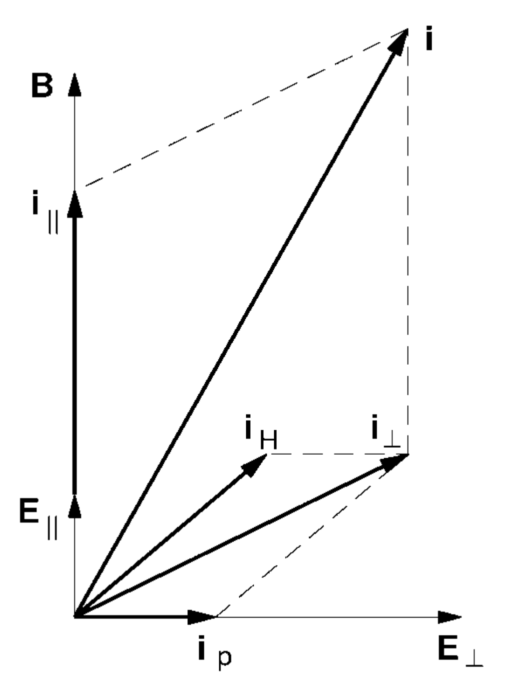
The current density **j** is a vector field with dimension [**i**] = Am^{-2}.



The total current I through the surface S is

$$I = \int_S \mathbf{j} \cdot d\mathbf{S}$$

Electric conductivity in a magnetized plasma II



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

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

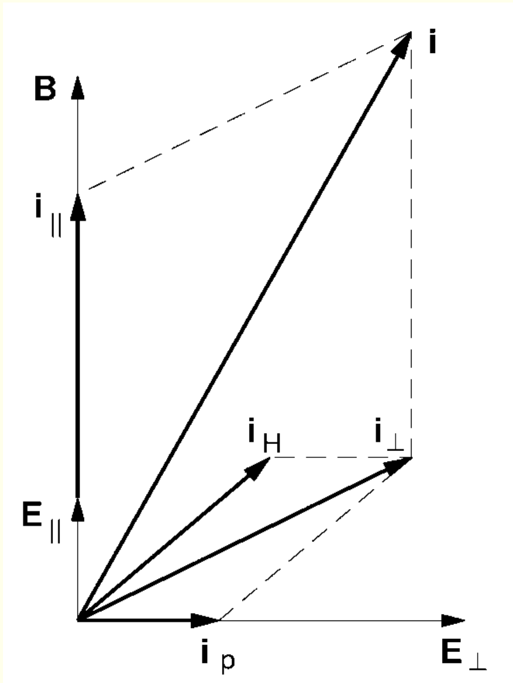
$$\sigma_{//} = \sigma_e + \sigma_i$$

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

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

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

Electric conductivity in a magnetized plasma II



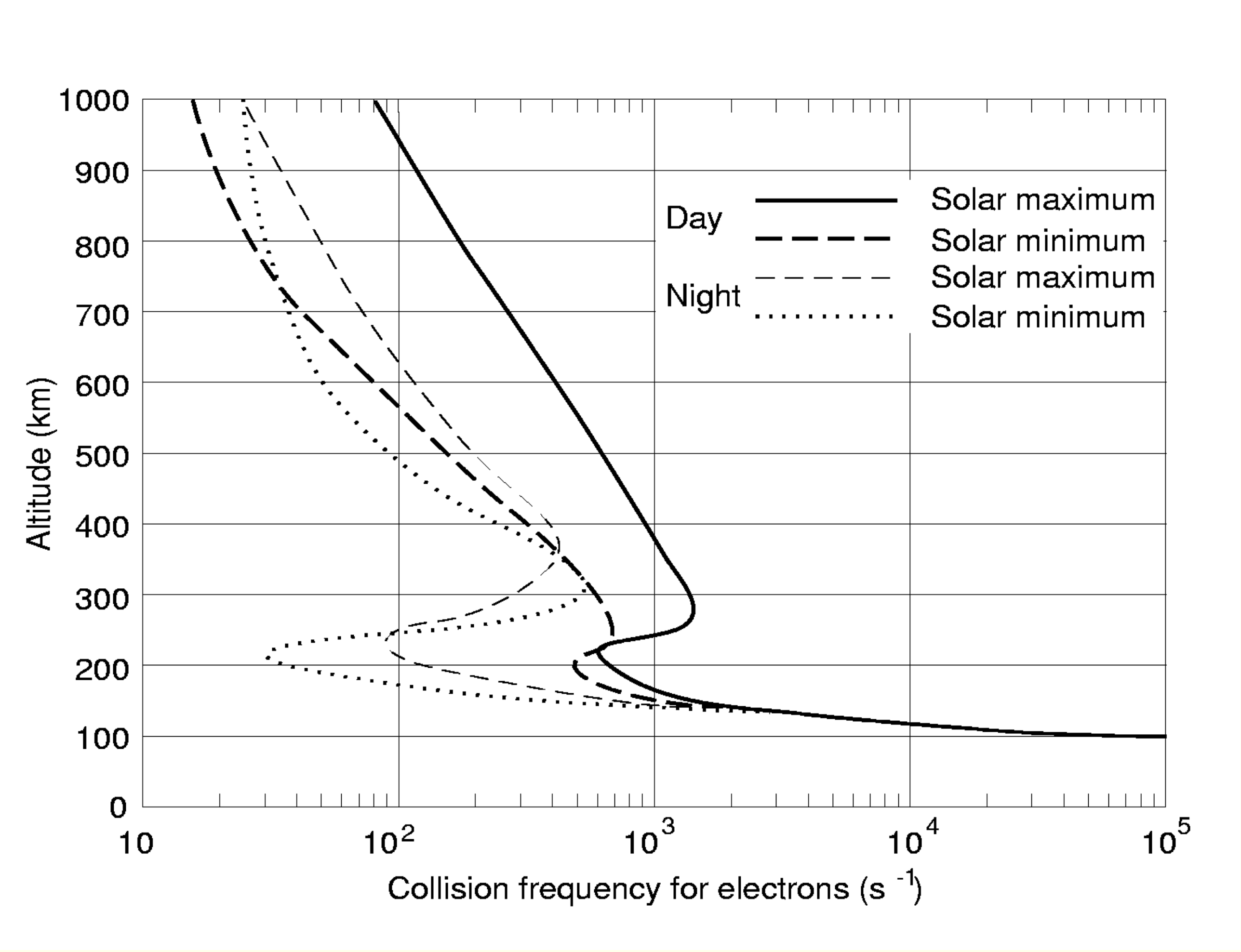
$$\mathbf{i} = \boldsymbol{\sigma} \cdot \mathbf{E}$$

$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_P & \sigma_H & 0 \\ -\sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_{//} \end{pmatrix}$$

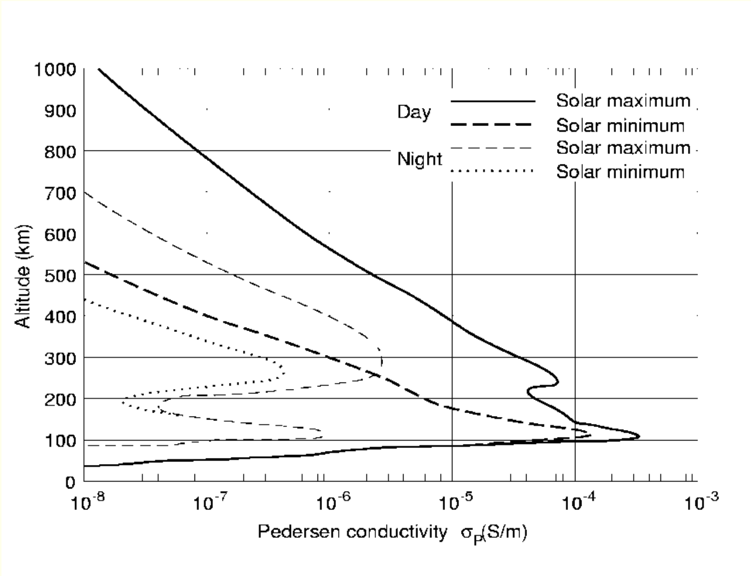
May be formulated as a tensor equation

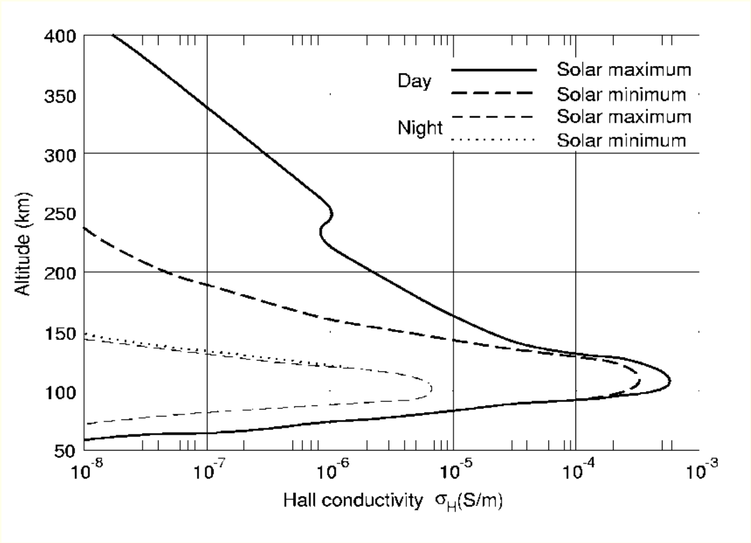
conductivity tensor

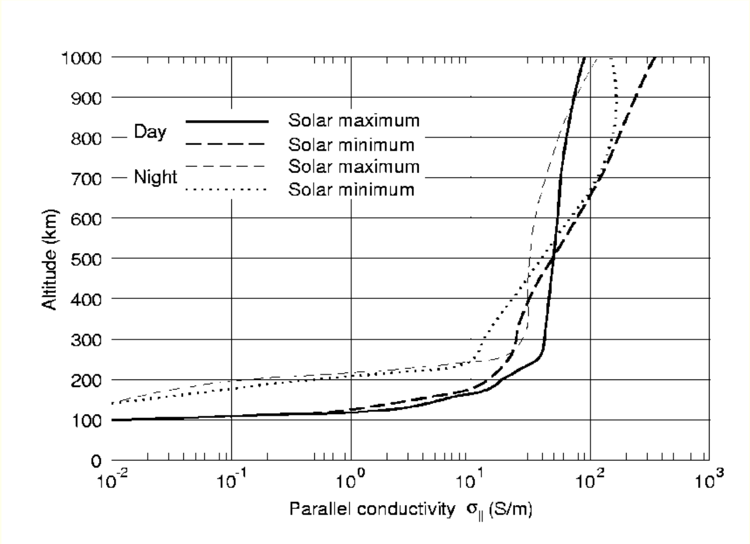
Collisional frequency



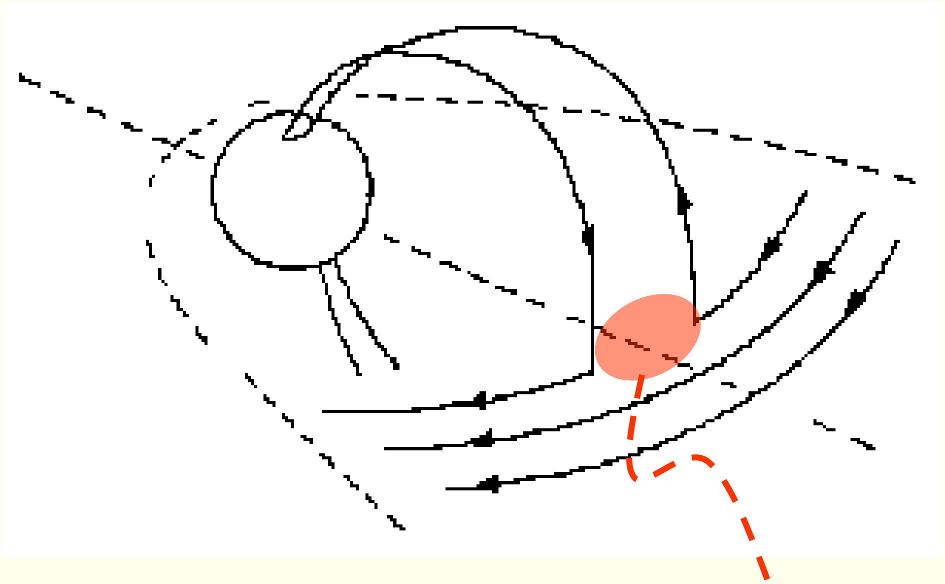
Ionospheric conductivities







Consequence: Birkeland currents



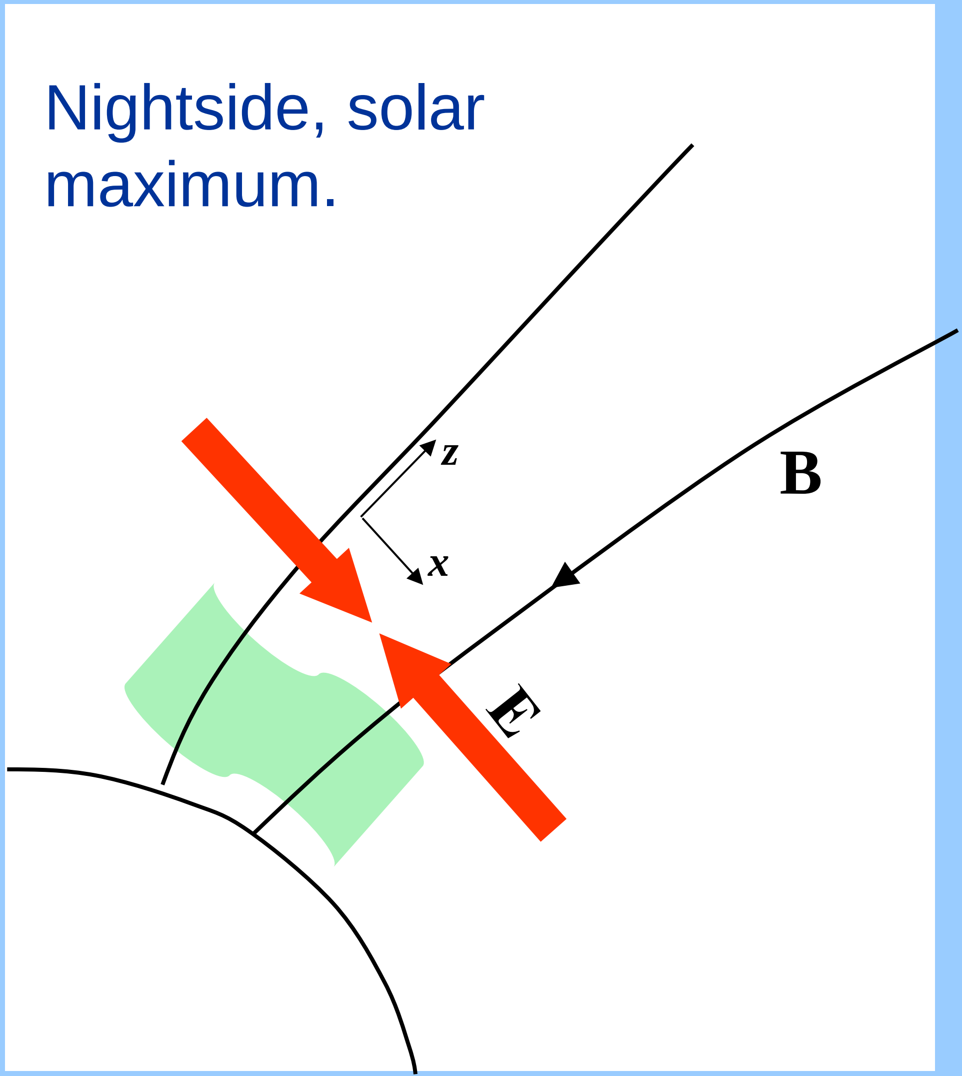
When the conductivity out in the magnetosphere is low, it is easier for the current to close through the ionosphere via currents parallel to the geomagnetic field. Such currents are called *Birkeland* currents.

Exemple: Electric field 700 km above the aurora.

$$\mathbf{E} = E_x \hat{\mathbf{x}} + E_y \hat{\mathbf{y}}$$

$$E_x = 1\,\mathrm{Vm}^{-1}$$

$$E_z = 1\,\mu\mathrm{Vm}^{-1}$$



$j_P = j_x = 0.01\ \mu\mathrm{Am}^{-2}$, $j_{//} = j_z = 40\ \mu\mathrm{Am}^{-2}$ — Yellow

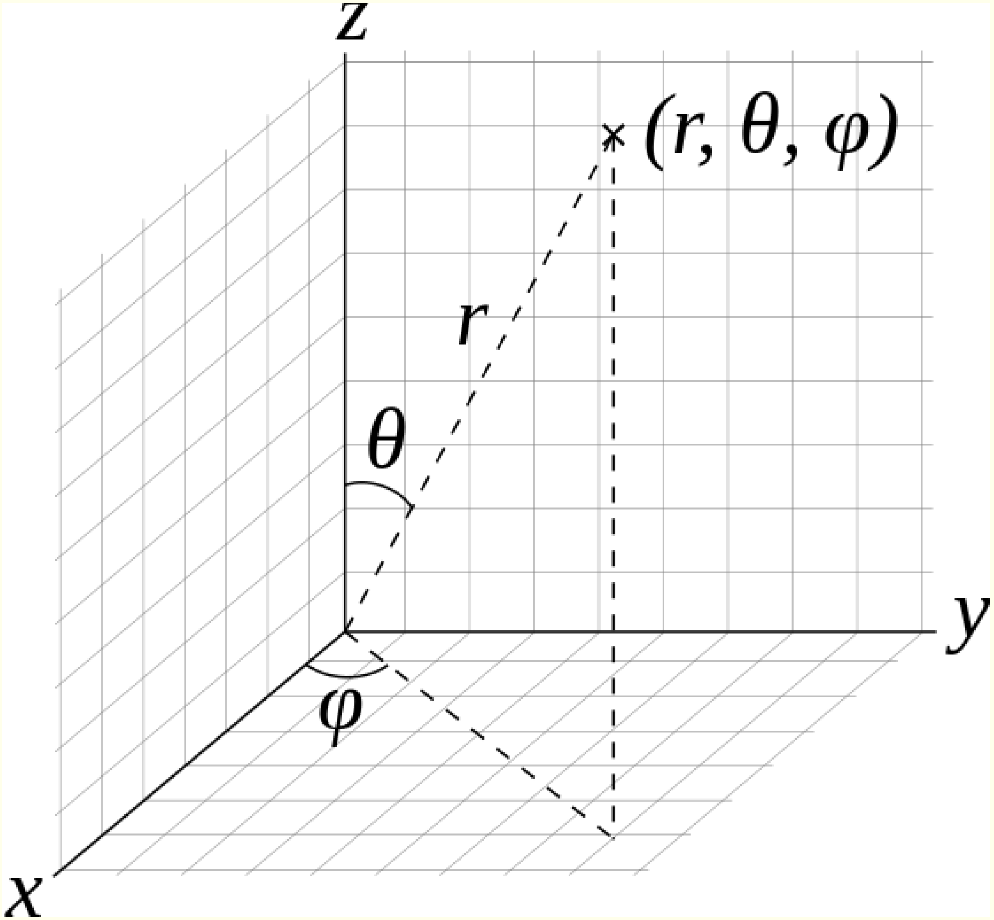
$j_P = j_x = 10.0\ \mu\mathrm{Am}^{-2}$, $j_{//} = j_z = 4.0\ \mu\mathrm{Am}^{-2}$ — Red

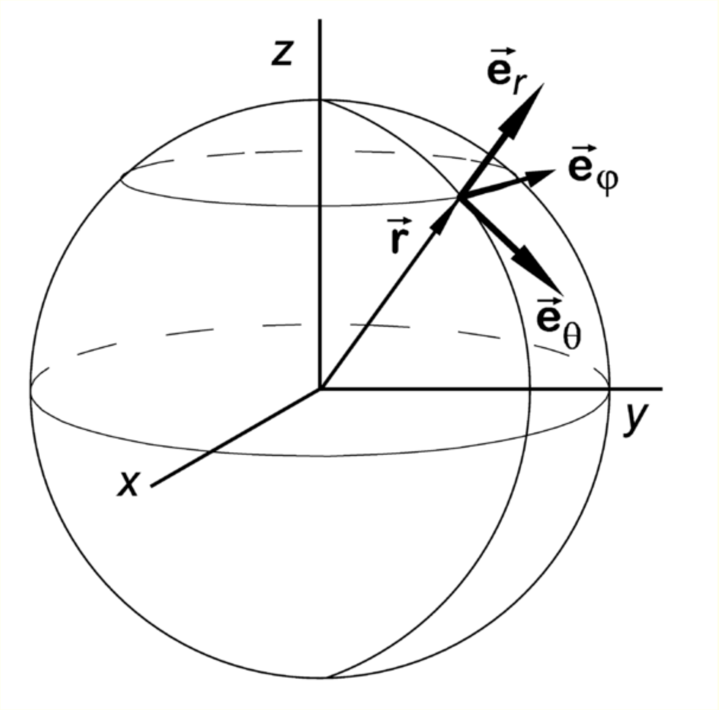
$j_P = j_x = 1.0\ \mu\mathrm{Am}^{-2}$, $j_{//} = j_z = 40\ \mathrm{mAm}^{-2}$ — Blue

How do we define
”the magnetosphere”?

The region in space where the magnetic field is dominated by the geomagnetic field.

Polar (spherical) coordinates





$$r = \sqrt{x^2 + y^2 + z^2}$$

$$\theta = \arccos\left(\frac{z}{r}\right)$$

$$\varphi = \arctan\left(\frac{y}{x}\right)$$

$$x = r\,\sin\theta\,\cos\varphi$$

$$y = r\,\sin\theta\,\sin\varphi$$

$$z = r\,\cos\theta$$

Geomagnetic field

Approximated by a dipole close to Earth.

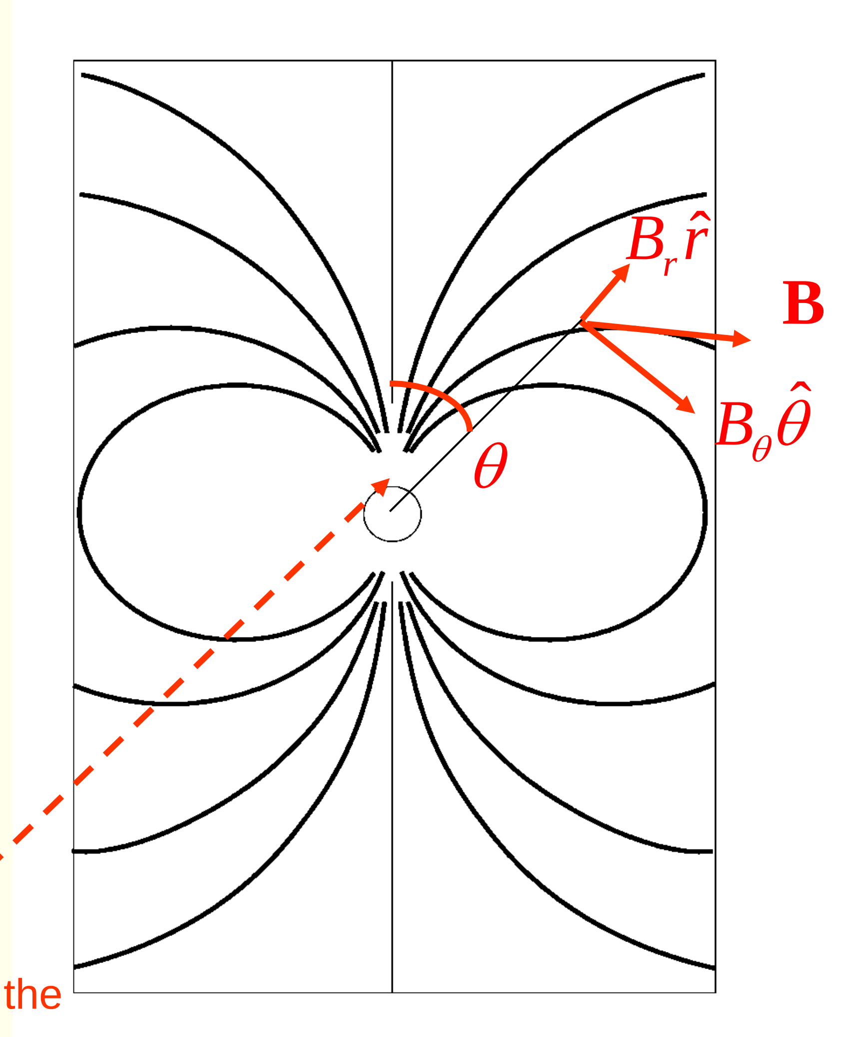
$$B_r = B_p \left(\frac{R_E}{r}\right)^3 \cos\theta$$

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

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

magnetic dipole moment

Magnetic field at the "north pole"



Geomagnetic field

Alternative formulation of dipole field

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

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

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

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

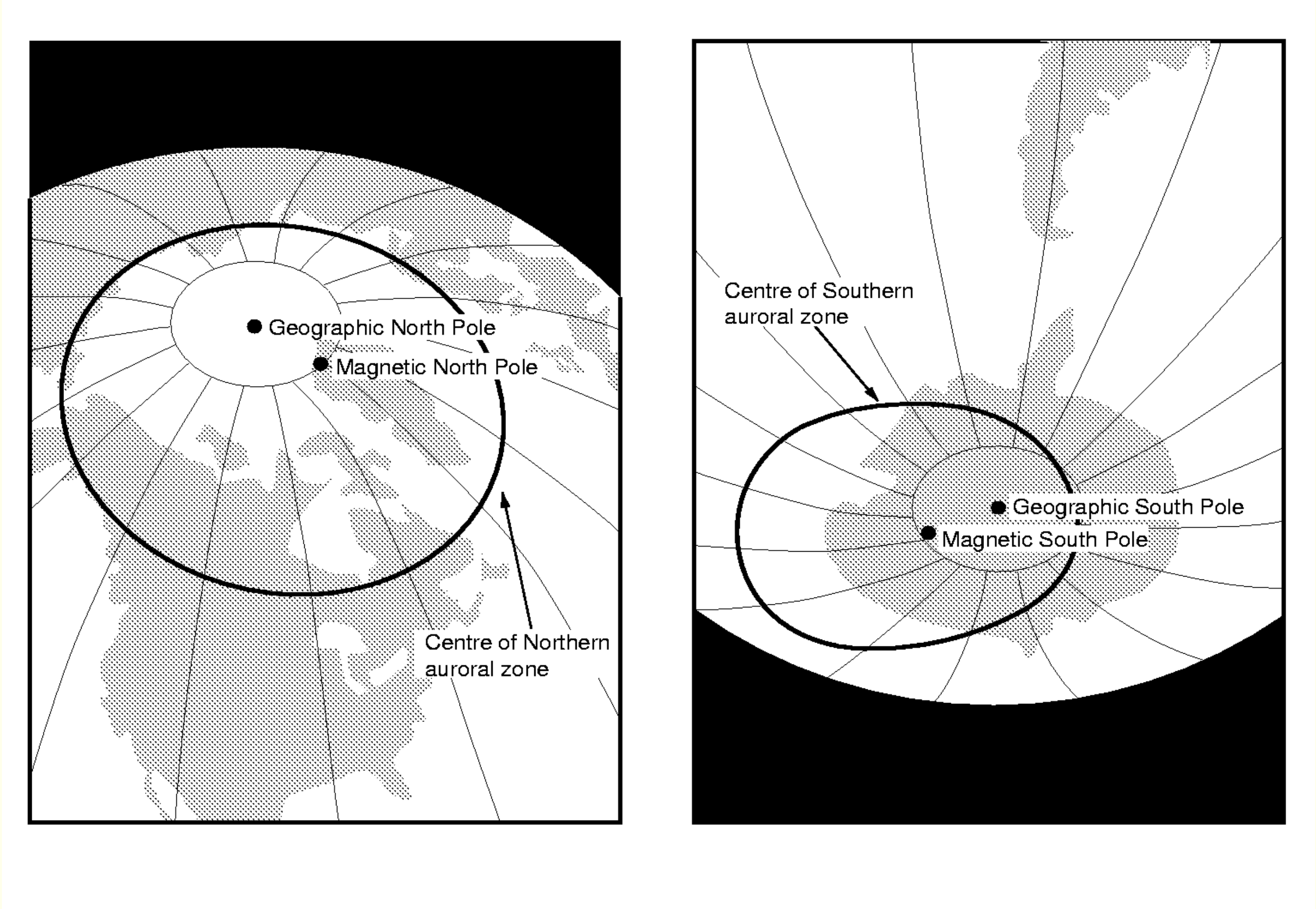
$$a = \frac{2\pi R_E^3 B_p}{\mu_0}$$

magnetic dipole moment

Geomagnetic field

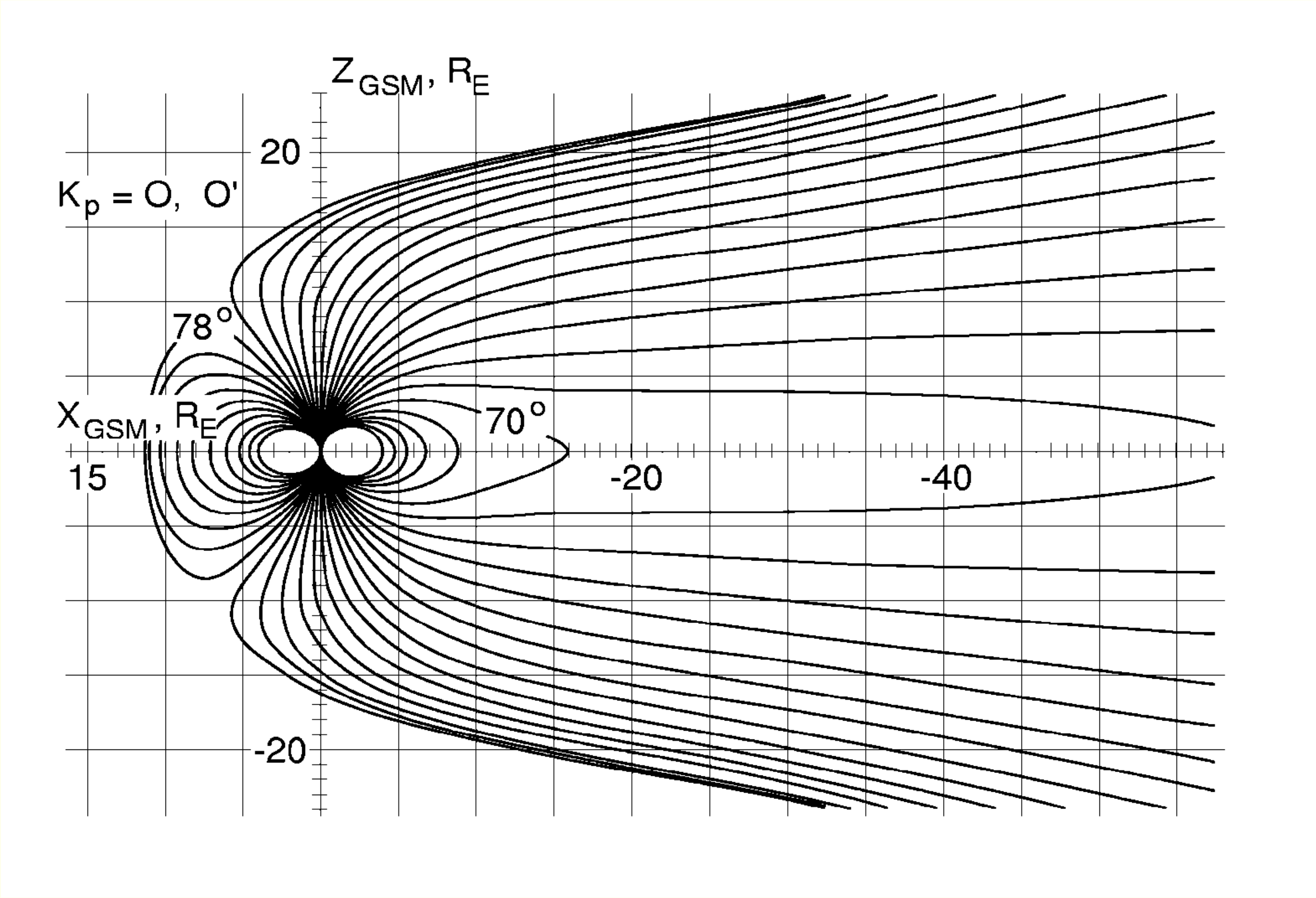
- Angle between dipole axis and spin axis: $\approx 11°$
- The geographic north pole is a magnetic south pole, and vice versa.
- $B_{equator} = 31\ \mu\text{T}$,

  $B_{pole} = 62\ \mu\text{T}$



Geomagnetic field

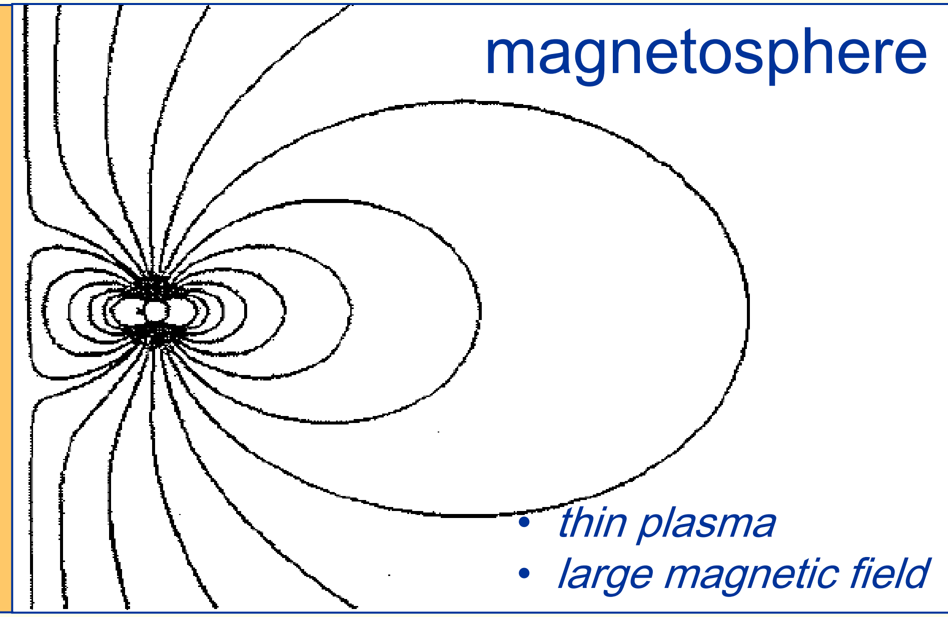
Modified by solar wind into tail-like configuration



Stand-off distance from pressure balance

solar wind

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



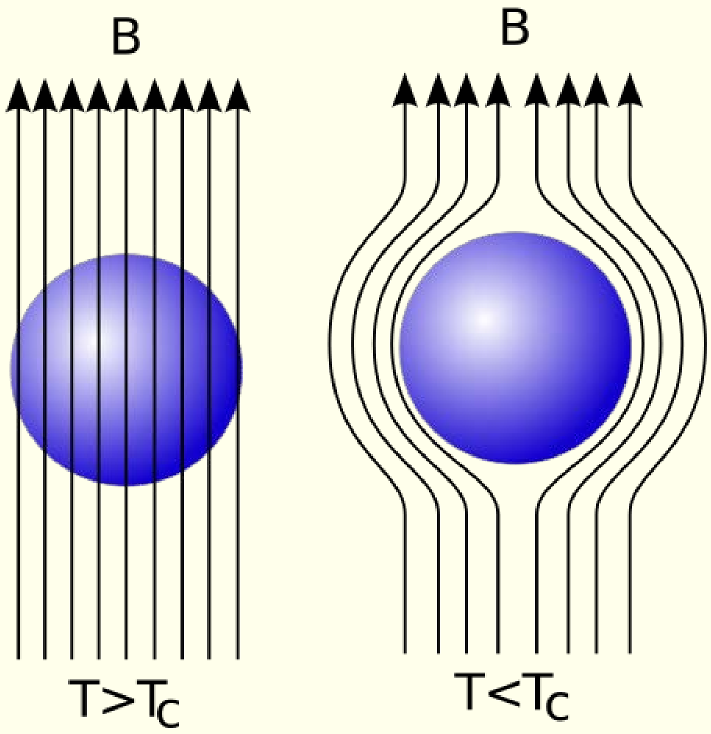
Dynamic pressure:

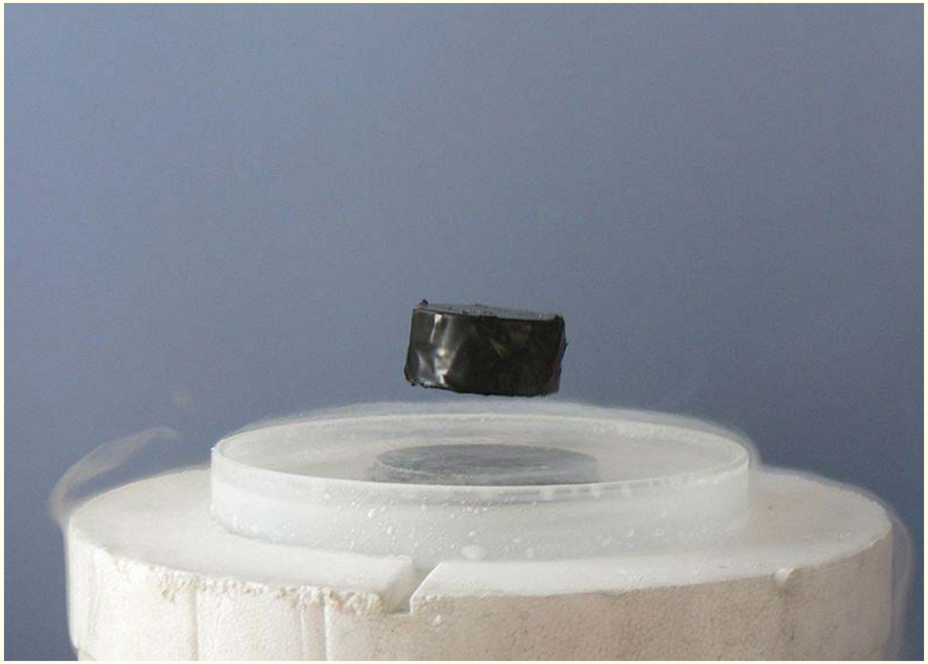
$$p_d = \rho_{SW} v_{SW}^2$$

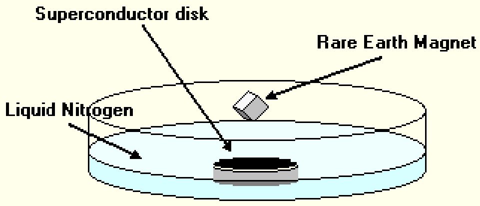
Magnetic pressure:

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

Meissner effect in super-conductors

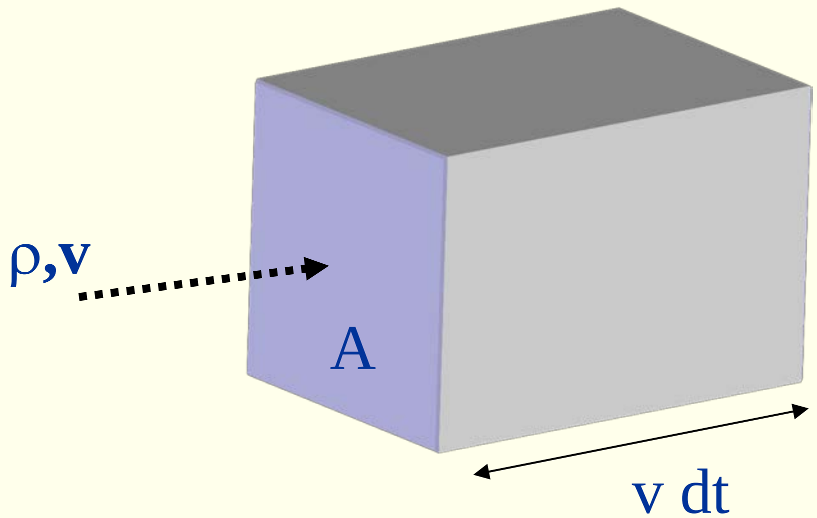






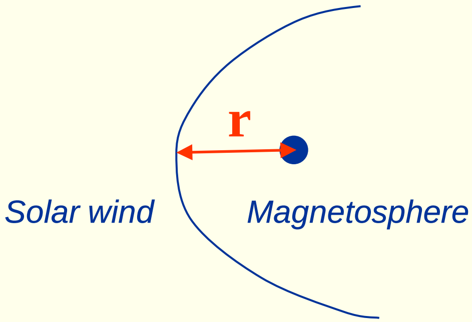
The Meissner Effect

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: $$p_B = \frac{1}{2\mu_0} B^2$$

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

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

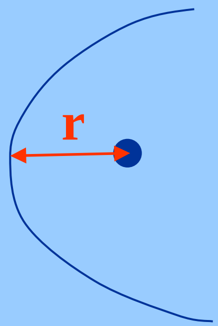
$$r = \left(\frac{\mu_0 a}{4\pi} \right)^{1/3} \left(2\mu_0 \rho_{SW} v_{SW}^2 \right)^{-1/6}$$

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

Standoff distance

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

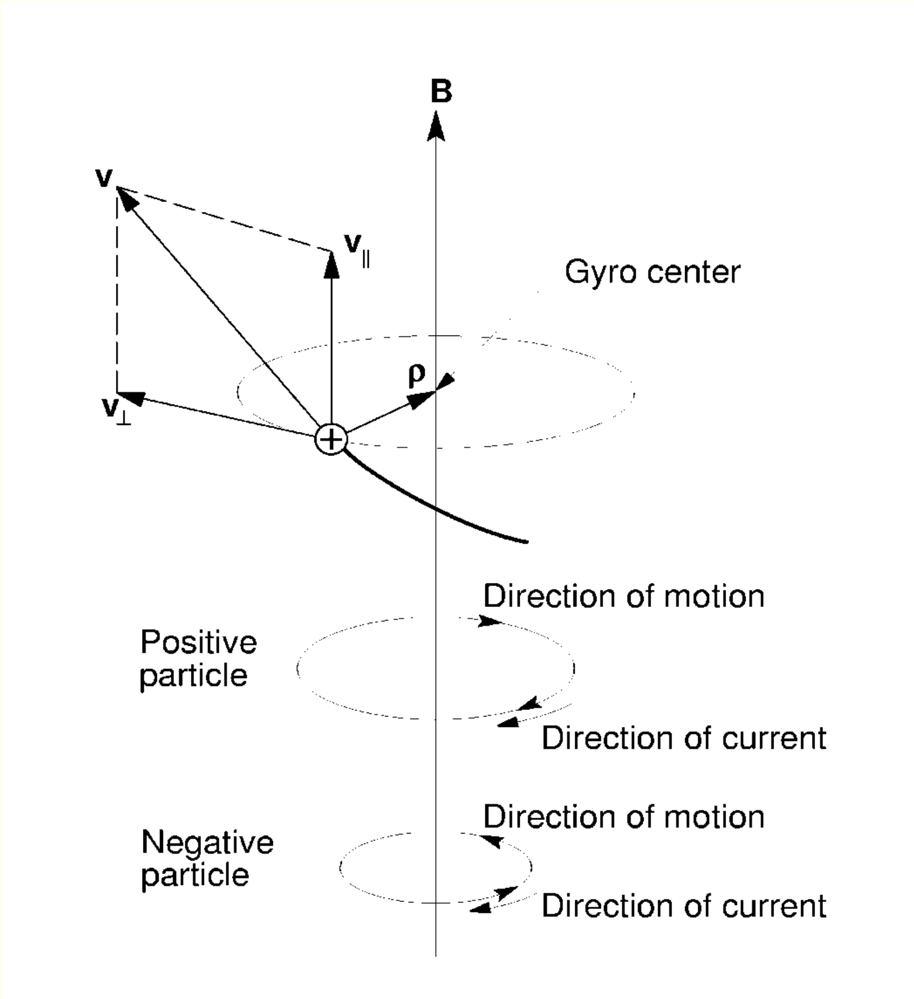


$$r = \left(\frac{\mu_0 a}{4\pi}\right)^{1/3} \left(2\mu_0 \rho_{SW} v_{SW}^2\right)^{-1/6}$$

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

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:

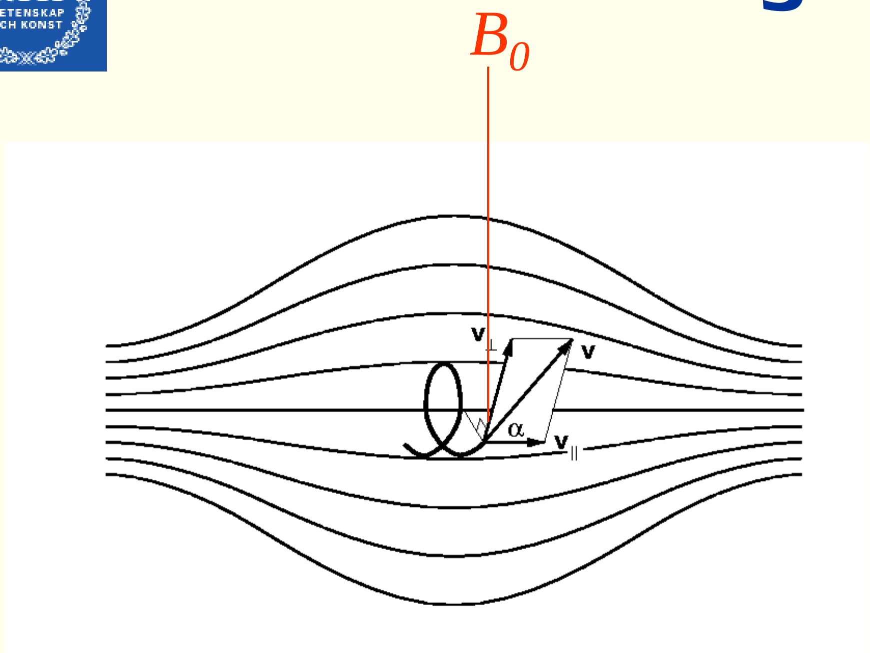
An **adiabatic invariant** is a property of a physical system which stays constant when changes are made slowly.

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) ➡

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

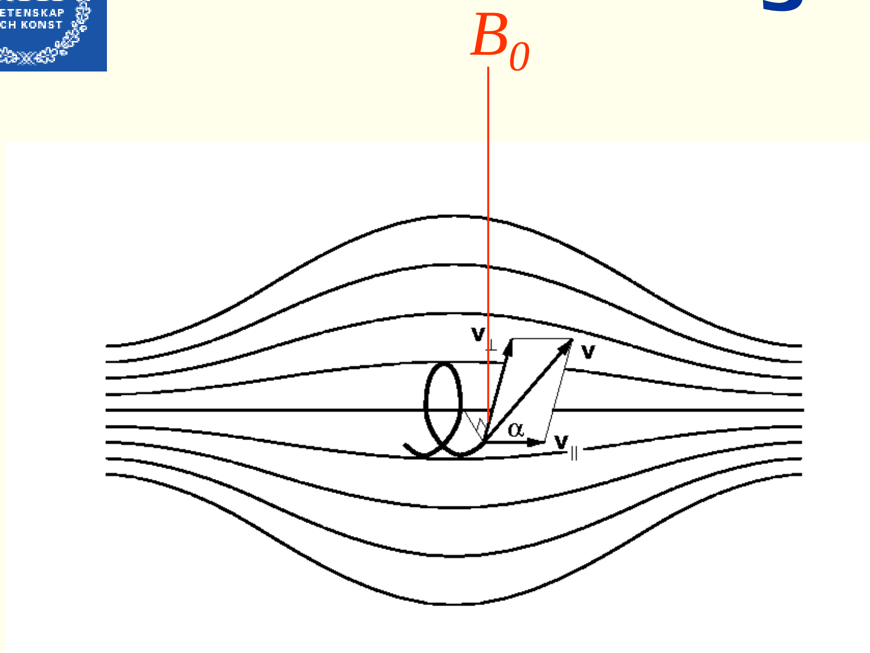
What happens with α as the particle moves into the stronger magnetic field?

Red	Yellow
α increases	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) ➡

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

particle turns when α = 90° ➡

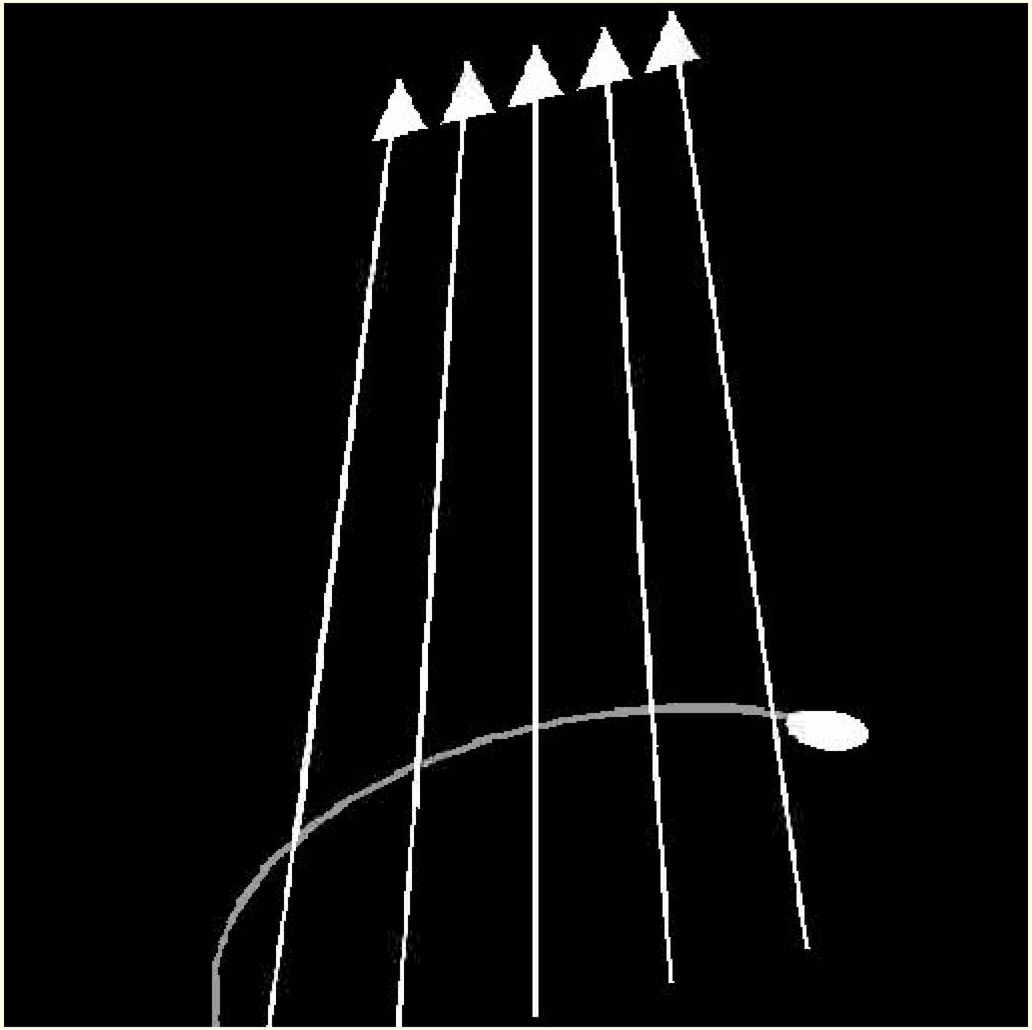
$$\frac{B_{turn}}{\sin^2 90^\circ} = \frac{B_0}{\sin^2\alpha}$$ ➡

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

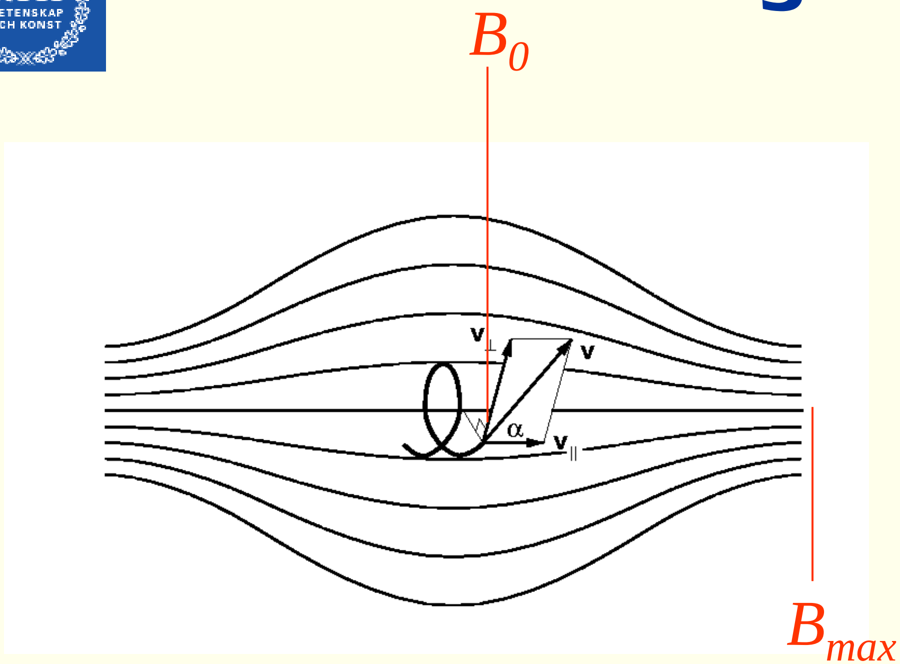
The magnetic moment μ is an ***adiabatic invariant***.

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

Magnetic mirror



Magnetic mirror



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

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

particle turns when 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

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

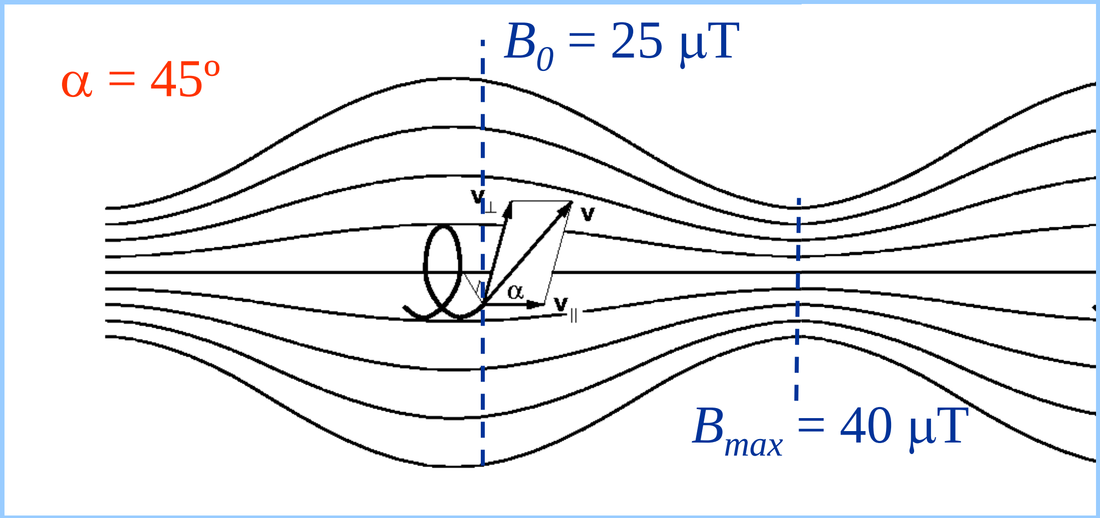
$$\alpha > \alpha_{lc} = \arcsin\sqrt{B_0 / B_{\max}}$$

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

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

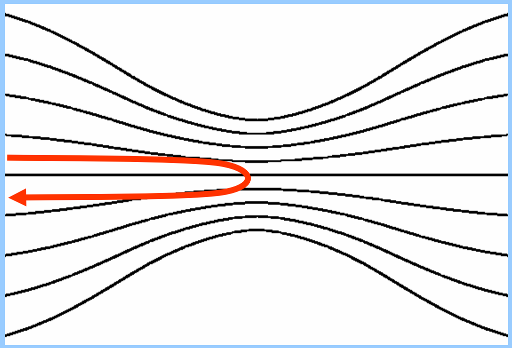
$$\mu = \frac{mv_\perp^2}{2B} = \frac{mv^2\sin^2\alpha}{2B}$$

What will happen to the particle?

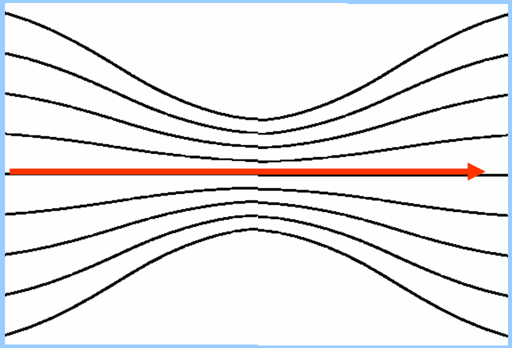


$$\alpha_{lc} = \arcsin\sqrt{B_0 / B_{\max}}$$

Blue It will mirror

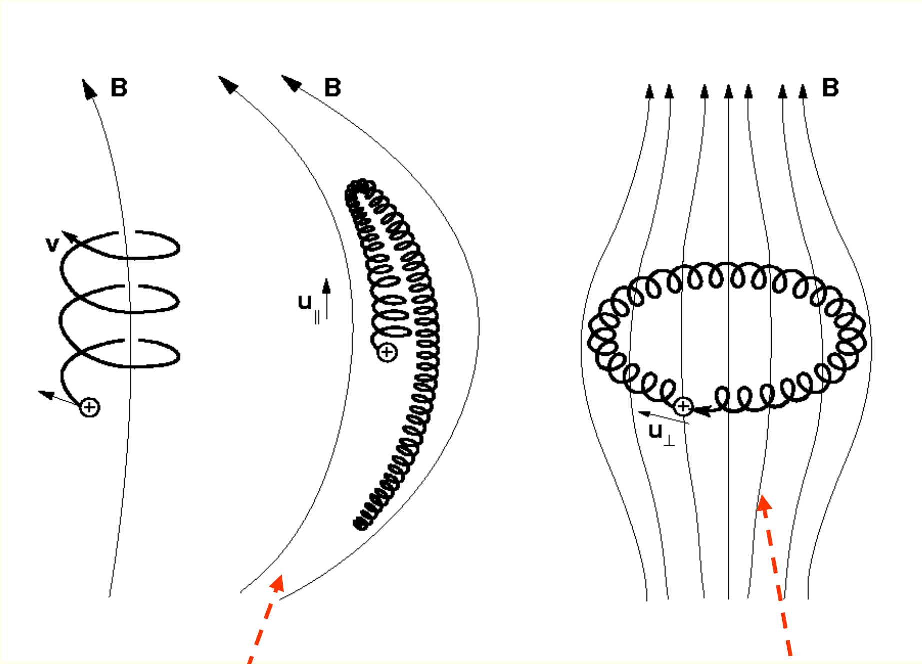


Yellow It will escape



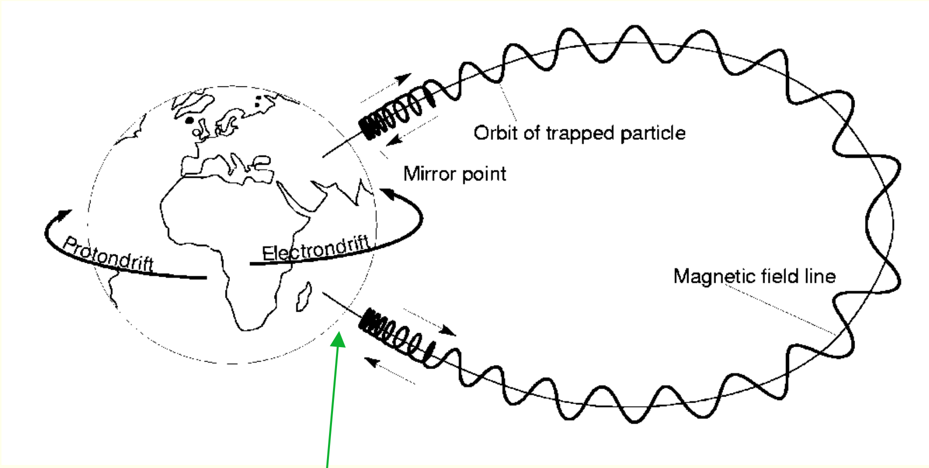
Particle motion in geomagnetic field

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



Magnetic mirror

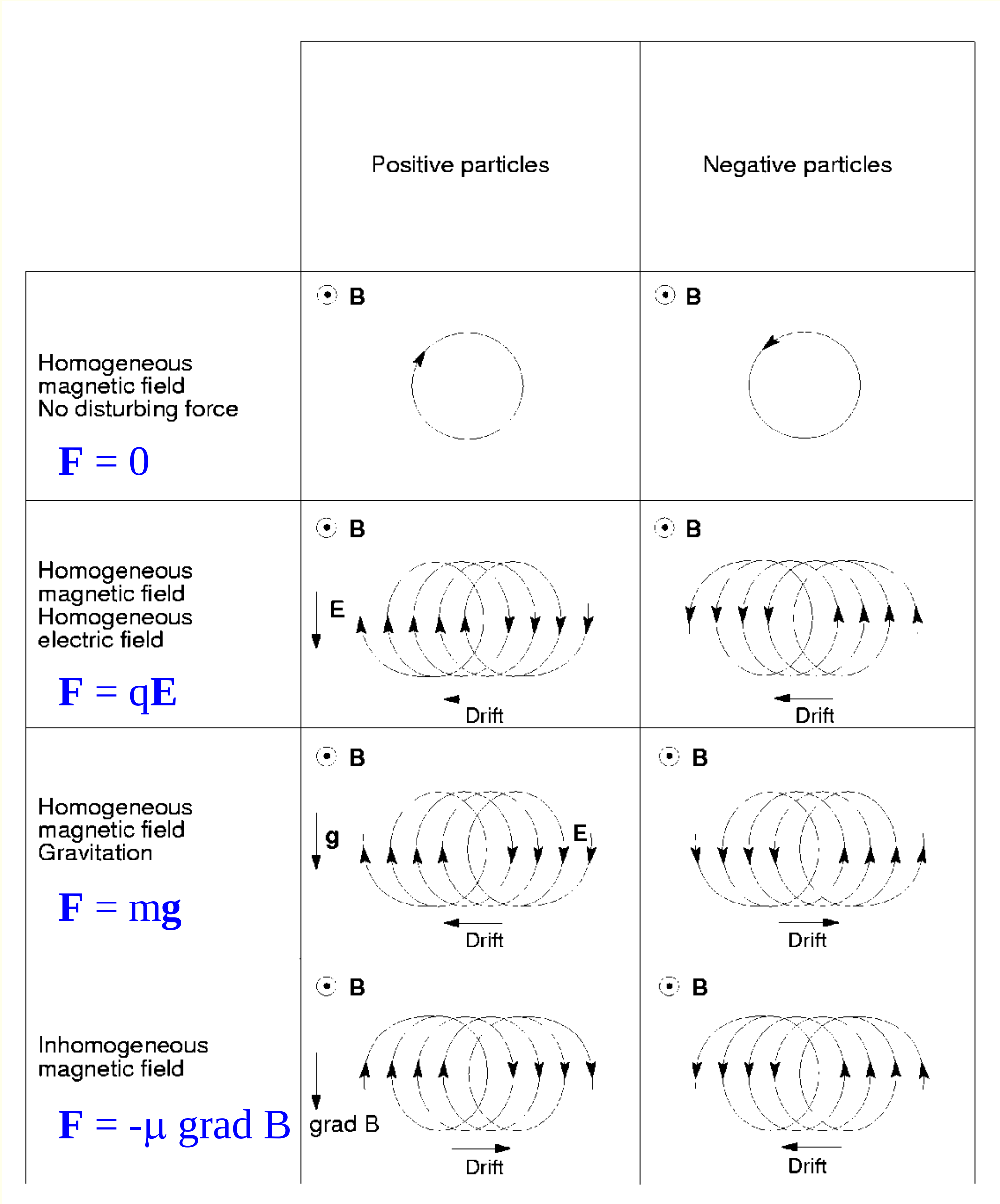
grad B drift



Particles in the loss cone create the aurora!

Drift motion

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

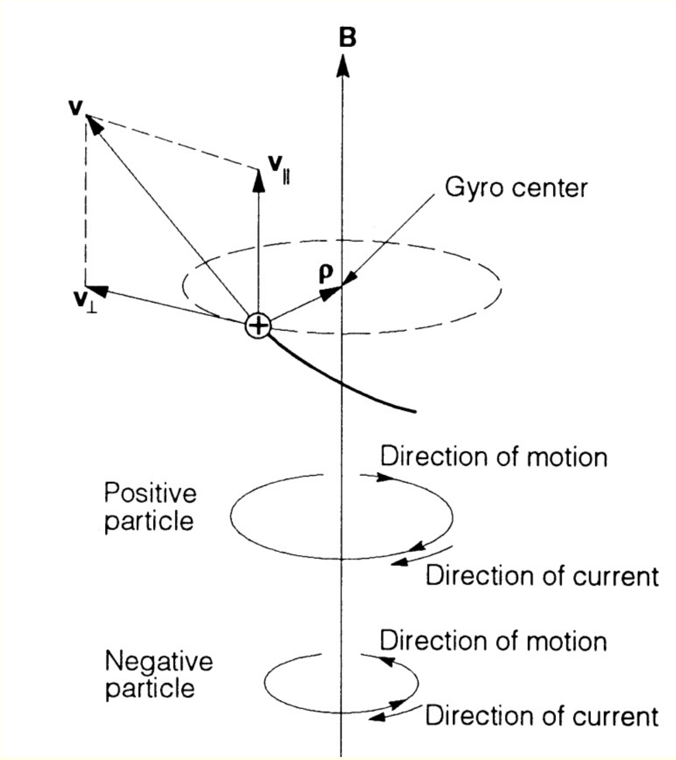


Force on magnetic dipole

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

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

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



Last Minute!

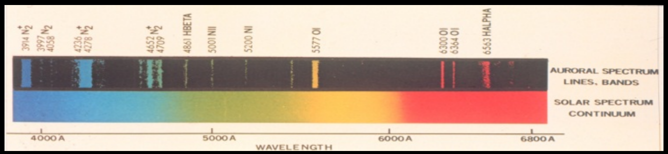
Last Minute!

- 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

Courses at the Alfvén Laboratory

EF2230 EXPERIMENTAL METHODS IN SPACE PLASMA PHYSICS , 6 ECTS credits, period 2

- operation principles of experimental techniques in space plasma physics
- interpretation of measurements
- technical implementations of various measurements techniques
- identify major limitations, and order of magnitude estimate of performance



Hands-on:

- Critical analysis and oral presentation
- Data aquisition or analysis using commercial software