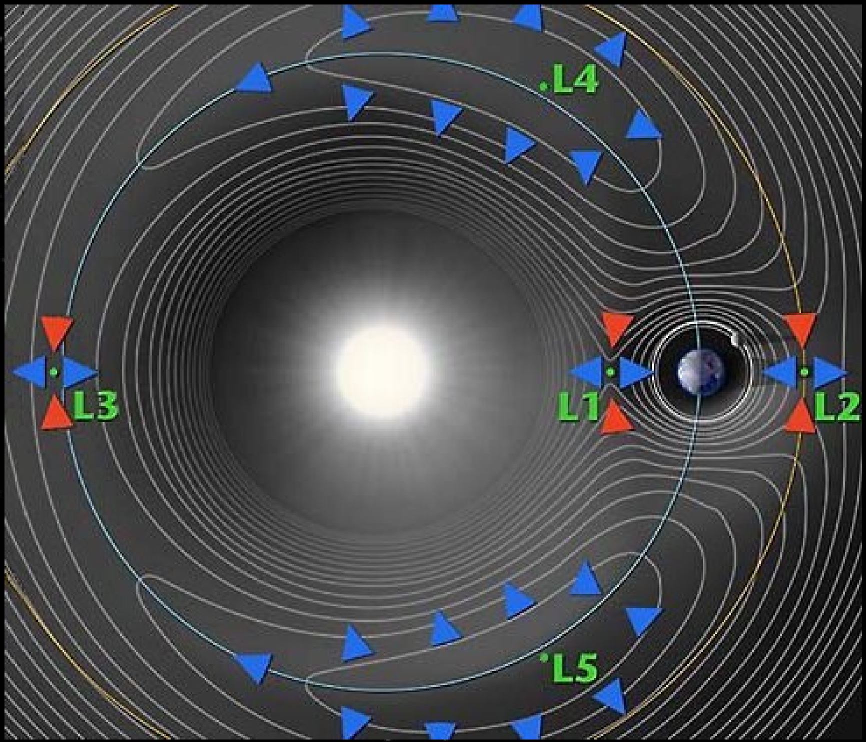
SOHO
(Solar and Heliospheric Observatory)



SOHO orbits the first Lagrange point

ESA - NASA collaboration

Last lecture (4)

- Solar wind
  - magnetic structure
- Ionosphere
  - ionospheric layers

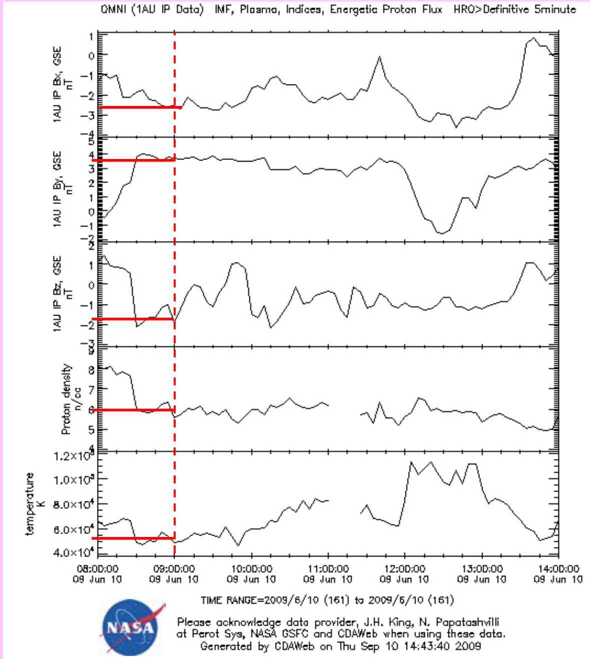
Today's lecture (5)

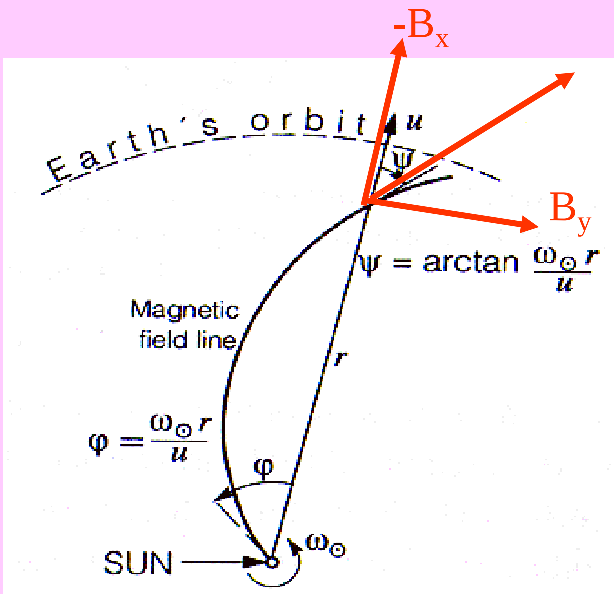
- Ionosphere
  - ionospheric layers
  - index of refraction
  - reflection of radio waves
  - particle drift motion in magnetized plasma
  - electrical conductivity in magnetized plasma
- Magnetosphere?

Today

Activity	Date	Time	Room	Subject	Litterature
L1	2/9	10-12	Q33	Course description, Introduction, The Sun 1, Plasma physics 1	**CGF** Ch 1, 5, (p 110-113)
L2	4/9	10-12	Q21	The Sun 2, Plasma physics 2	**CGF** Ch 5 (p 114-121), 6.3
L3	8/9	13-15	Q36	Solar wind, The ionosphere and atmosphere 1, Plasma physics 3	**CGF** Ch 6.1, 2.1-2.6, 3.1-3.2, 3.5, **LL** Ch III, Extra material
T1	10/9	10-12	Q33	Mini-group work 1	
L4	15/9	13-15	Q31	The ionosphere 2, Plasma physics 4	**CGF** Ch 3.4, 3.7, 3.8
T2	17/9	10-12	Q33	Mini-group work 2	
L5	19/9	15-17	Q31	The Earth's magnetosphere 1, Plasma physics 5	**CGF** 4.1-4.3, **LL** Ch I, II, IV.A
L6	23/9	8-10	Q31	The Earth's magnetosphere 2, Other magnetospheres	**CGF** Ch 4.6-4.9, **LL** Ch V.
T3	24/9	14-16	Q21	Mini-group work 3	
L7	29/9	11-13	Q36	Aurora, Measurement methods in space plasmas and data analysis 1	**CGF** Ch 4.5, 10**, LL** Ch VI, Extra material
T4	1/10	15-17	Q31	Mini-group work 4	
L8	2/10	15-17	Q34	Space weather and geomagnetic storms	**CGF** Ch 4.4, **LL** Ch IV.B-C, VII.A-C
L9	8/10	13-15	Q36	Interstellar and intergalactic plasma, Cosmic radiation, Swedish and international space physics research.	**CGF** Ch 7-9
T5	9/10	15-17	Q31	Mini-group work 5	
L10	13/10	15-17	Q33	Guest lecture (preliminary): Swedish astronaut Christer Fuglesang	
T6	16/10	10-12	Q36	Round-up	
Written exami-nation	30/10	8-13	M33, M37, M38		

Mini-groupwork 2





a)

$$\psi = \arctan \frac{\omega_{sun} r}{u_{sw}} \quad \Rightarrow \quad u_{sw} = \frac{\omega_{sun} r}{\tan \psi}$$

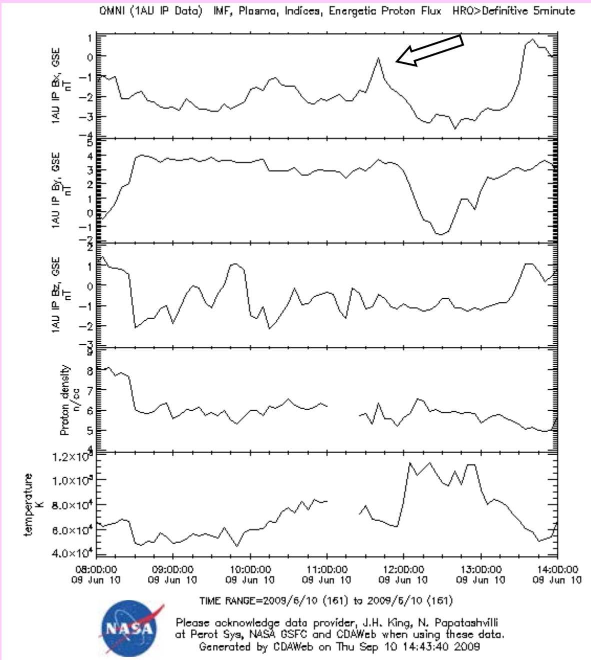
$\omega_{sun} = 2\pi/T = 2.9 \cdot 10^{-6}\ s^{-1}$ (T = 25 days at equator)

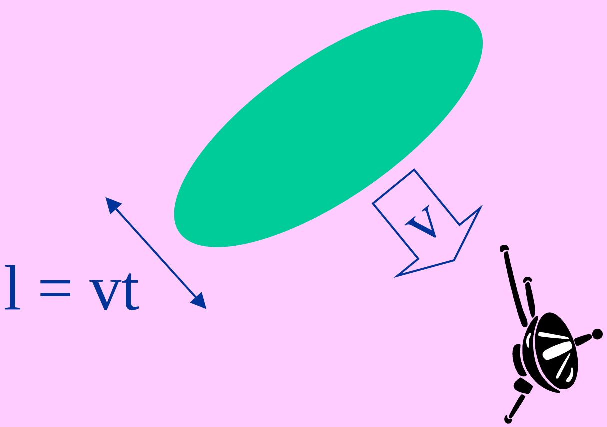
r = 1 A.U.

$\tan \psi = |B_y/B_x| \approx 3.6/2.6$ (from figure) $\quad (\psi = 41°)$

With these figures I get u_{sw} = 313 km/s

Mini-groupwork 2





b)

The magnetic Reynolds number is calculated by using typical plasma flow velocities v_c and typical length scales of magnetic field variations l_c

Use solar wind velocity obtained in a) for typical flow velocity. To obtain l_c, multiply the time t it takes the magnetic field structure (indicated in the figure), to pass over the satellite and use l_c, $= vt$. I get $l_c = 2.8 \cdot 10^8$ m.

Using a temperature of $5 \cdot 10^4$ K, we can evaluate the conductivity, remembering that the temperature should be given in eV. We get the conversion from

$$W = \frac{3}{2} k_B T$$

which gives the result that 1 eV corresponds to a temperature of 7729 K. We then get $T = 6.5$ eV, and

$\sigma = 3.1 \cdot 10^4$ S/m

Putting in the numbers I get

$R_m = \mu_0 \, \sigma \, v_c \, l_c \approx 9.8 \cdot 10^{14} >> 1$

So the solar wind magnetic field is frozen into the plasma to a very good approximation.

Energy - temperature

Average energy of molecule/atom:

$$E = \frac{3}{2} k_B T \quad \Rightarrow$$

$$T = \frac{2E}{3k_B}$$

1 eV = $1.6 \cdot 10^{-19}$ J $\Rightarrow$

$$T = \frac{2E}{3k_B} = \frac{2 \cdot 1.6 \cdot 10^{-19}\,\mathrm{J}}{3 \cdot 1.38 \cdot 10^{-23}\,\frac{\mathrm{J}}{\mathrm{K}}} = 7729\,\mathrm{K}$$

But beware!

In plasma physics, usually:

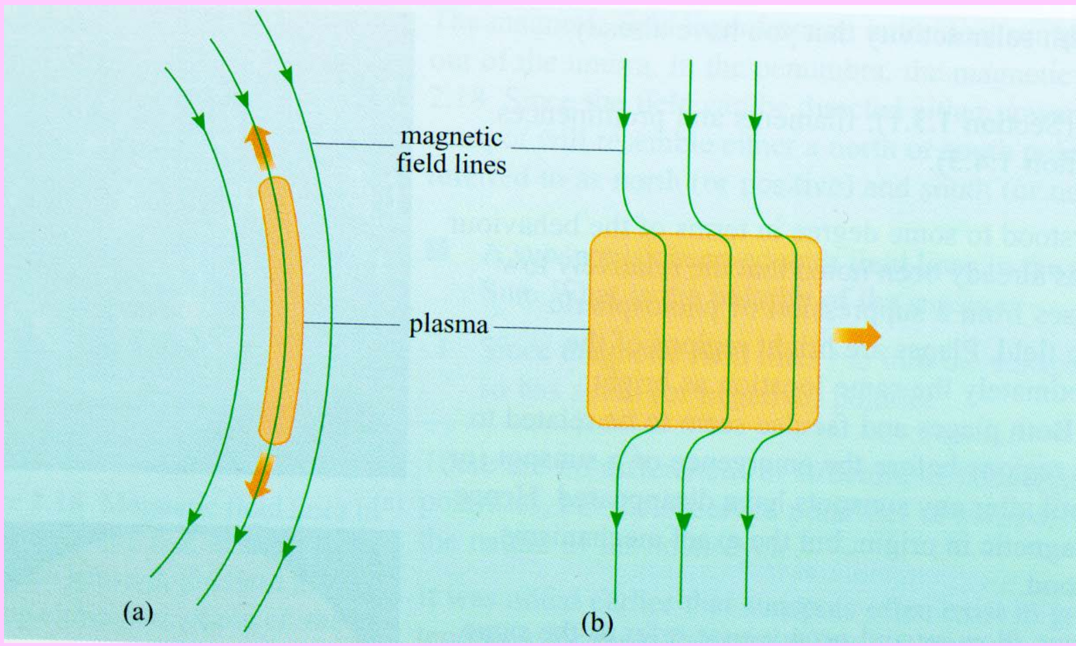
$$E = \cancel{\frac{3}{2}} k_B T \quad \Rightarrow$$

$$T = \frac{E}{k_B}$$

$$1\ \text{eV} = 1.6 \cdot 10^{-19}\ \text{J} \Rightarrow$$

$$E = k_B T = \frac{1.6 \cdot 10^{-19}\ \text{J}}{1.38 \cdot 10^{-23}\ \frac{\text{J}}{\text{K}}} = 11594\,\text{K}$$

Does the plasma follow the magnetic field (a) or the other way around (b)?



Depends on relative energy density (pressure)

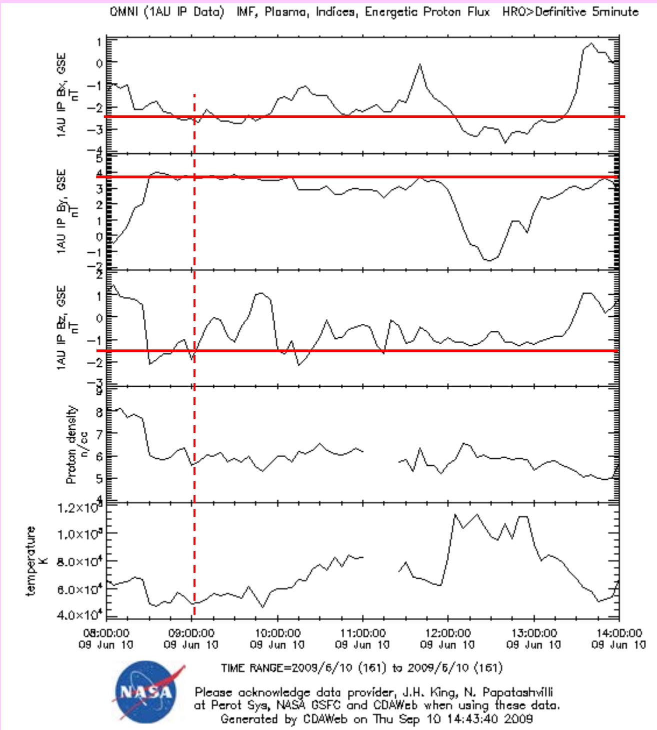
$$p_{pl} = nk_B T$$

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

$$\beta = \frac{p_{pl}}{p_B}$$

$\beta << 1$ $\beta >> 1$

Mini-groupwork 2



c)

$$\rho = n_e m_p = 6.1\cdot10^{6}\cdot1.67\cdot10^{-27} = 1.02\cdot10^{-20}$$

Then the kinetic energy density is (v = 313 km/s):

$$\rho v^2/2 = 5.0\cdot10^{-10}\ \mathrm{Jm}^{-3}$$

The magnetic energy density is (using values of figure)

$$\frac{B^2}{2\mu_0} = \frac{\left(B_x^2 + B_y^2 + B_z^2\right)^2}{2\mu_0} = (2.6^2 + 3.6^2 + 1.7^2)\cdot(10^{-9})^2/2\mu_0 = 9\cdot10^{-12}\ \mathrm{Jm}^{-3}$$

The ratio between the kinetic and magnetic energy densities is approximately **50,** thus the plasma motion determines the magnetic field configuration, and not the other way around.

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Space

Space Report

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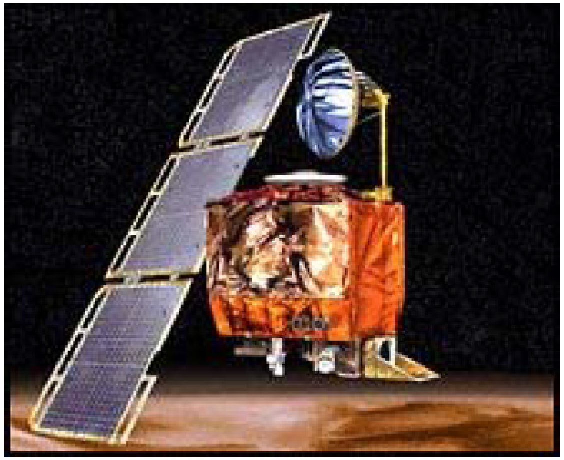
Mystery of Orbiter Crash Solved

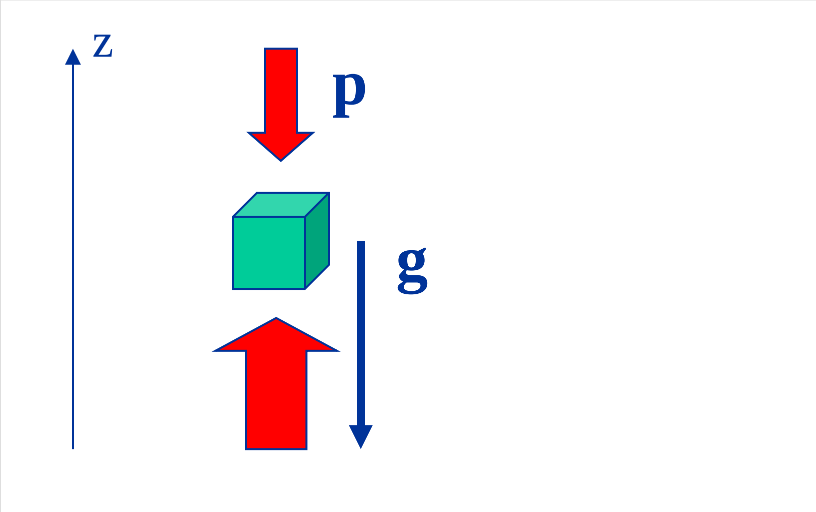
By Kathy Sawyer
Washington Post Staff Writer
Friday, October 1, 1999; Page A1



Scientists do not yet know what caused the Mars Orbiter to crash. (AP)

NASA's Mars Climate Orbiter was lost in space last week because engineers failed to make a simple conversion from English units to metric, an embarrassing lapse that sent the $125 million craft fatally close to the Martian surface, investigators said yesterday.

Atmospheric scale height



$$-\frac{dp}{dz} = g\rho_m$$ hydrostatic equilibrium for a volume element

$$p = nk_BT = \frac{\rho k_BT}{m}$$ ideal gas law

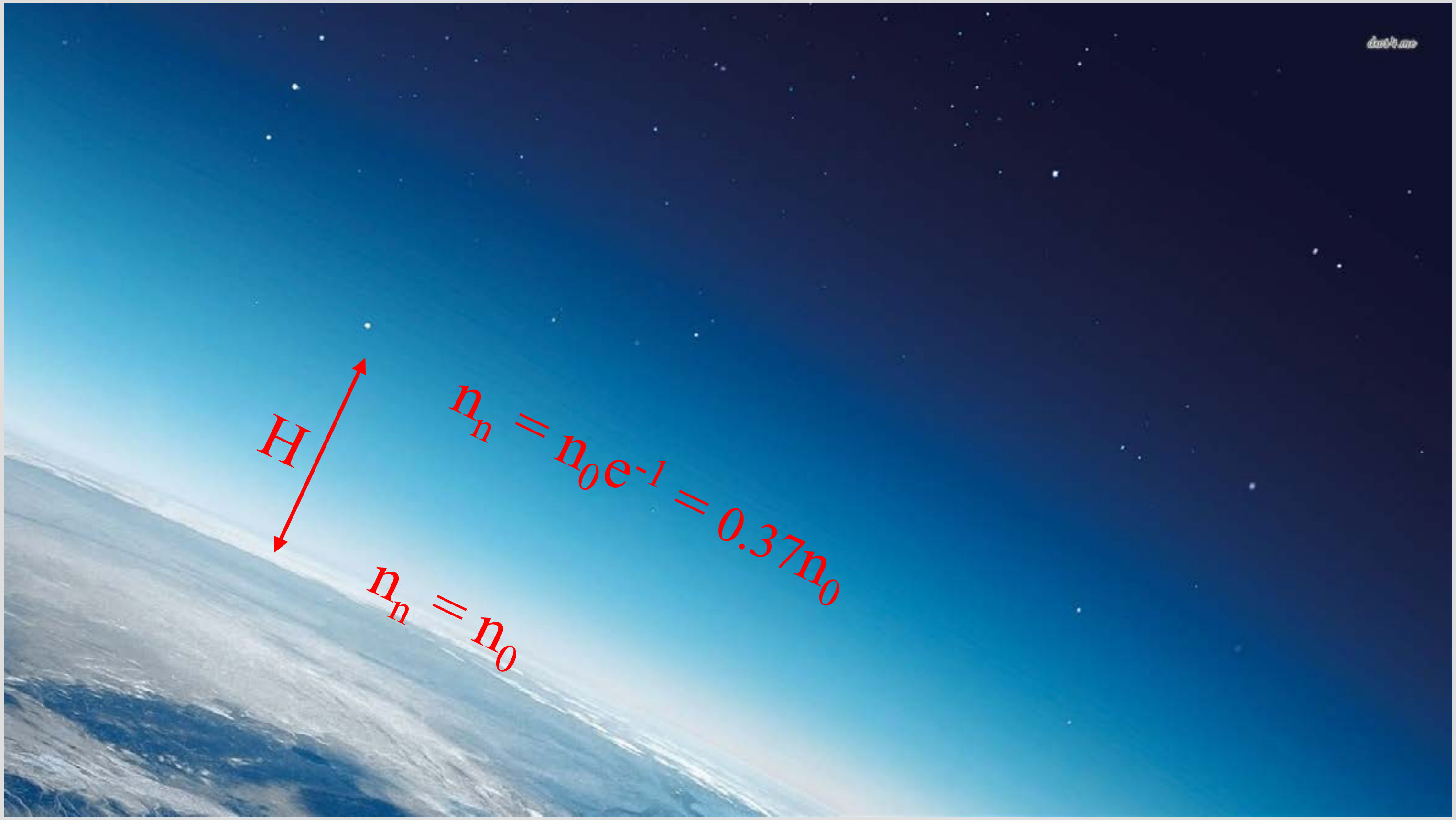
$$-\frac{k_BT}{m}\frac{d\rho_m}{dz} = g\rho_m$$ if T is constant

$$\rho_m = const \cdot e^{-z/(k_BT/gm)} = const \cdot e^{-z/H}$$

Scale height

$H = k_BT/gm$

Atmospheric scale height



$$\rho_m = const \cdot e^{-z/(k_B T/gm)} = const \cdot e^{-z/H}$$

Scale height

$H = k_B T/gm$

Ionization and recombination

Continuity equation

$$\frac{dn_e}{dt} = q - r$$

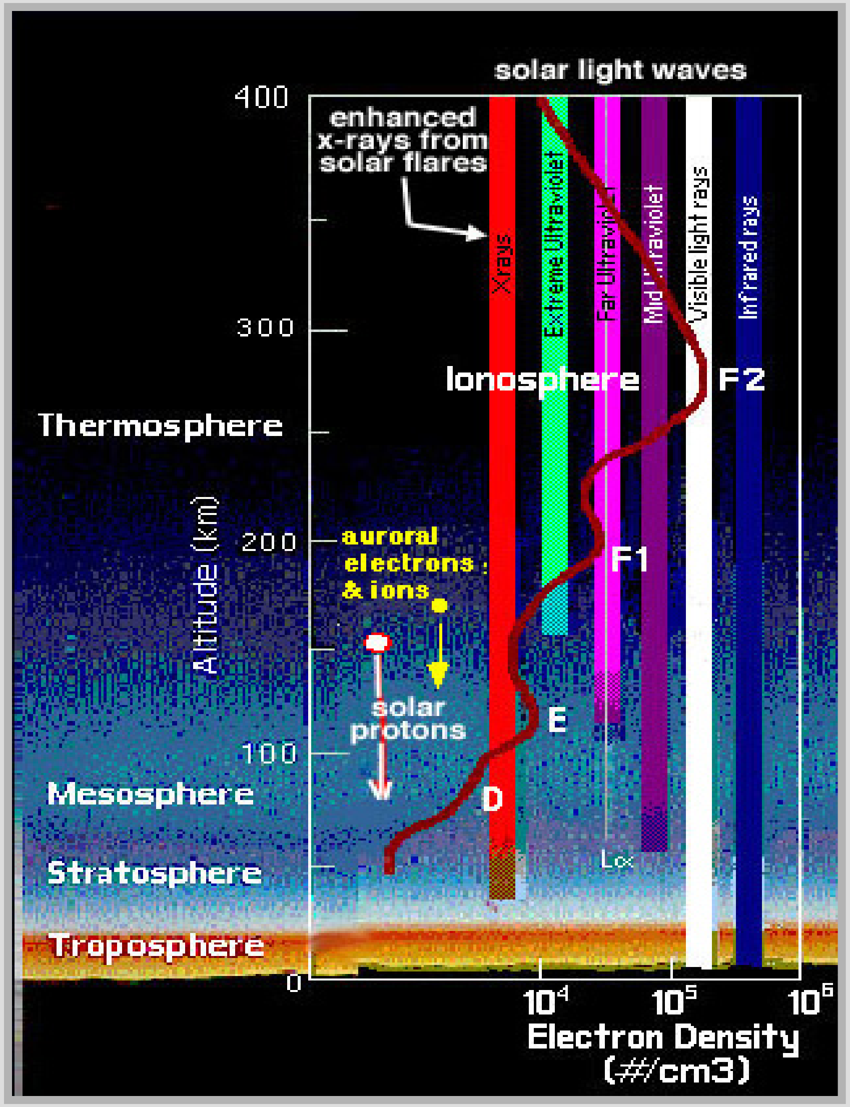
$$q = a_i I n_n$$

Ionization ($m^{-3}s^{-1}$)

Recombination ($m^{-3}s^{-1}$)

$$r = a_r n_e n_i = a_r n_e^2$$

Example: $e + O_2^+ \rightarrow O + O$ (dissociative recombination)



UV and X–ray radiation

$$\frac{dI}{dz} = I n_n a_a$$

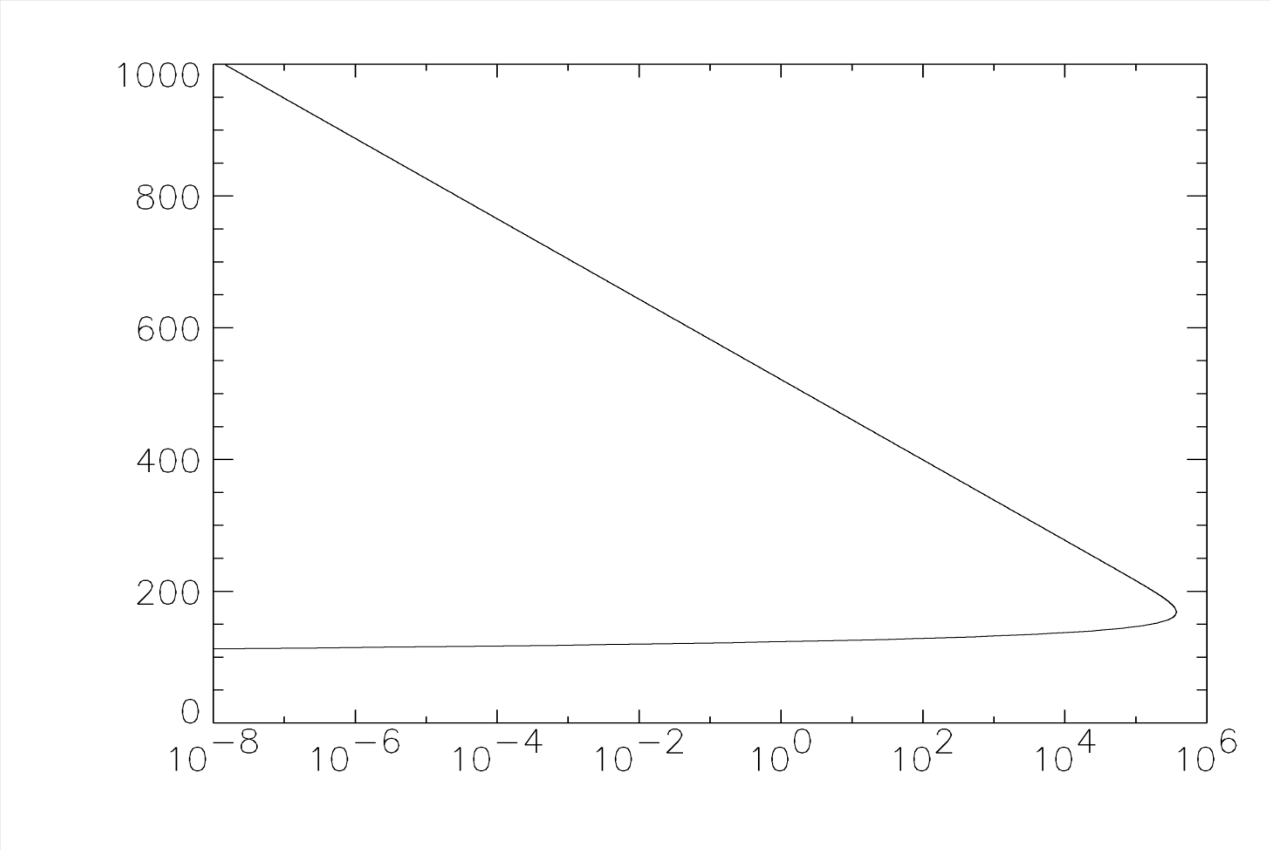
Electron density in Chapman layer

$$n_e = \left\{ \frac{a_i}{a_r} I_0 n_0 e^{-\left(H a_a n_0 e^{-z/H} + z/H\right)} \right\}^{1/2}$$

”F1-region” - simple model calculation

O_2 dominating species, 30 nm UV radiation

$a_a = 9.3\times10^{-23}$
$a_j = 9.3\times10^{-23}$
$a_r = 3.0\times10^{-14}$
$T = 500$
$m = 16*2*amu$
$n_0 = 2.7\times10^{25}\ m^{-3}$
$I_0 = 1.5\times10^{14}$ photons/m^2/s



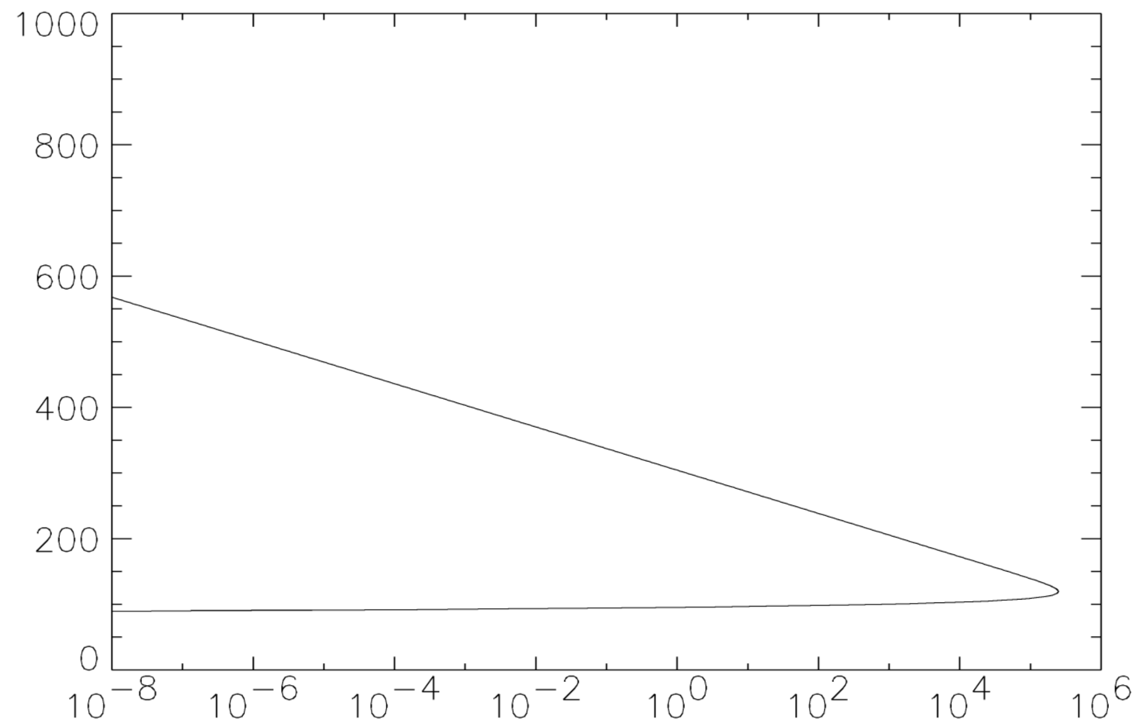
What does it look like in reality?

- Temperature not constant
- Many different wavelengths in solar radiation
- Several different molecules and atoms in neutral atmosphere. Composition also depends on altitude.

”E-region” - simple model calculation

O_2 dominating species, 10 nm X-ray radiation

$a_a = 9.3\times10^{-23}$
$a_j = 9.3\times10^{-23}$
$a_r = 3.0\times10^{-14}$
$T = 270$
$m = 16*2*amu$
$n_0 = 2.7\times10^{25}\ m^{-3}$
$I_0 = 3.6\times10^{13}$ photons/m²/s

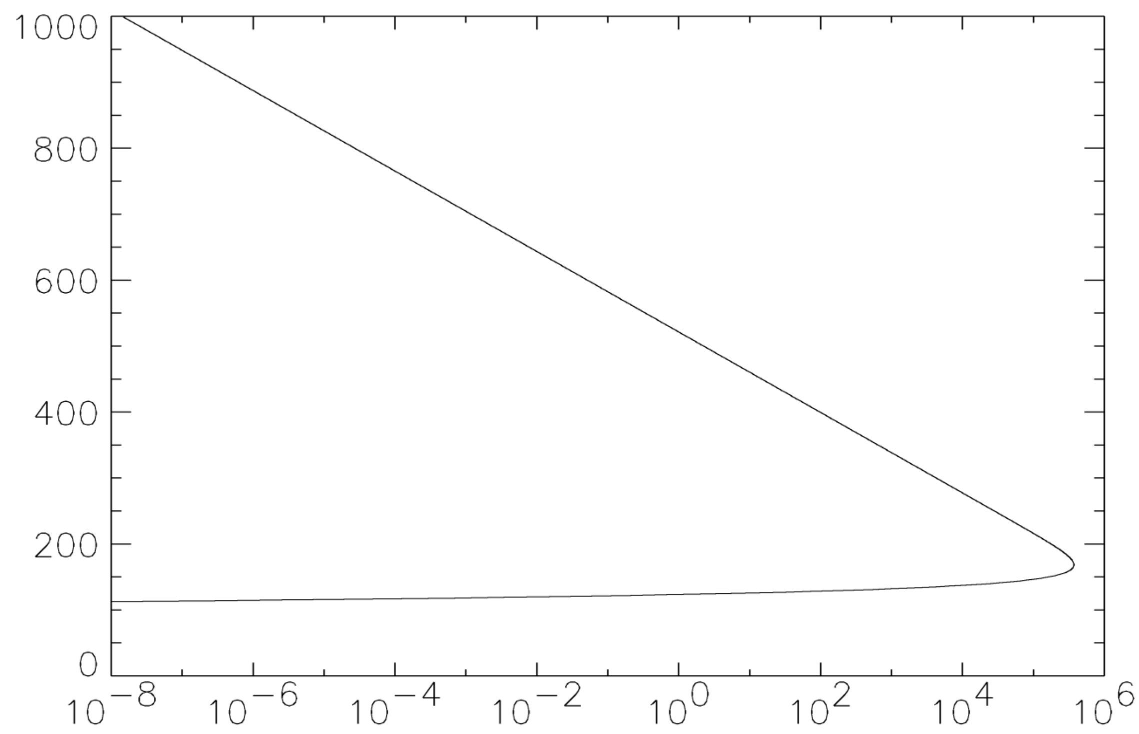


N_2^+ produced, but rapidly lost through charge exchange: $N_2^+ + O_2 \rightarrow N_2 + O_2^+$

"F1-region" - simple model calculation

O_2 dominating species, 30 nm UV radiation

$a_a = 9.3\times10^{-23}$
$a_j = 9.3\times10^{-23}$
$a_r = 3.0\times10^{-14}$
$T = 500$
$m = 16*2*amu$
$n_0 = 2.7\times10^{25}\ m^{-3}$
$I_0 = 1.5\times10^{14}$ photons/m²/s



”F2-region” - simple model calculation

O dominating species, 30 nm UV radiation

$a_a = 9.3\times10^{-23}$

$a_j = 9.3\times10^{-23}$

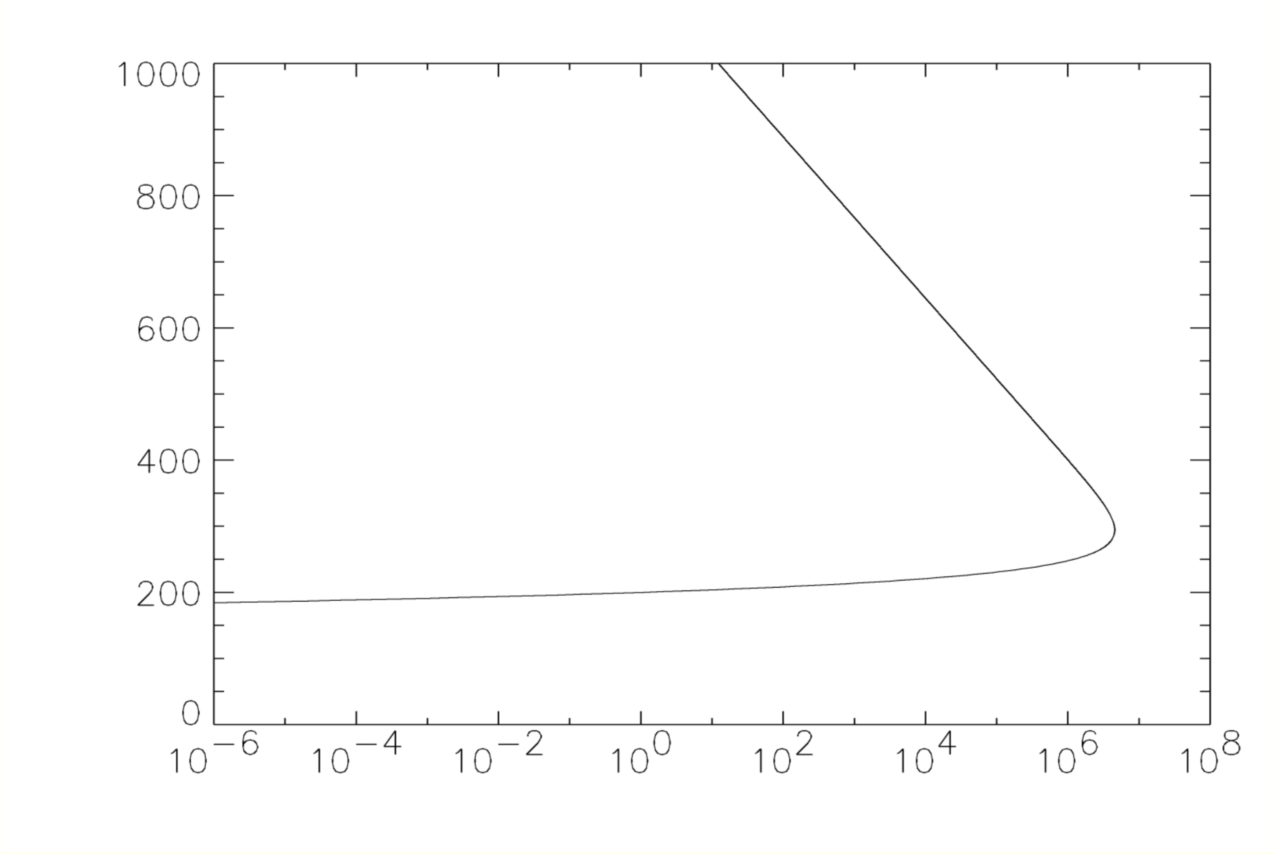
$a_r = 1.0\times10^{-16}$

$T=500$

$m = 16*\mathrm{amu}$

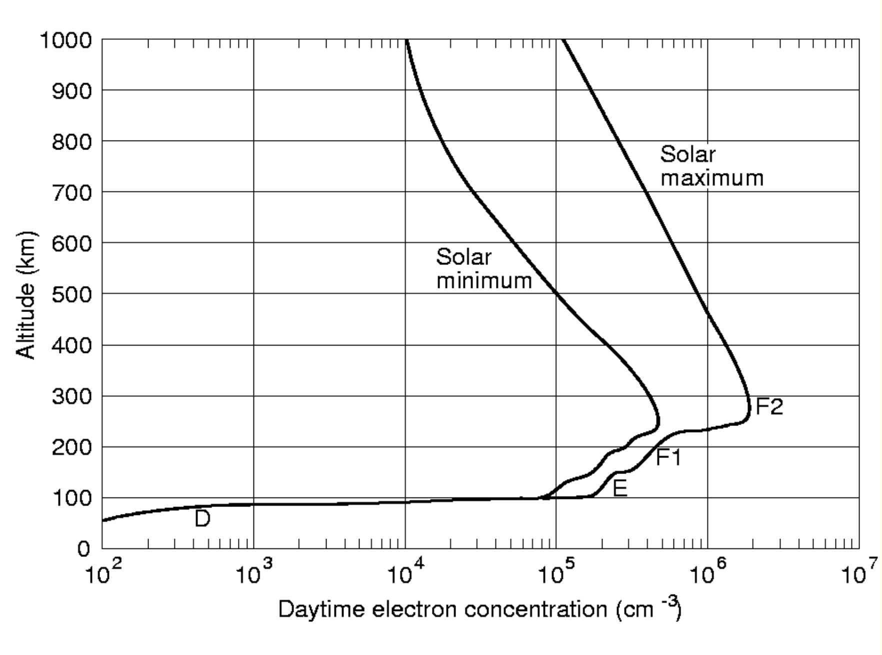
$n_0 = 2.7\times10^{25}\ \mathrm{m}^{-3}$

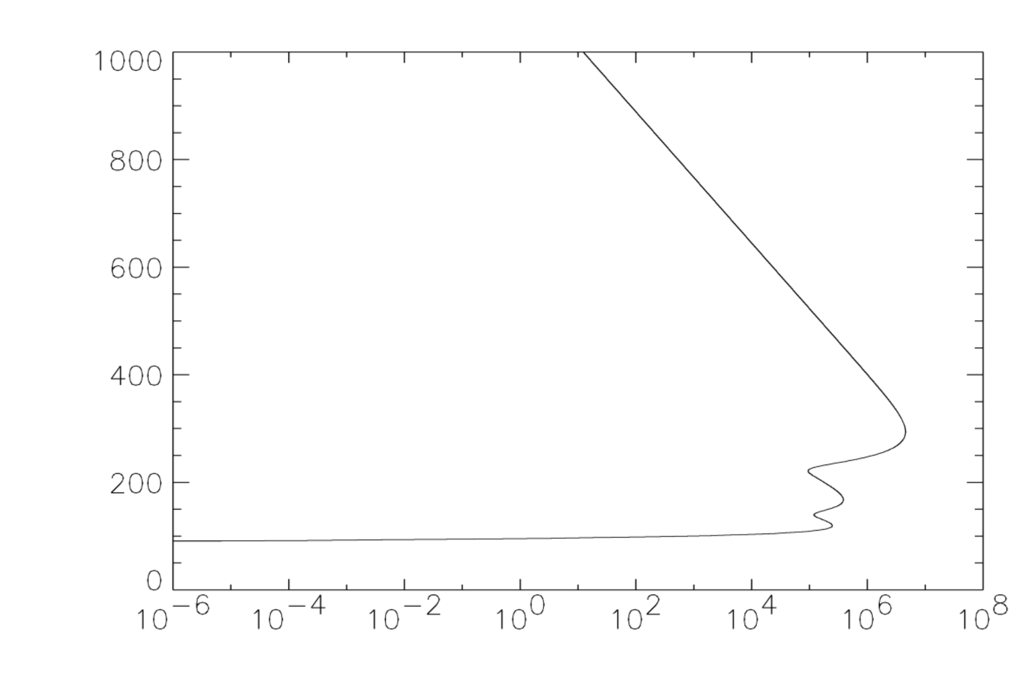
$I_0 = 1.5\ \times10^{14}$ photons/m^2/s



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

NO^+ created by chemical reaction $N_2^+ + O \rightarrow NO^+ + N$

Propation of radio waves in the ionosphere

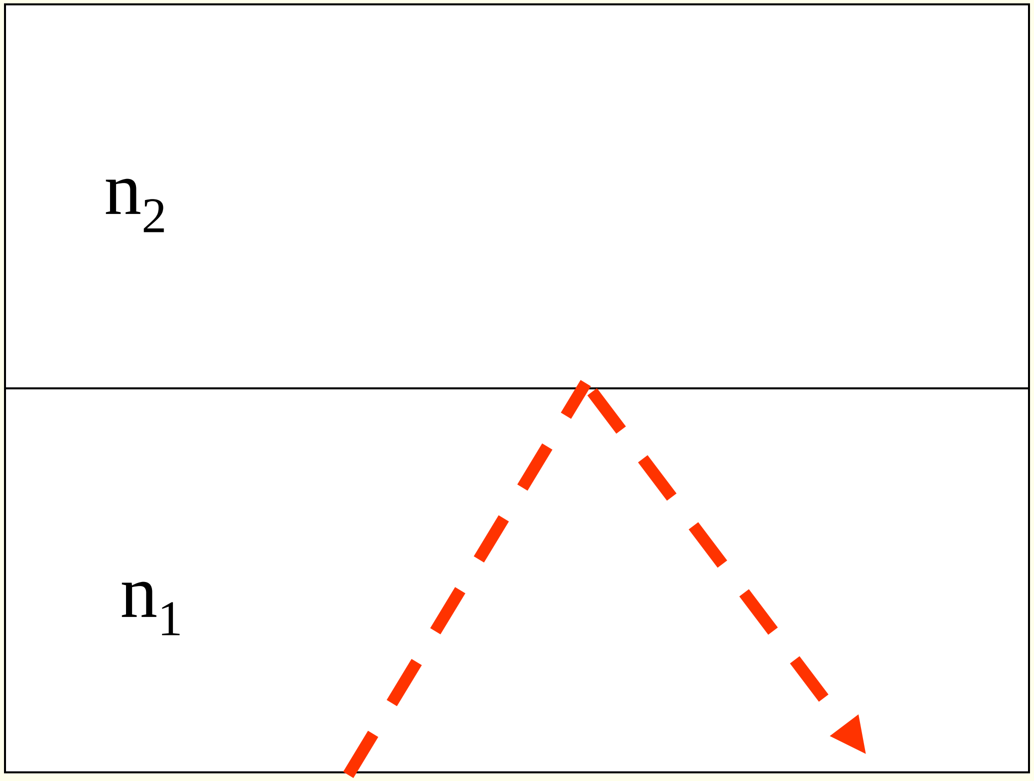
1. Absorption/damping

Takes place in the D-region due to high collision frequency. (Collisions with neutral atoms.)

2. Reflection

takes place in the F-region due to large gradients in the refraction index.

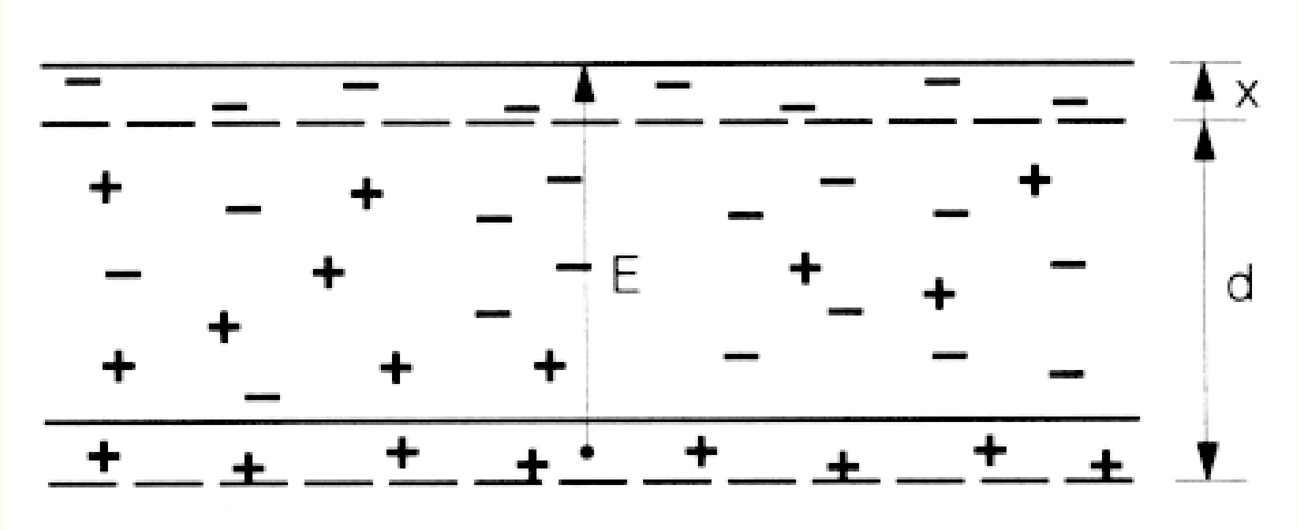
Reflection of radio waves



Total reflection at a sharp boundary (or large gradient) if

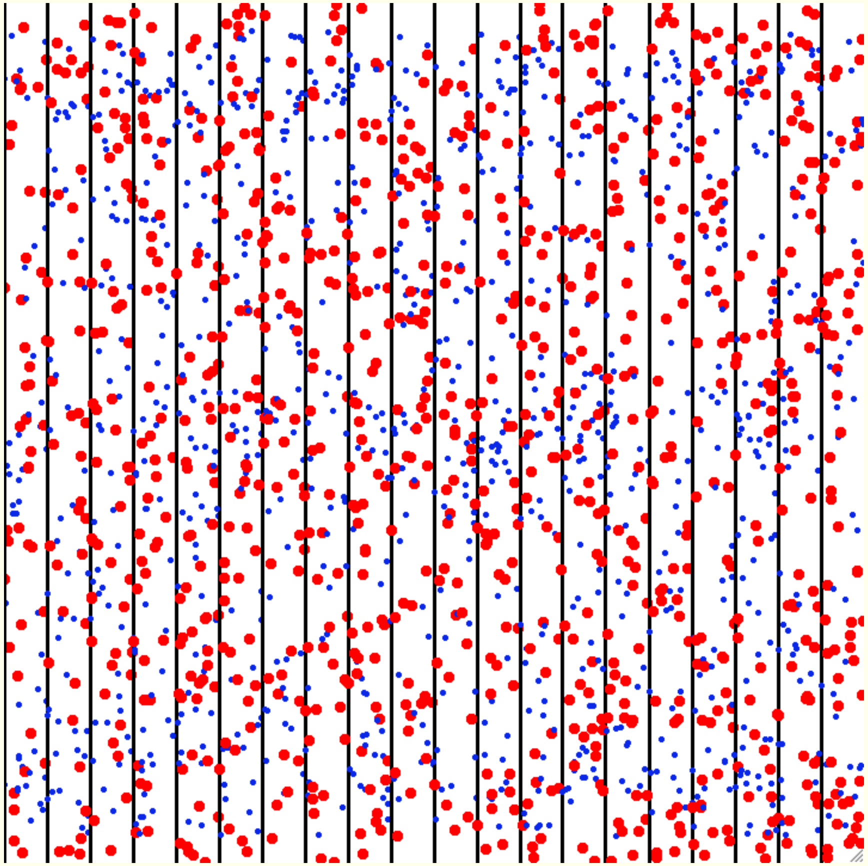
$$\boxed{n_2 < n_1}$$

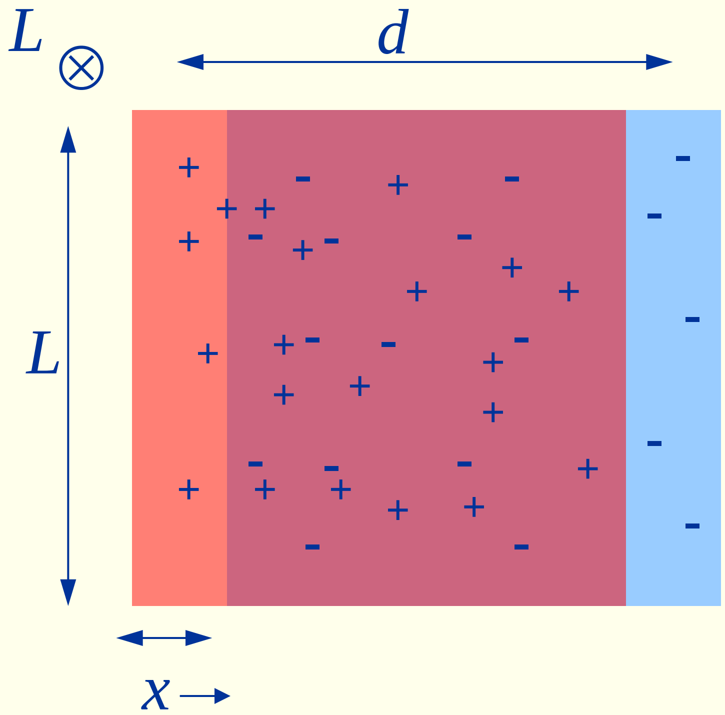
Plasma frequency



Charge imbalance creates an electric field which tends to even out the imbalance.

Plasma oscillations parallel to B





Newtons law on an individual electron inside the slab:

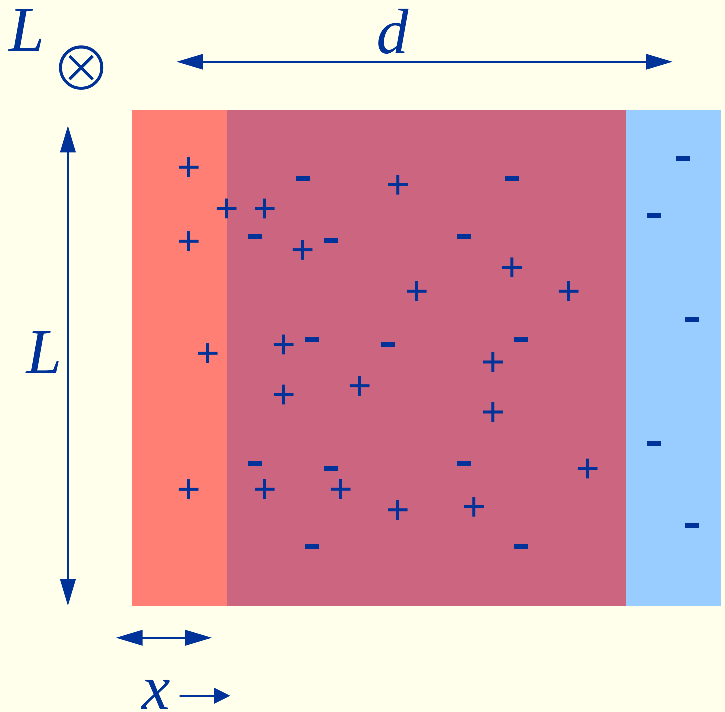
$$F = m_e a$$

$$F = -eE$$

Surface charge density

$$E = \frac{\sigma}{\varepsilon_0}$$

$$\sigma = -e n_e x$$



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

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

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

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

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

What is the plasma frequency f_{pe} at the daytime E-region, close to solar minimum? (see Fälthammar p 28)

$$f_{pe} = \frac{\omega_{pe}}{2\pi} \equiv \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$$

Blue	7 kHz	Yellow	400 MHz
Green	3 MHz	Red	2 GHz

$$f = \frac{\omega_{pe}}{2\pi} \equiv \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} = \frac{1}{2\pi}\sqrt{\frac{(1.6\cdot 10^{-19})^2}{8.854\cdot 10^{-12} 0.91\cdot 10^{-30}}}\sqrt{n_e} =$$

$$8.97\sqrt{n_e} = 8.97\sqrt{10^5\cdot 10^6} = 2.8\cdot 10^6\ Hz = 2.8\,MHz$$

Green

Index of refraction for electromagnetic waves in a plasma

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

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

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

$\Rightarrow$

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

$\Rightarrow$

Index of refraction for electromagnetic waves in a plasma

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

Does not represent E.M. wave

(4) $\Rightarrow$

$$-k^2\mathbf{E}=\mu_0\left(-i\omega\right)en_e\frac{ie\mathbf{E}}{\omega m_e}+\frac{1}{c^2}\left(-i\omega\right)^2\mathbf{E}$$

$\Rightarrow$

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

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

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

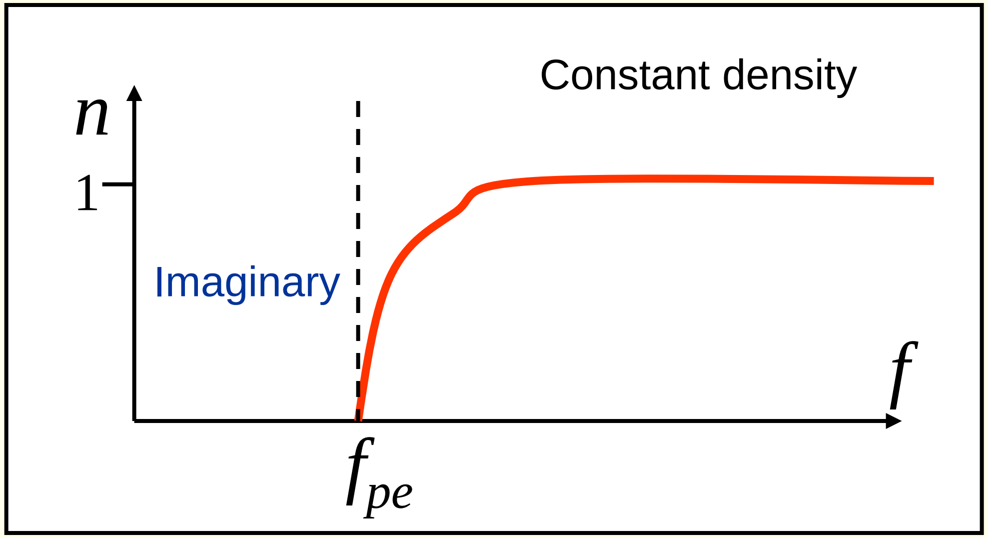
$\therefore$

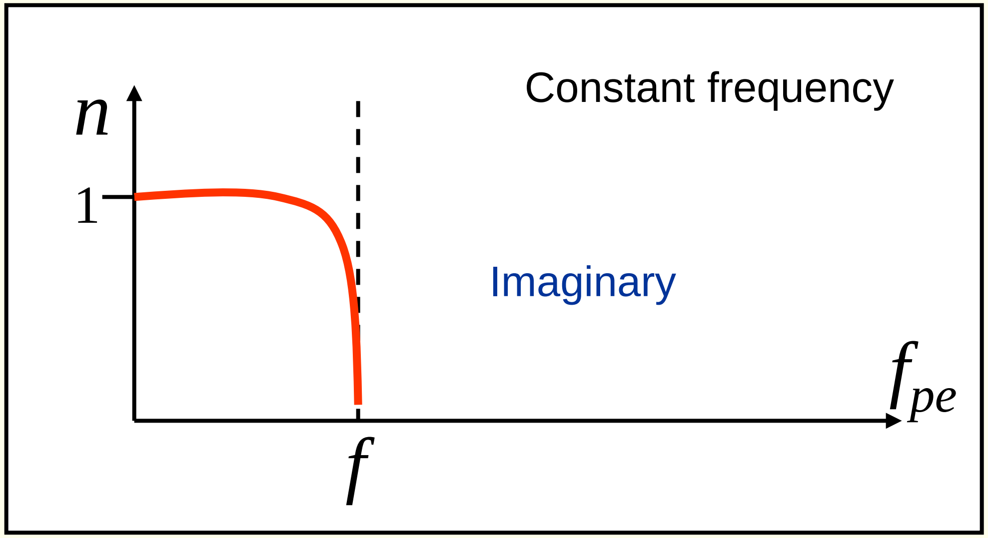
$$\boxed{n=\sqrt{1-\frac{\omega_p^2}{\omega^2}}=\sqrt{1-\frac{f_p^2}{f^2}}}$$

Refraction index for plasma

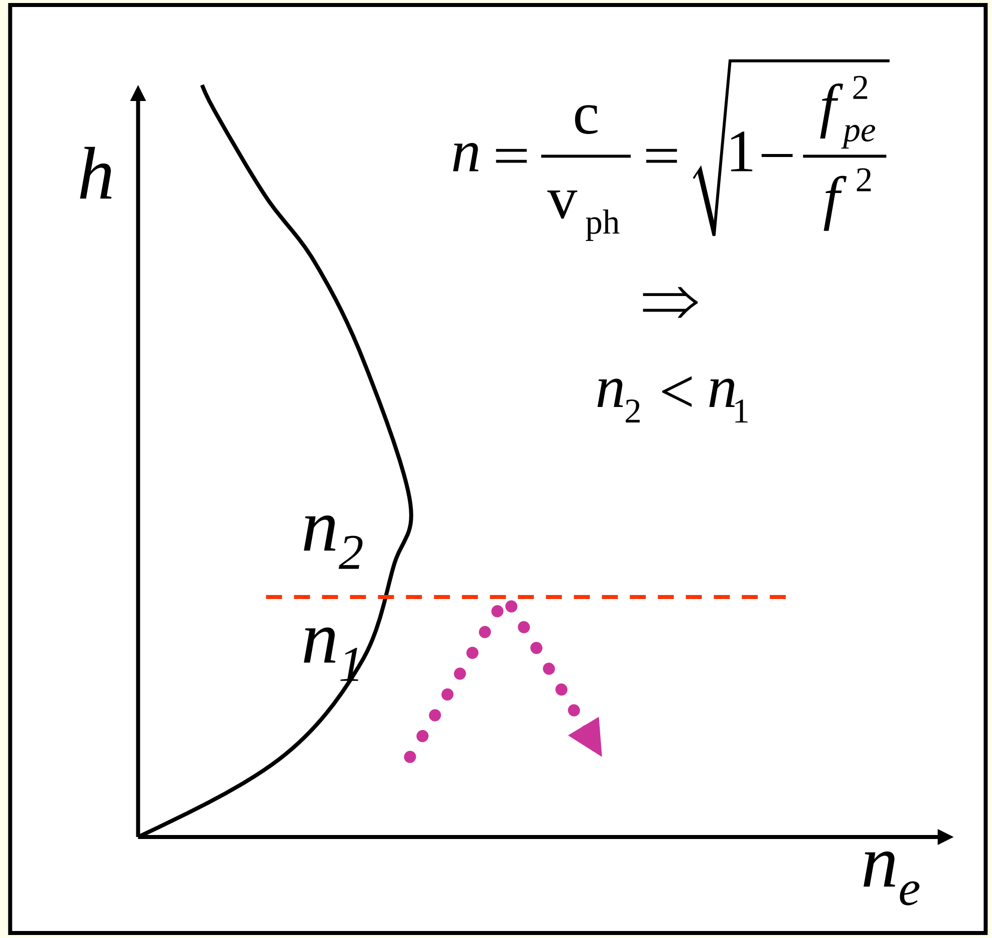
$$n = \frac{c}{v_{ph}} = \sqrt{1 - \frac{f_{pe}^2}{f^2}}$$

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





Where does the total reflection take place?

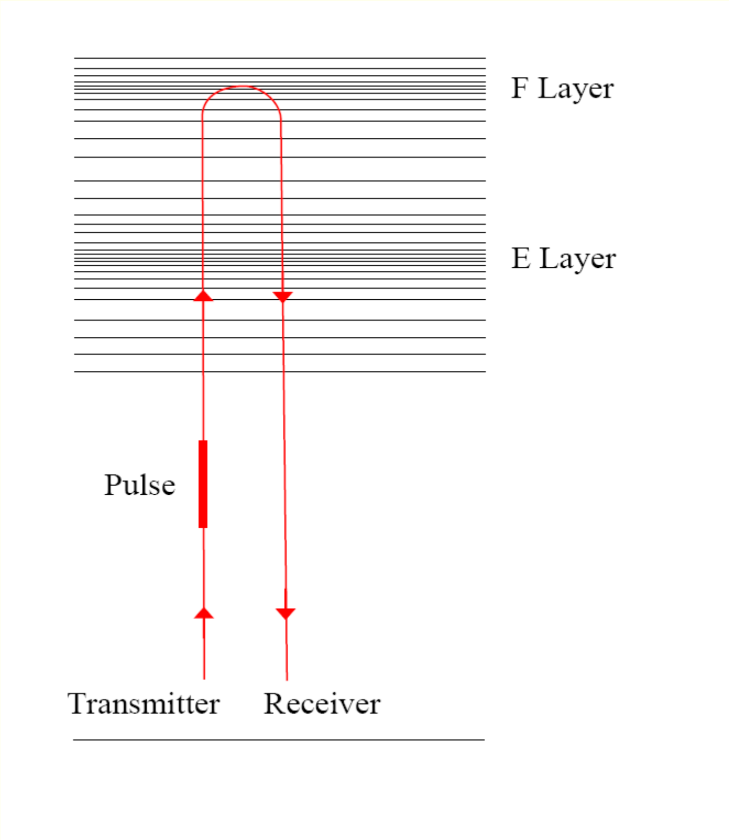


Large gradient when

$$\boxed{f \approx f_{pe}}$$

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

Ionosonde



The pulse will be reflected where

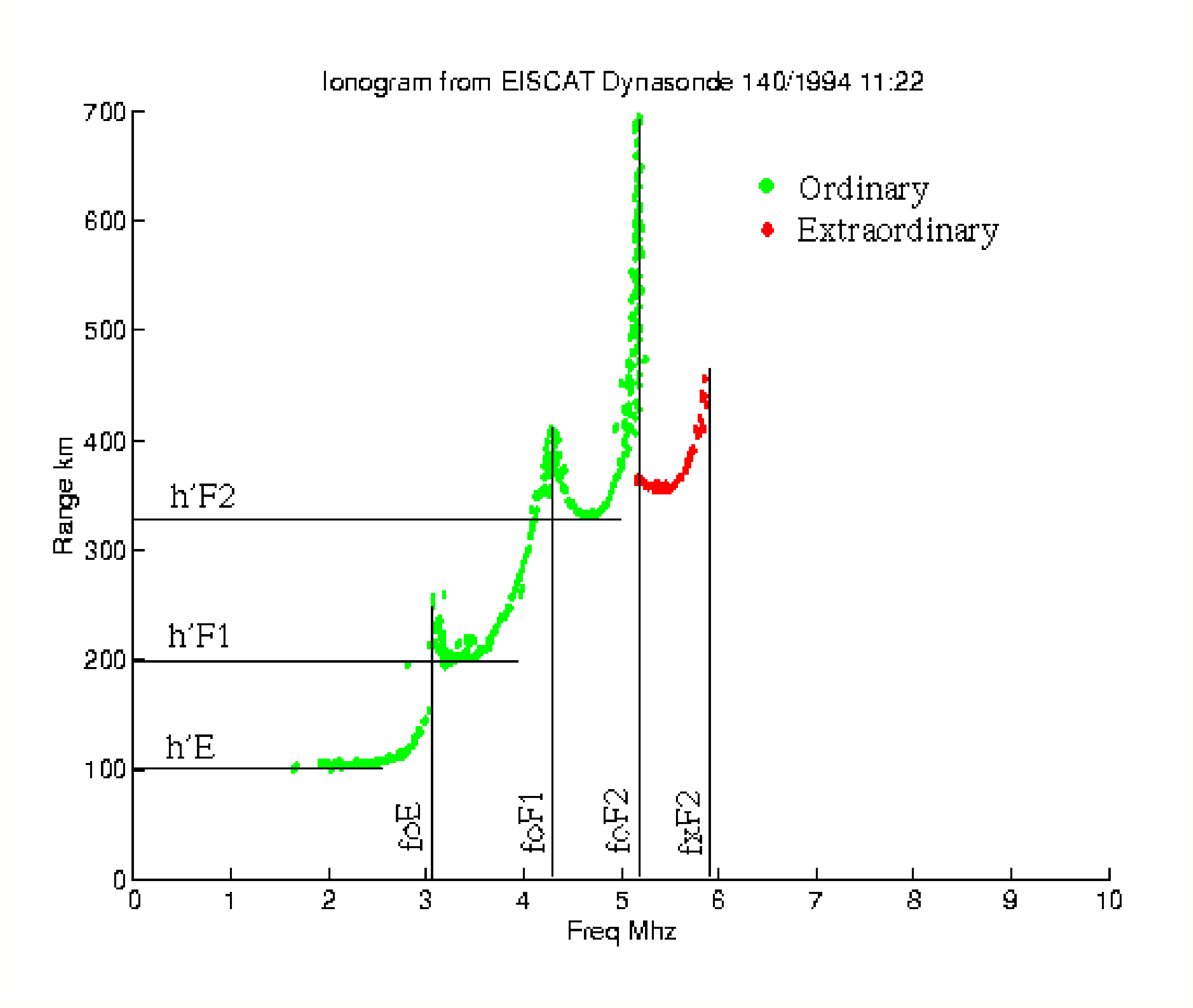
$$f = f_{pe}$$

The altitude will be determined by

$$2h = ct$$

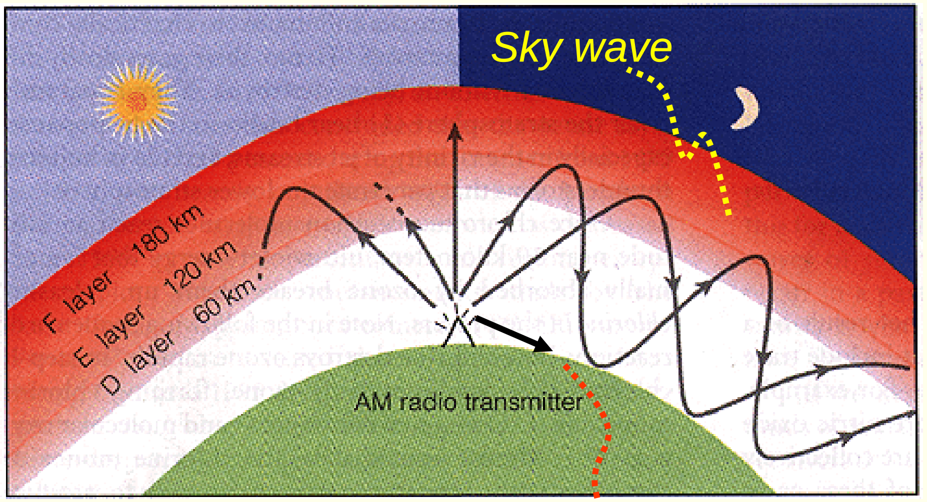
Where t is the time between when the pulse is sent out and the registered again.

Ionogram



Ionogram from EISCAT Dynasonde 140/1994 11:22
Ordinary
Extraordinary
Range km
Freq Mhz
h'F2
h'F1
h'E
foE
foF1
foF2
fxF2
0
100
200
300
400
500
600
700
1
2
3
4
5
6
7
8
9
10

Reflection of radio waves



F2-layer during night:

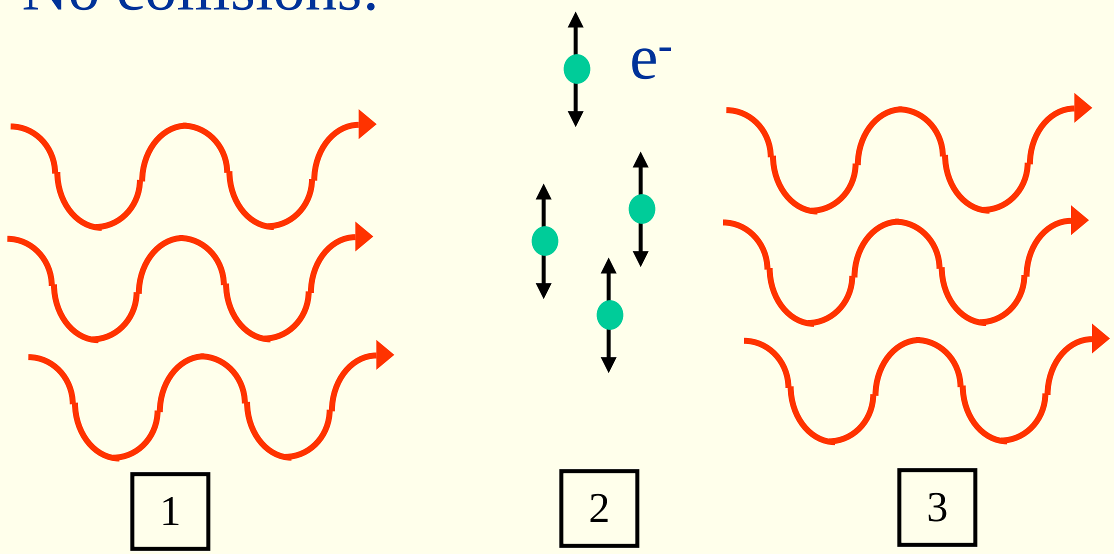
$$n_e = 5 \cdot 10^{11}\ \mathrm{m}^{-3} \quad \Rightarrow$$

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

= HF/short wave

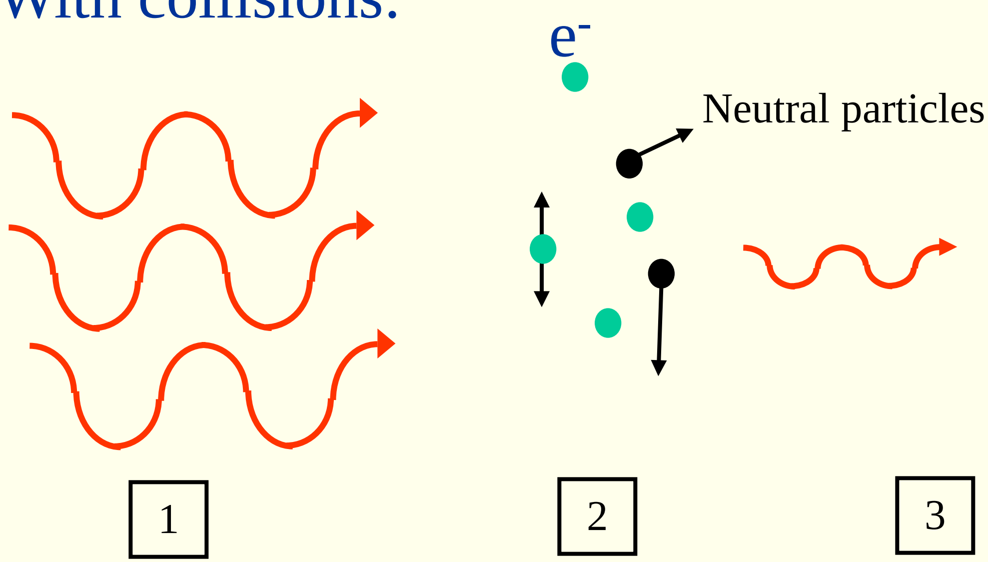
Absorption of radio waves

No collisions:



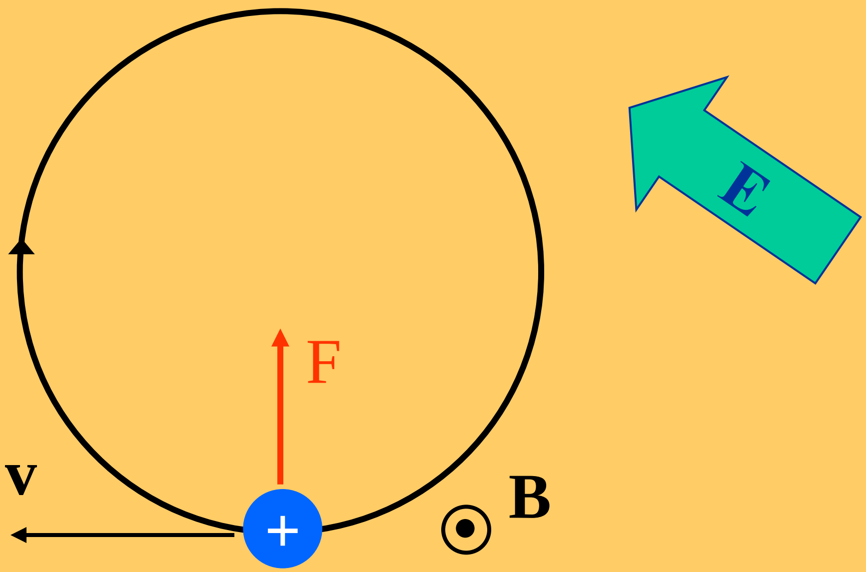
Absorption of radio waves

With collisions:



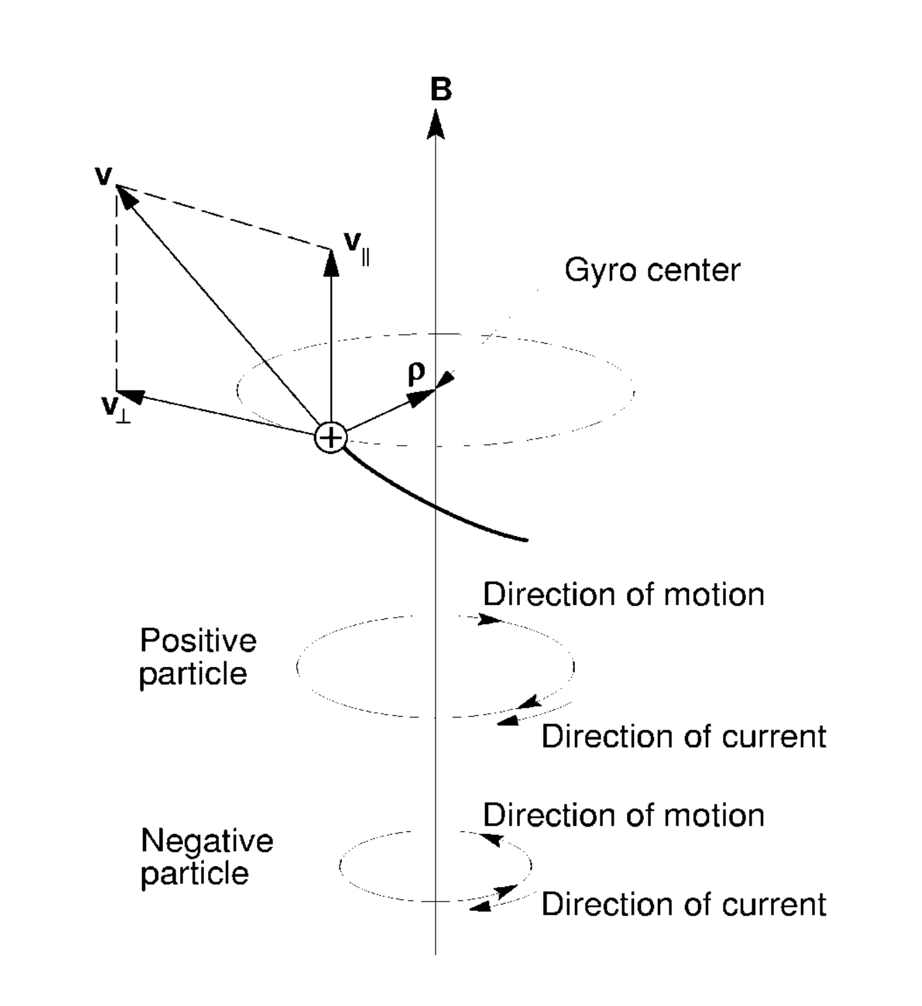
Think about this:

$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$



What happens if you add an electric field $\mathbf{E}$?

Particle motion in magnetic field



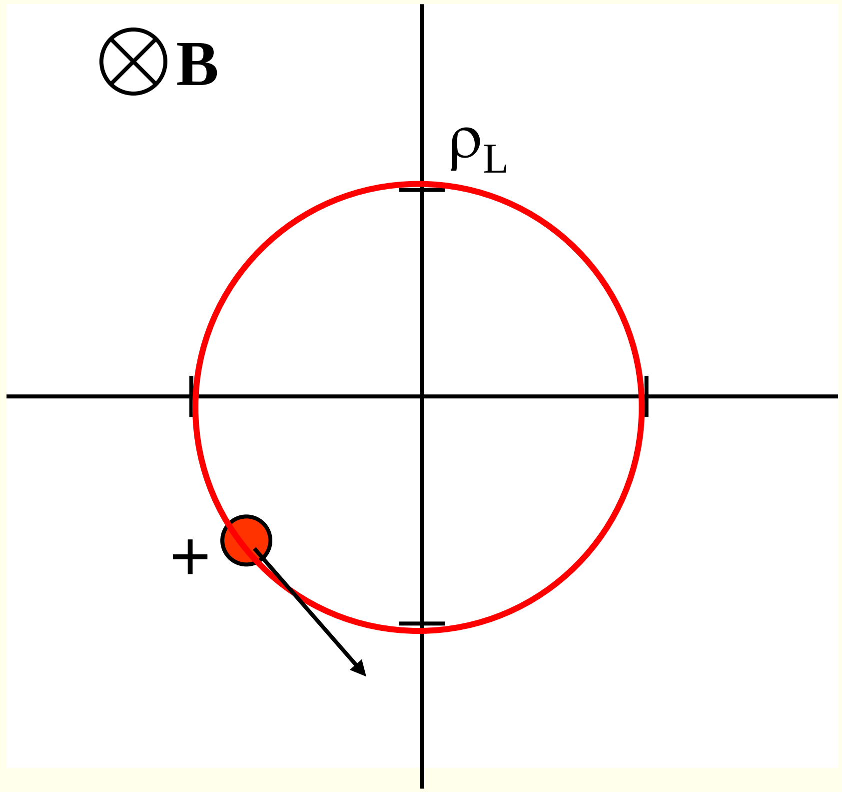
gyro radius

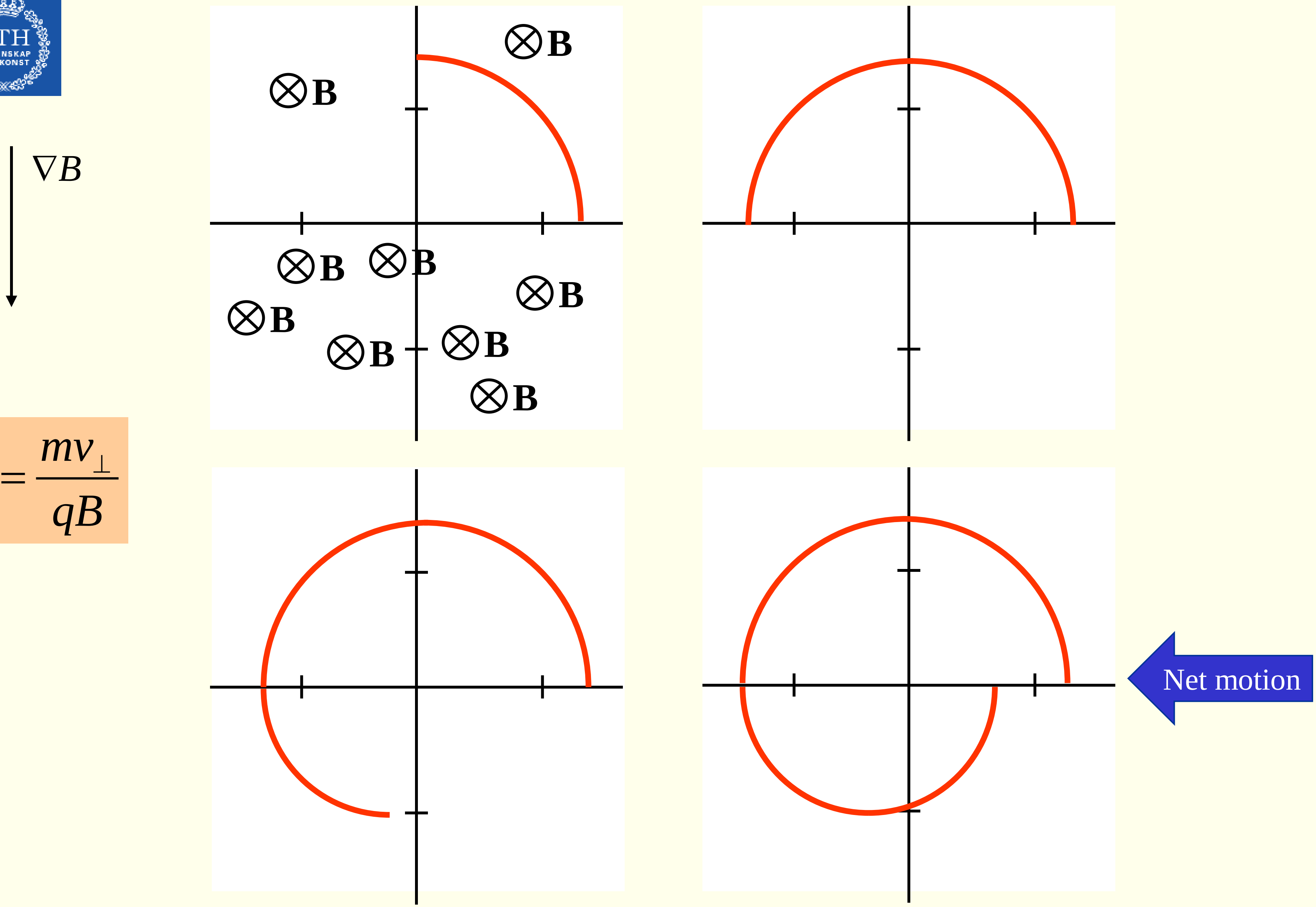
$$\rho = \frac{mv_\perp}{qB}$$

gyro frequency

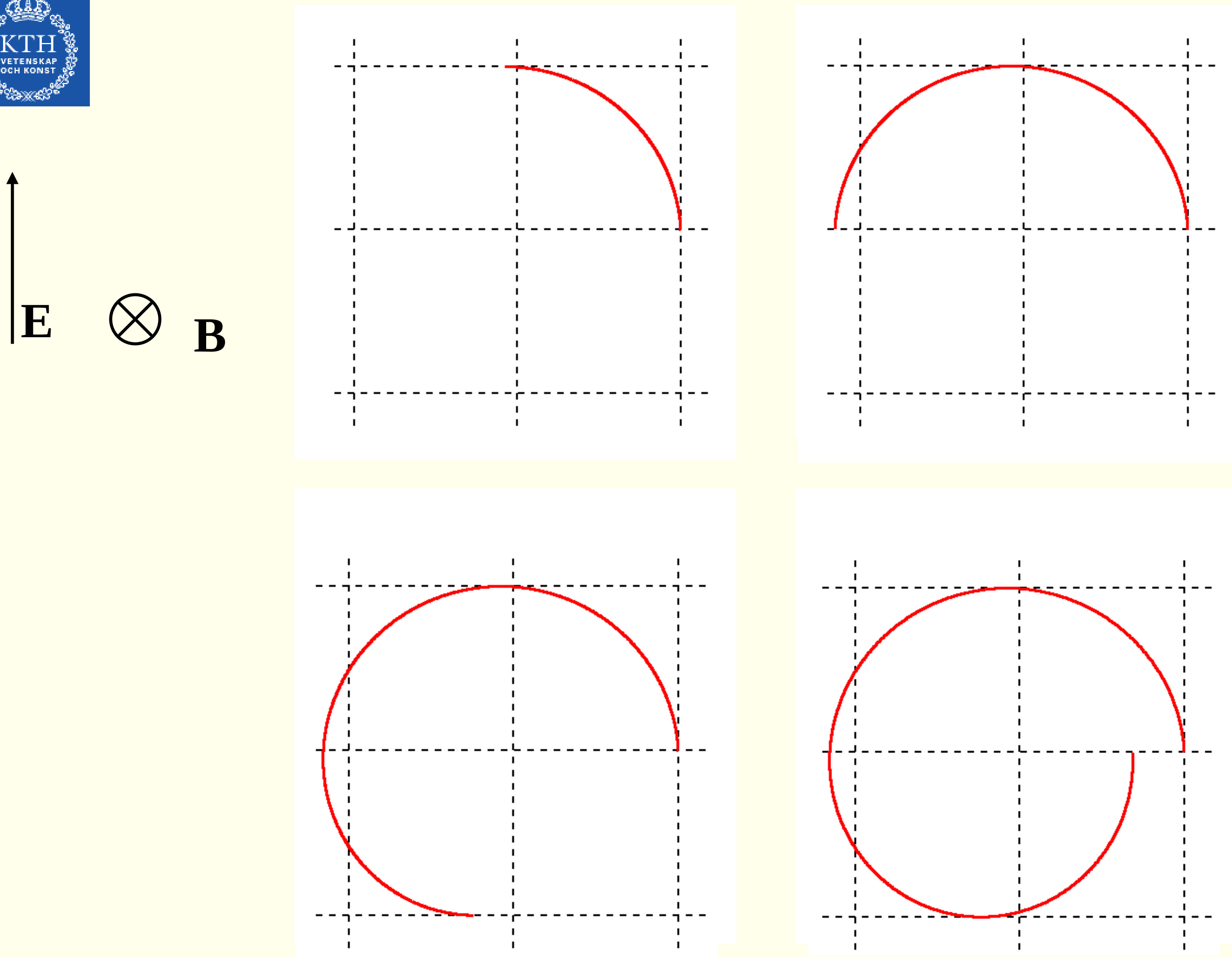
$$\omega_g = \frac{qB}{m}$$

Drift motion



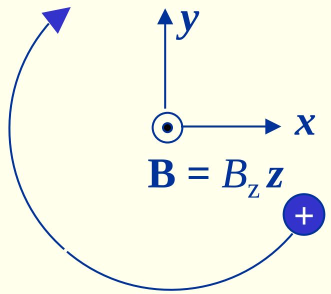


$$\rho = \frac{mv_\perp}{qB}$$


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:

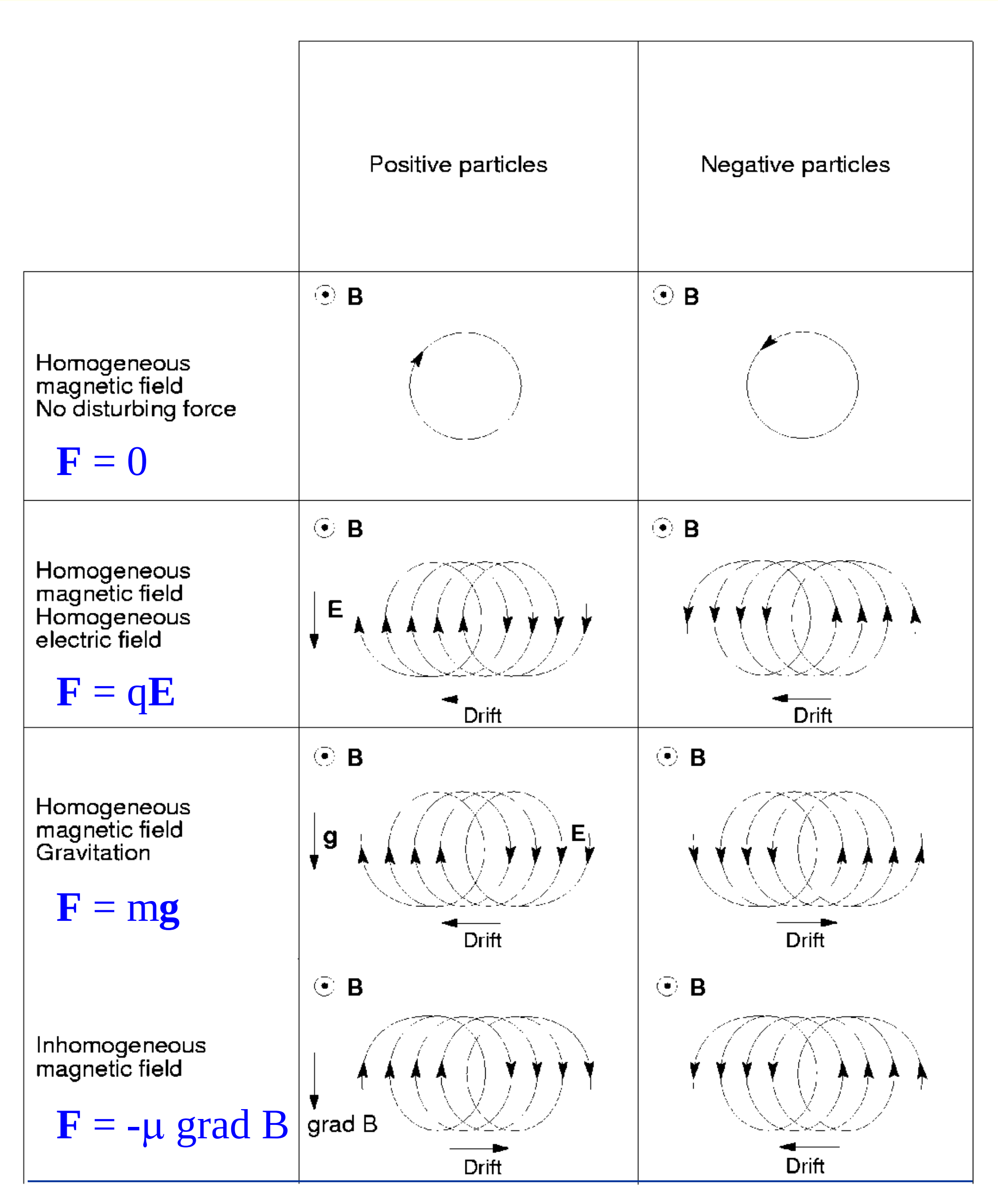
$$v_{drift,y} = -\frac{E_x}{B} = -\frac{E_x B_z}{B^2} = \frac{(\mathbf{E}\times\mathbf{B})_y}{B^2}$$

In general:

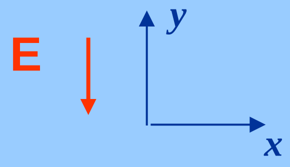
$$\boxed{\mathbf{v}_{drift} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = \frac{q\mathbf{E}\times\mathbf{B}}{qB^2} = \frac{\mathbf{F}\times\mathbf{B}}{qB^2}}$$

Drift motion

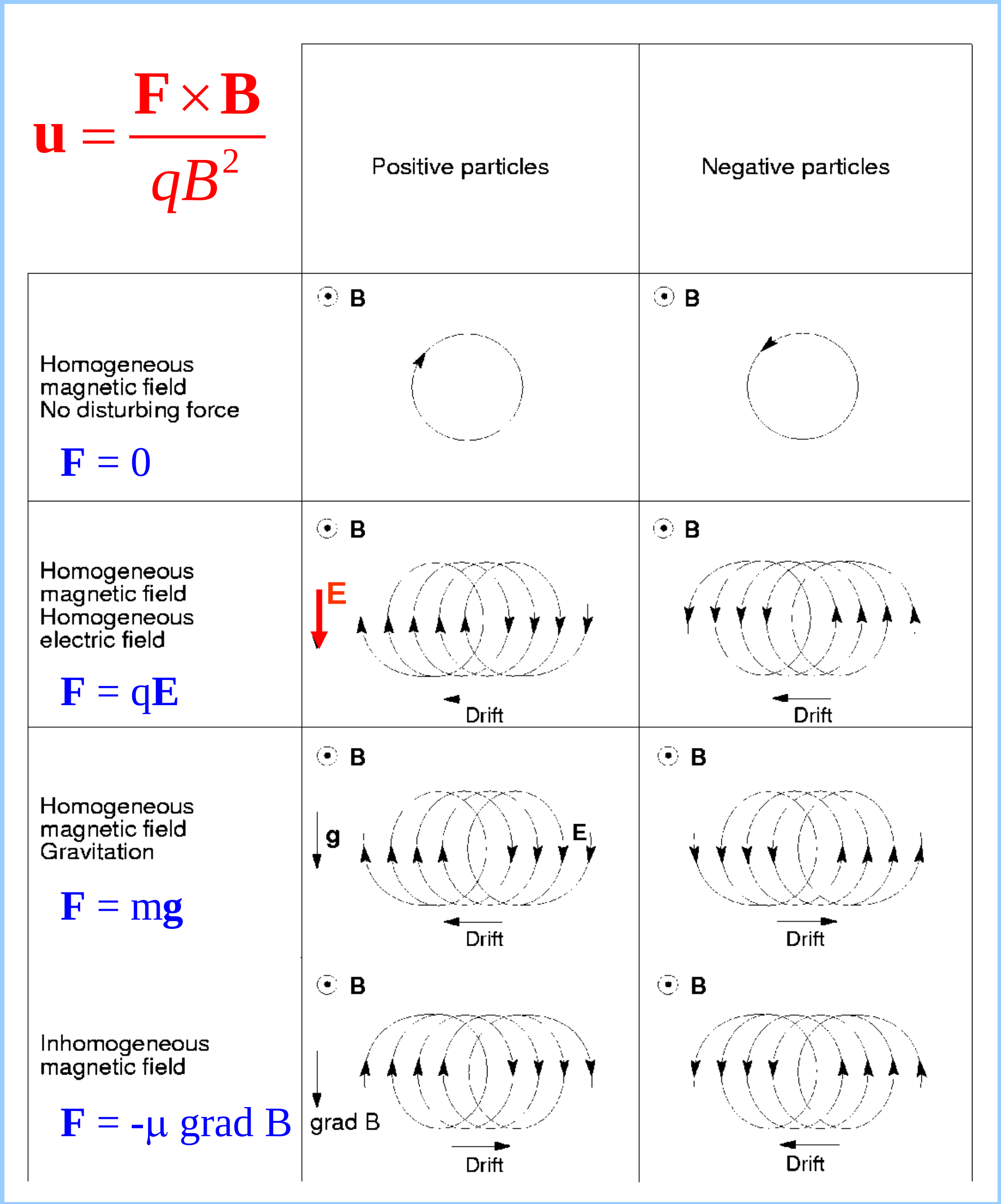
$$\mathbf{u}_{drift} = \frac{\mathbf{F} \times \mathbf{B}}{qB^2}$$



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?



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



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

Blue $\mathbf{I} = 0$

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

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

Last Minute!