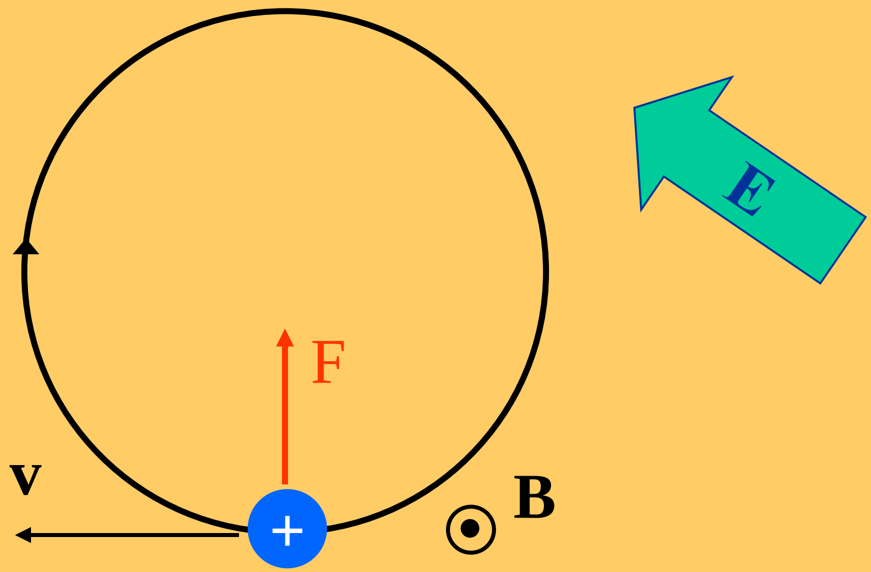
# Think about this:

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




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

# Last lecture (3)

- Solar activity
- Solar wind – basic facts
- Solar wind – magnetic structure

# Today's lecture (4)

- Ionosphere

  - layers

  - radio wave reflection

# Schedule

10×2 h Lectures

6×2 h Tutorials

L = Lecture, T = Tutorial

| Activity | Date | Time | Room | Subject | Litterature |
|---|---|---|---|---|---|
| L1 | 29/8 | 13-15 | E52 | Course description, Introduction, The Sun 1, Plasma physics 1 | **CGF** Ch 1, 5, (p 110-113) |
| L2 | 1/9 | 15-17 | L52 | The Sun 2, Plasma physics 2 | **CGF** Ch 5 (p 114-121), 6.3 |
| L3 | 5/9 | 13-15 | E51 | 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 | 8/9 | 15-17 | D41 | Mini-group work 1 | |
| L4 | 12/9 | 13-15 | E35 | The ionosphere 2, Plasma physics 4 | **CGF** Ch 3.4, 3.7, 3.8 |
| L5 | 14/9 | 10-12 | V32 | The Earth's magnetosphere 1, Plasma physics 5 | **CGF** 4.1-4.3, **LL** Ch I, II, IV.A |
| T2 | 15/9 | 15-17 | E51 | Mini-group work 2 | |
| L6 | 19/9 | 13-15 | M33 | The Earth's magnetosphere 2, Other magnetospheres | **CGF** Ch 4.6-4.9, **LL** Ch V. |
| T3 | 22/9 | 15-17 | E51 | Mini-group work 3 | |
| L7 | 26/9 | 13-15 | E31 | Aurora, Measurement methods in space plasmas and data analysis 1 | **CGF** Ch 4.5, 10**, LL** Ch VI, Extra material |
| L8 | 28/9 | 10-12 | L52 | Space weather and geomagnetic storms | **CGF** Ch 4.4, **LL** Ch IV.B-C, VII.A-C |
| T4 | 29/9 | 15-17 | M31 | Mini-group work 4 | |
| L9 | 3/10 | 13-15 | E52 | Interstellar and intergalactic plasma, Cosmic radiation, | **CGF** Ch 7-9 |
| T5 | 6/10 | 15-17 | E31 | Mini-group work 5 | |
| L10 | 10/10 | 13-15 | E52 | Swedish and international space physics research. | |
| T6 | 13/10 | 15-17 | E31 | Round-up, old exams. | |
| Written examination | 26/10 | 8-13 | F2 | | |

# Mini groupwork 1

a)

$$h = \frac{17}{2} \cdot 6378 \text{ km}$$

The thermal energy is divided into motion in the three dimensions, two of which only give rise to a gyro motion around the magnetic field lines, with the motion along the magnetic field corresponding to an energy

$$E = \frac{k_B T}{2} = \frac{1.38 \cdot 10^{-23} \cdot 2 \cdot 10^{6}}{2} = 1.4 \cdot 10^{-17} \text{ J}$$

$$v = \sqrt{\frac{2E}{m_e}} = \sqrt{\frac{2 \cdot 1.4 \cdot 10^{-17}}{0.91 \cdot 10^{-30}}} = 5500 \text{ km/s}$$

Approximating the loop with a quarter-circle, the electron has to travel a length

$s = \pi h/2 = 85\ 000$ km

Then we get $t = 15$ s.

# Energy - temperature

Average energy of molecule/atom:

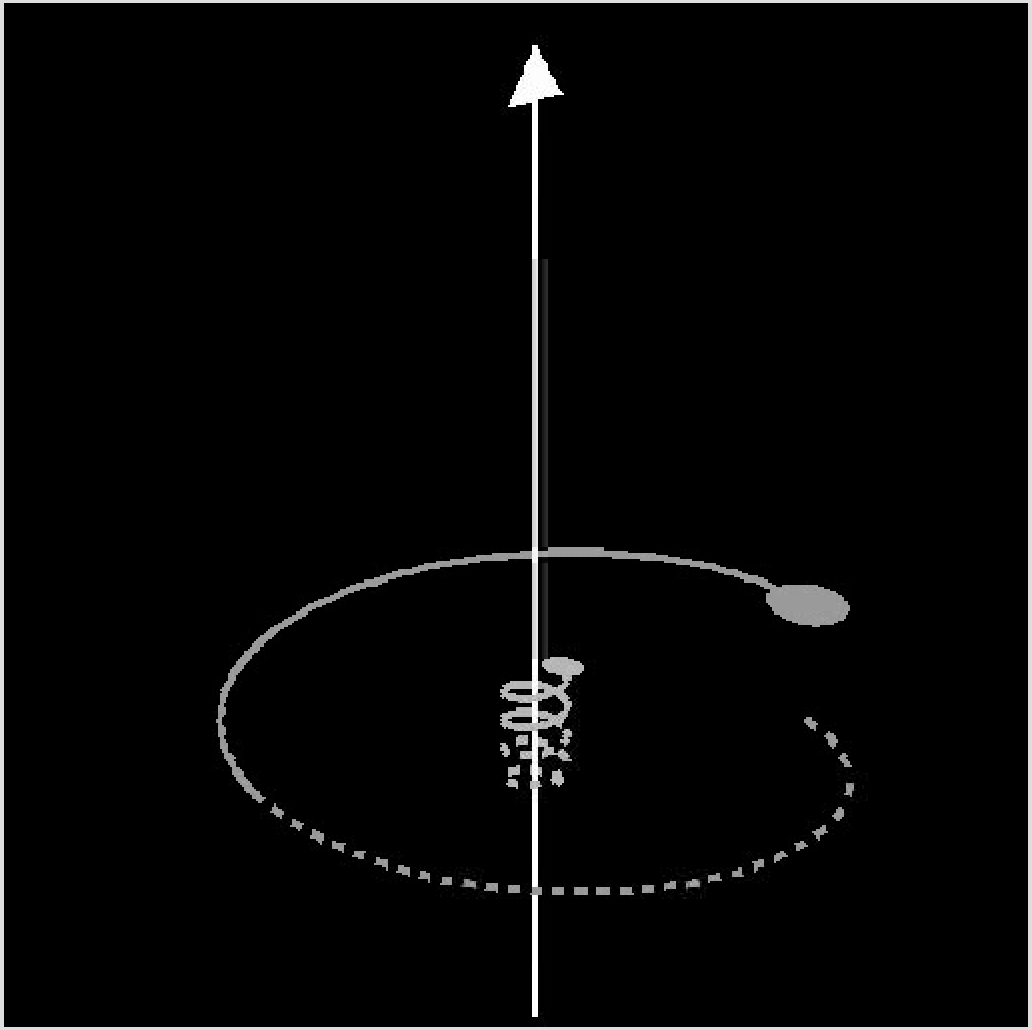
$$E = \frac{3}{2} k_B T \quad \Rightarrow$$

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

1 eV = 1.6·10$^{-19}$ J $\Rightarrow$

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

# Gyro motion



## Equipartion principle

Statistically the kinetic energy is equally distributed along the three dimensions:

$$E_{\parallel} = \frac{1}{2} k_B T$$

$$E_{\perp} = \frac{2}{2} k_B T$$

# Mini groupwork 1

b)

$$f_c = \frac{\omega_c}{2\pi} = \frac{1}{2\pi}\frac{qB}{m} \quad \Rightarrow$$

$$B = \frac{2\pi f_c m}{q} = \frac{2\pi \cdot 8 \cdot 10^{9} \cdot 0.91 \cdot 10^{-30}}{1.6 \cdot 10^{-19}} = 0.29 \text{ T}$$

The perpendicular energy is given by

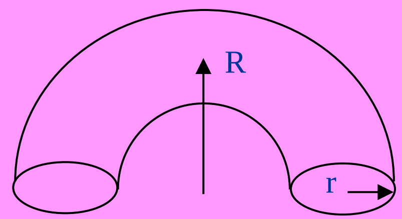
$$E = \frac{2k_B T}{2} = \frac{2 \cdot 1.38 \cdot 10^{-23} \cdot 2 \cdot 10^{6}}{2} = 2.8 \cdot 10^{-17} \text{ J}$$

$$v_\perp = \sqrt{\frac{2E}{m_e}} = \sqrt{\frac{2 \cdot 2.8 \cdot 10^{-17}}{0.91 \cdot 10^{-30}}} = 7.8 \cdot 10^{6} \text{ m/s}$$

$$\rho = \frac{m_e v_\perp}{qB} = \frac{0.91 \cdot 10^{-30} \cdot 7.8 \cdot 10^{6}}{1.6 \cdot 10^{-19} \cdot 0.29} = 1.5 \cdot 10^{-4} \text{ m}$$

# Mini groupwork 1

c) Model the flare by a half torus with minor axis r, and major axis. From the figure, estimate R = 8 $R_E$, and r = 2 $R_E$.



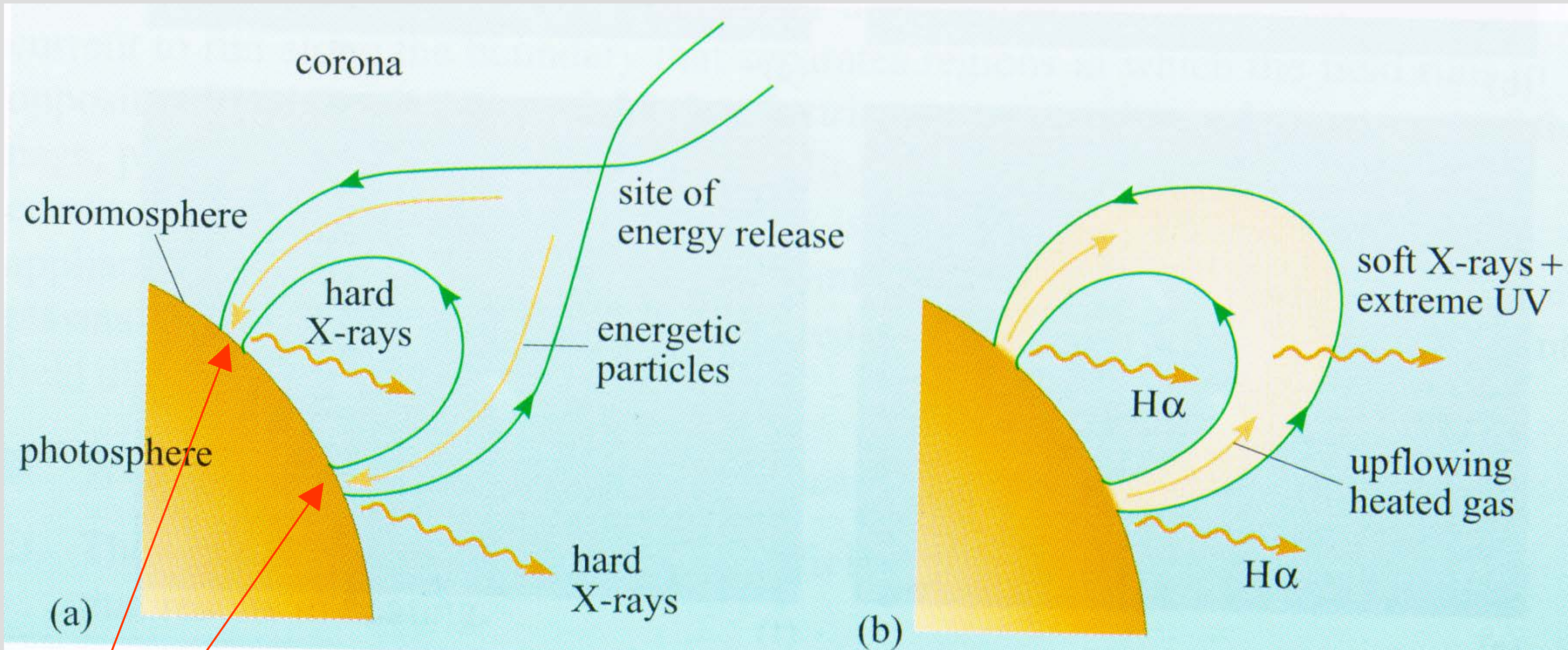

Let this half-torus be filled with a magnetic field of strength B ~ 0.36 T (using the value in b)). If the volume of the half-torus is V and the magnetic energy density is $p_B$, the total energy is

$$W = Vp_B = \pi R \pi r^2 \frac{B^2}{2\mu_0} = \pi^2 \cdot 8 \cdot 2^2 {R_E}^3 \frac{B^2}{2\mu_0}$$

$$= \pi^2 \cdot 32 \cdot (6378 \cdot 10^3)^3 \frac{(0.29)^2}{2\mu_0}$$

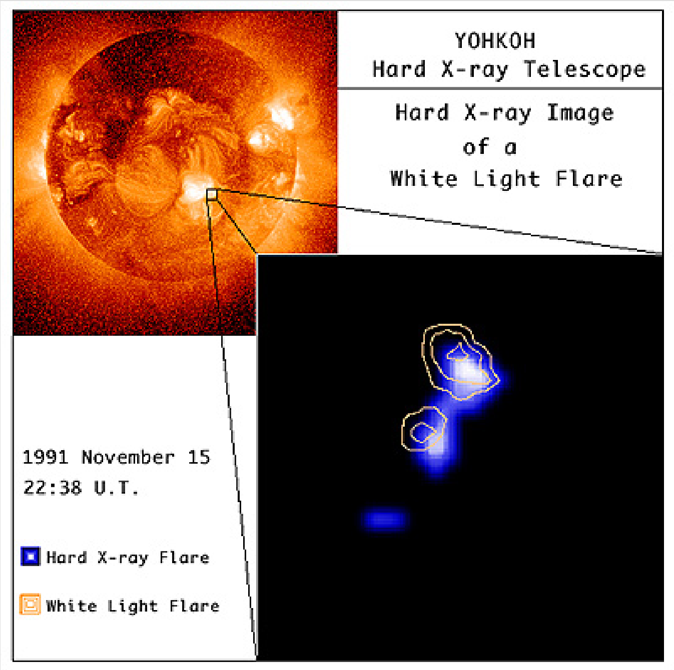
$$= 5.5 \cdot 10^{27}\ \mathrm{J}$$

# Solar flare mechanism

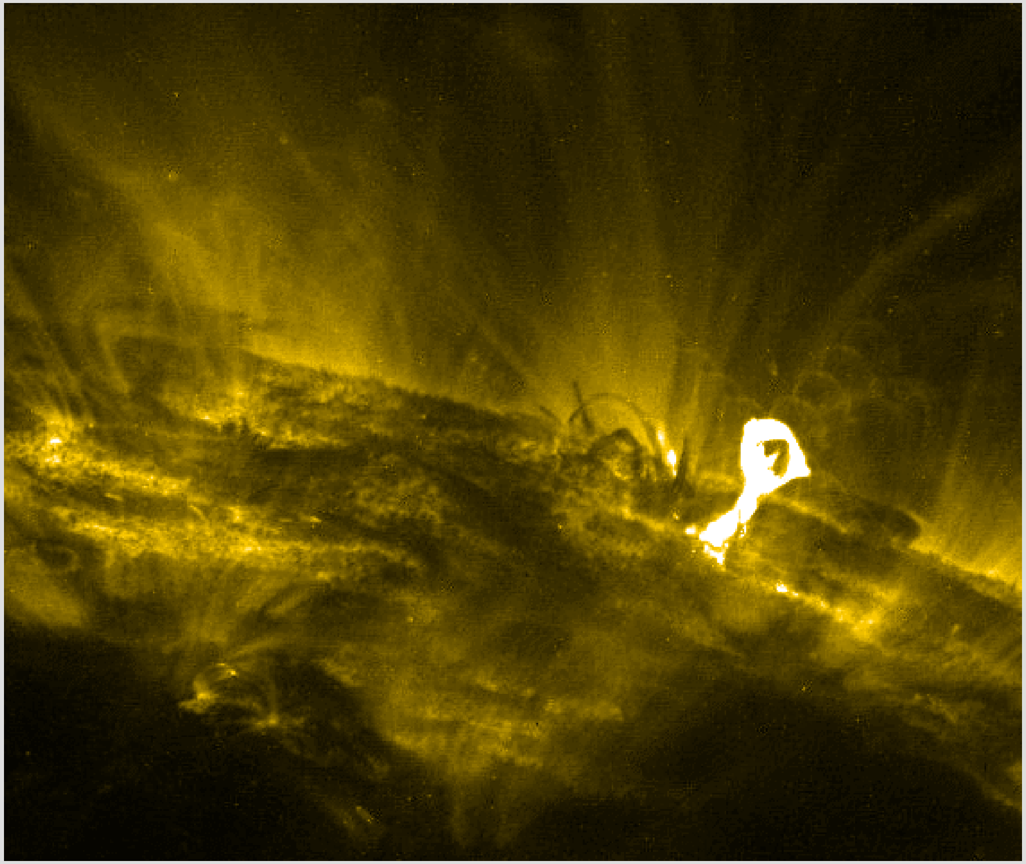



Electrons are accelerated, collide
with solar surface (photosphere)
and emit bremsstrahlung (X-rays).

# Solar flare observations




(a) double signature of x-ray emissions at foot of flare



(b) coronal loop filled with hot gas

# Frozen in magnetic flux *PROOF II*

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$

A

B

Order of magnitude estimate:

$$\frac{A}{B} = \frac{\nabla \times (\mathbf{v} \times \mathbf{B})}{\frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}} \approx \frac{\frac{v \Delta B}{L}}{\frac{\Delta B}{\mu_0 \sigma L^2}} = v L \mu_0 \sigma \equiv R_m$$

Magnetic Reynolds number $R_m$:

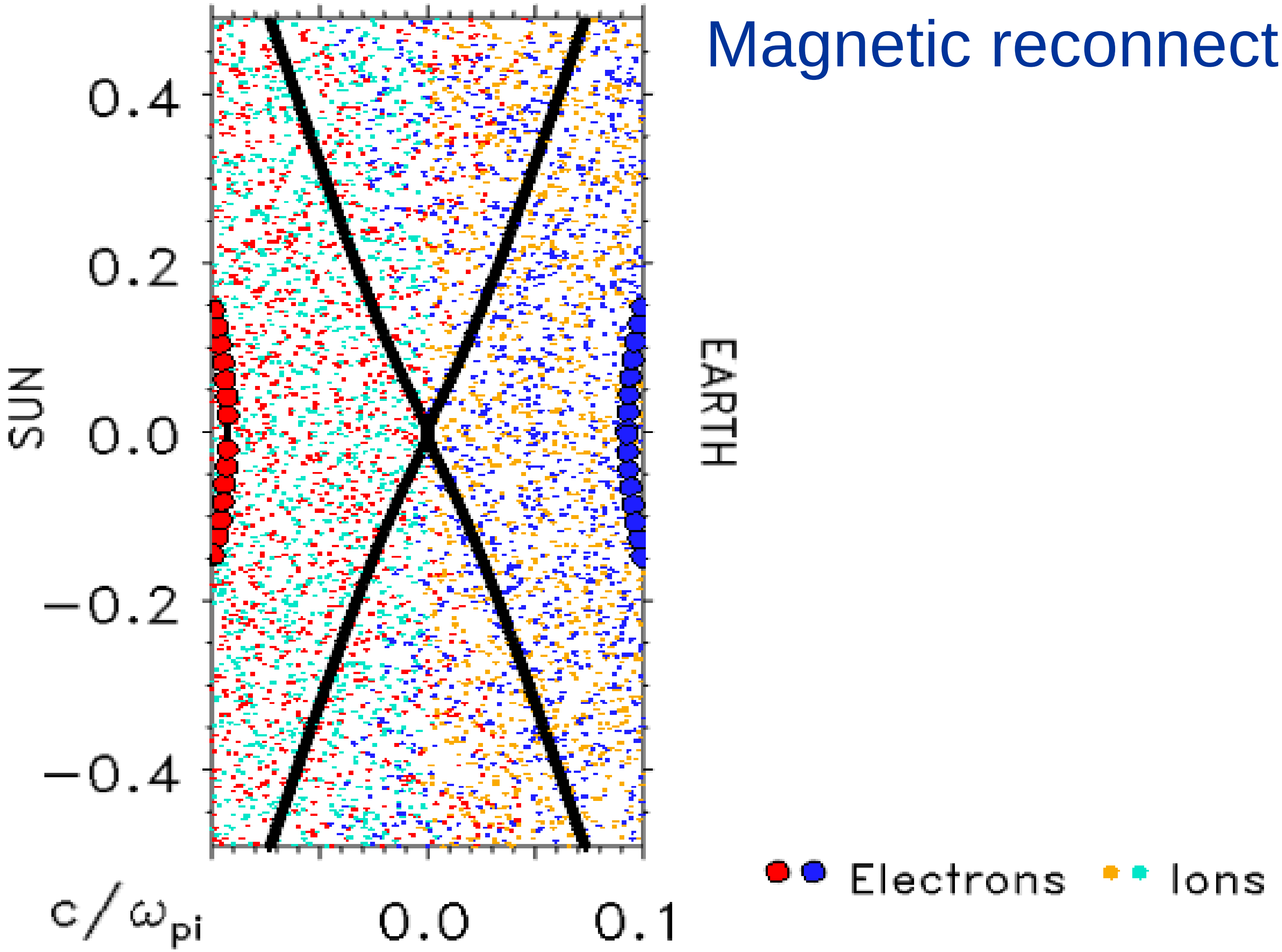
$$\mathrm{R_m} >> 1 \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Frozen-in fields!

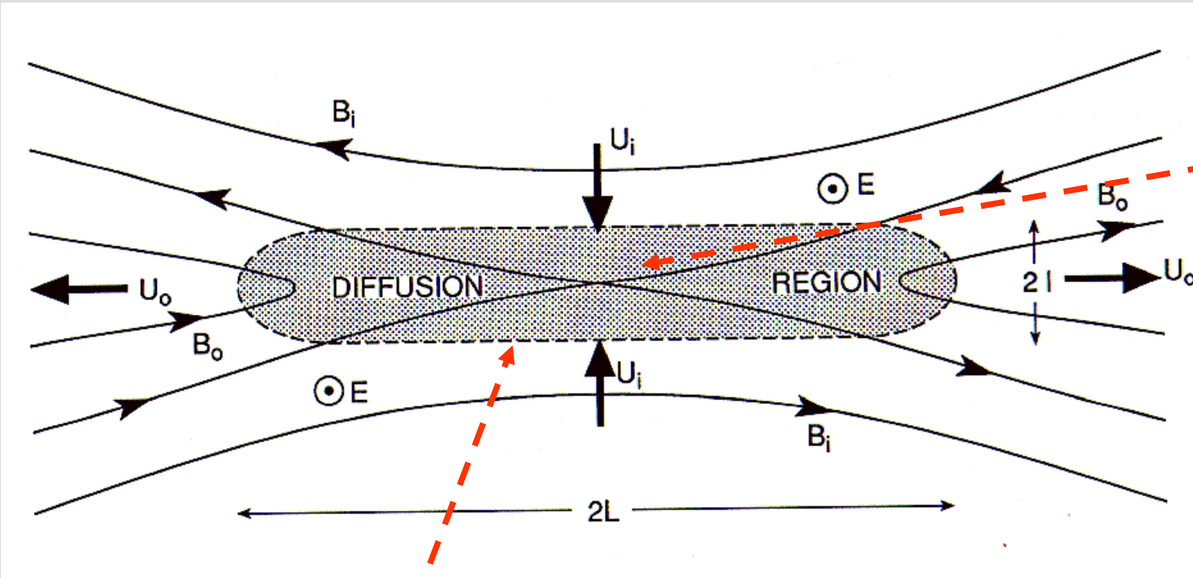
$$\mathrm{R_m} << 1 \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$

Diffusion equation!

# Magnetic reconnection



# Reconnection




In 'diffusion region':

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

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

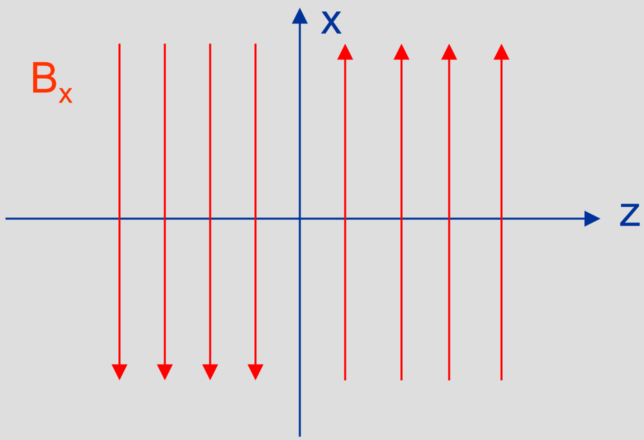
A second condition is that there are two regions of magnetic field pointing in *opposite* direction:

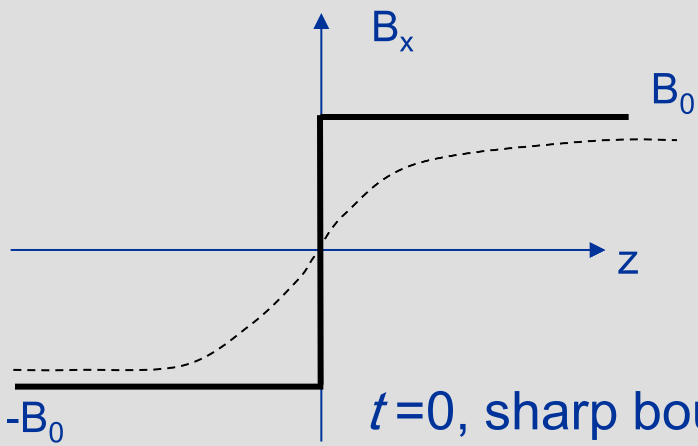
- Field lines are "cut" and can be re-connected to other field lines

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

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

# Reconnection in 1D




*t* =0, sharp boundary

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B} \longrightarrow \frac{\partial B_x}{\partial t} = \frac{1}{\mu_0 \sigma} \frac{\partial^2 B_x}{\partial z^2}$$

Diffusion equation! Has solution

$$B_x(z,t) = B_0 erf\left( \left[ \frac{\mu_0 \sigma}{4t} \right]^{1/2} z \right)$$

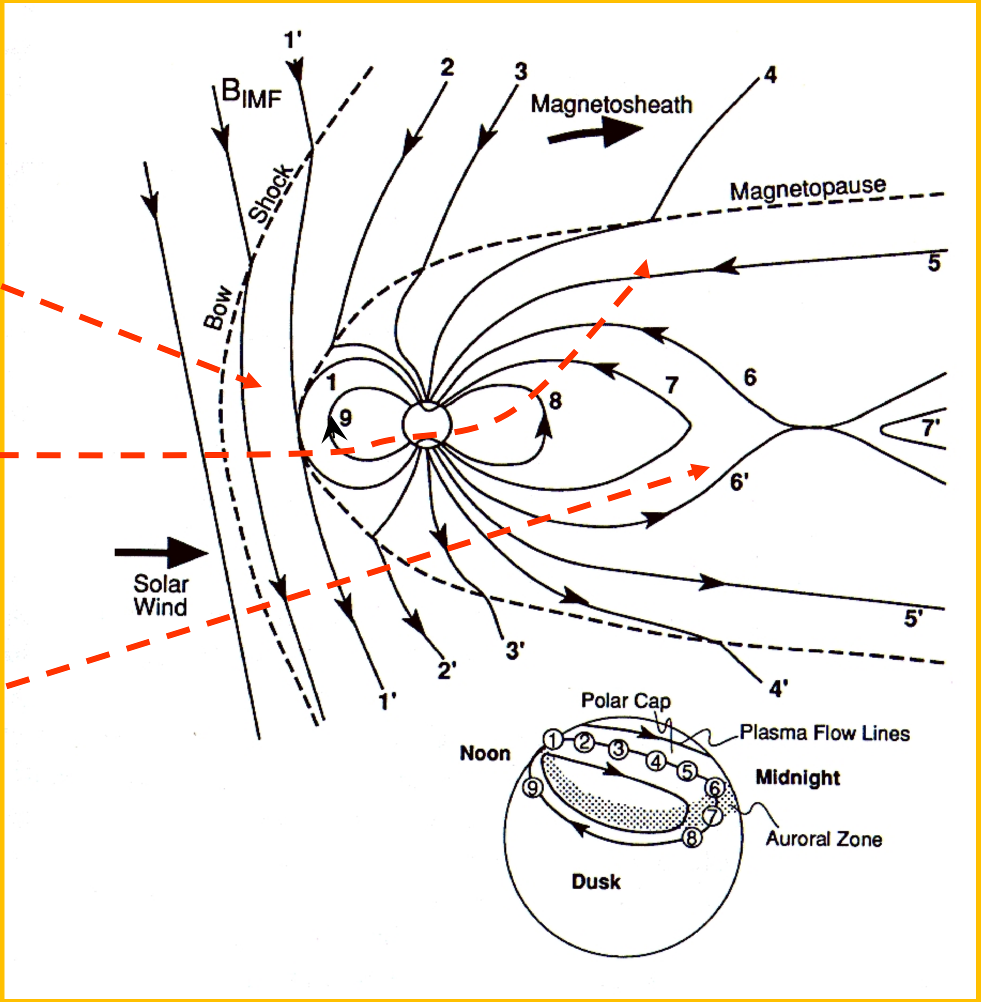
The total magnetic energy then decreases with time:

$$W_B = \int_{-\infty}^{\infty} \frac{B^2}{2\mu_0} dz$$

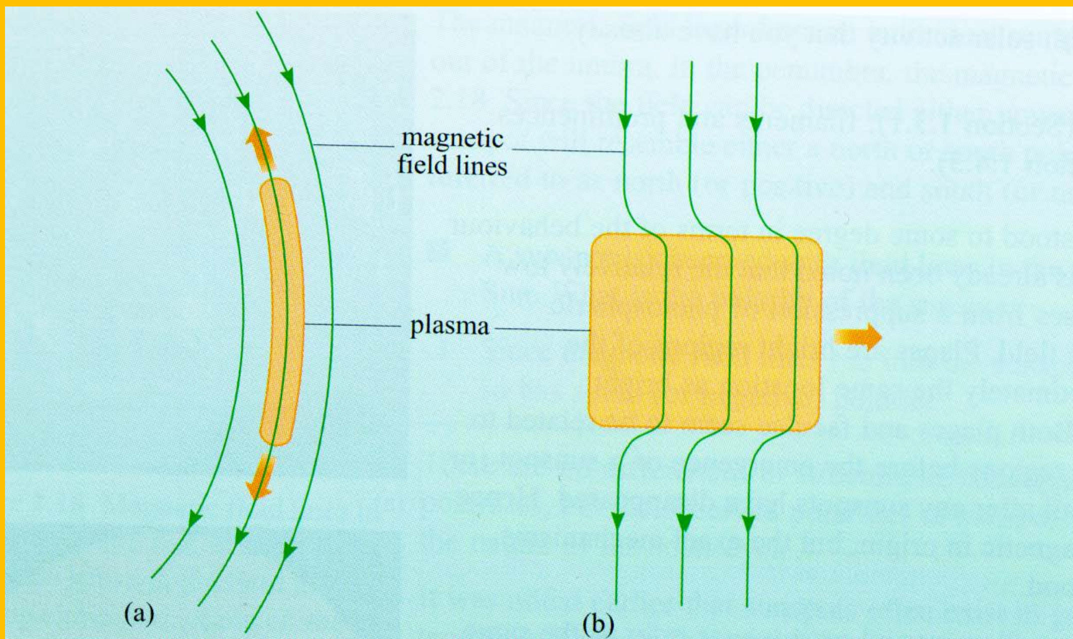
The magnetic energy is converted into heat and kinetic energy in 2D

# 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.



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




Depends on relative energy density (pressure)

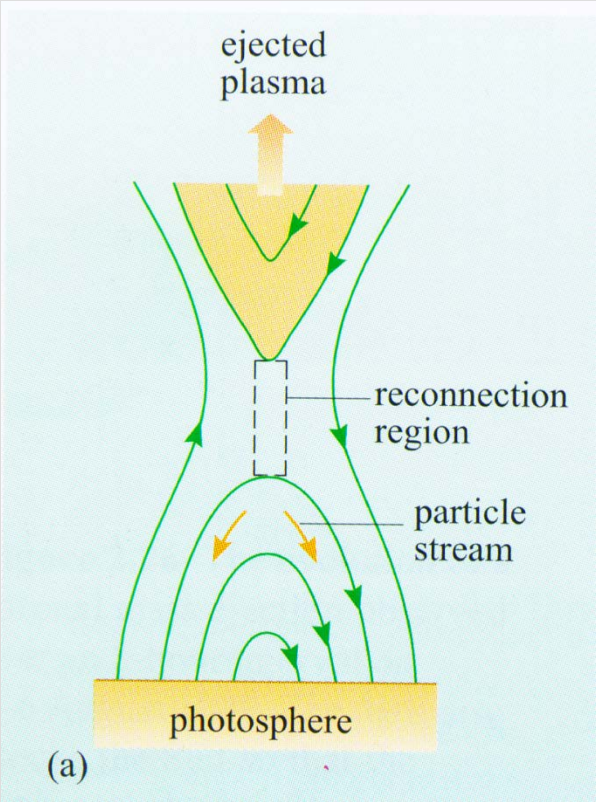
$$p_{pl} = nk_B T$$

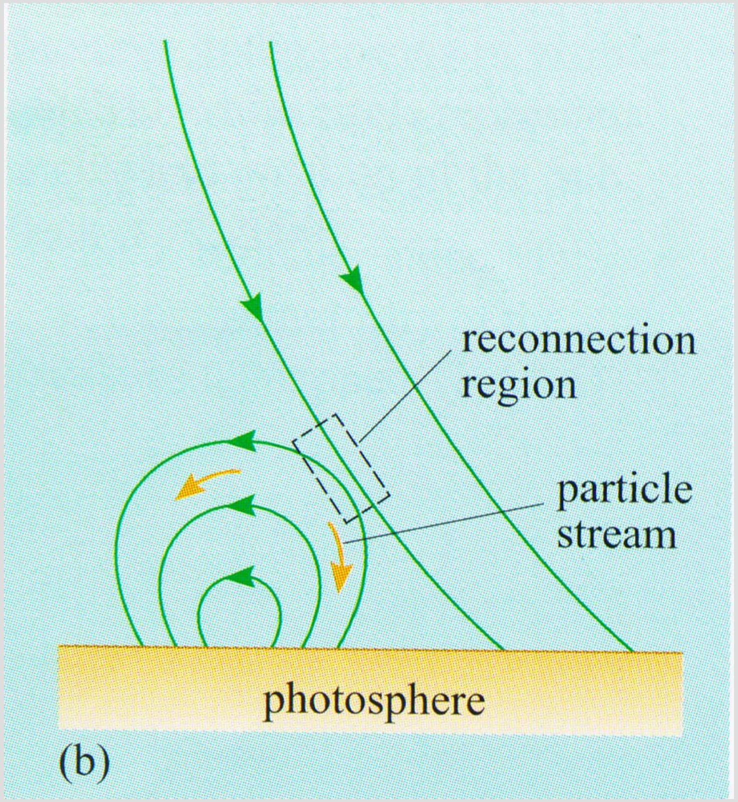
$$p_B = \frac{B^2}{2\mu_0}$$

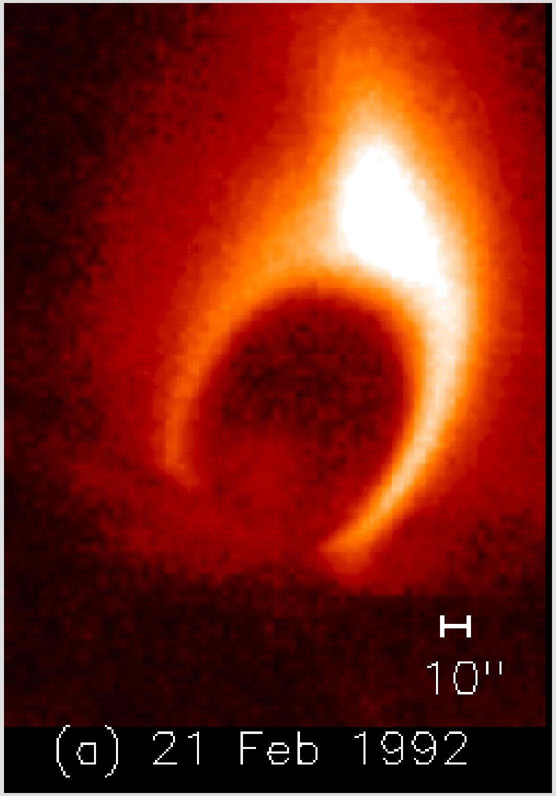
$$\beta = \frac{p_{pl}}{p_B}$$

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

# Solar flare
## *energization mechanism*



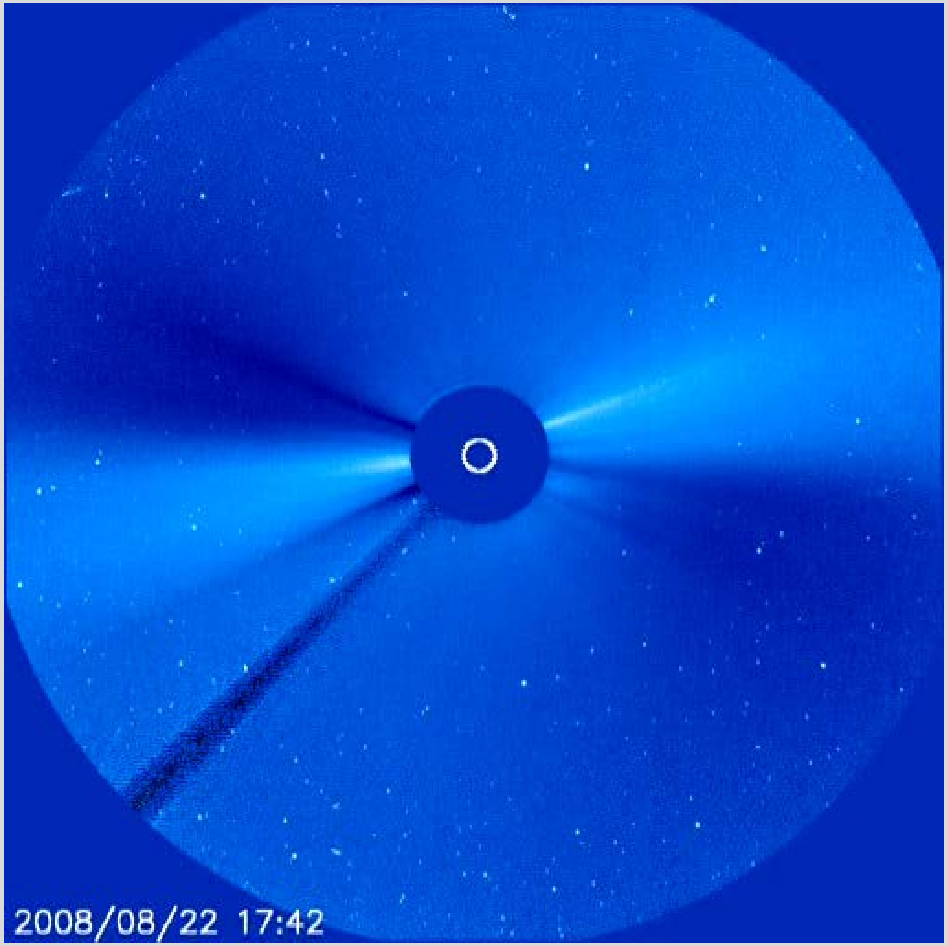




Two possible reconnection geometries

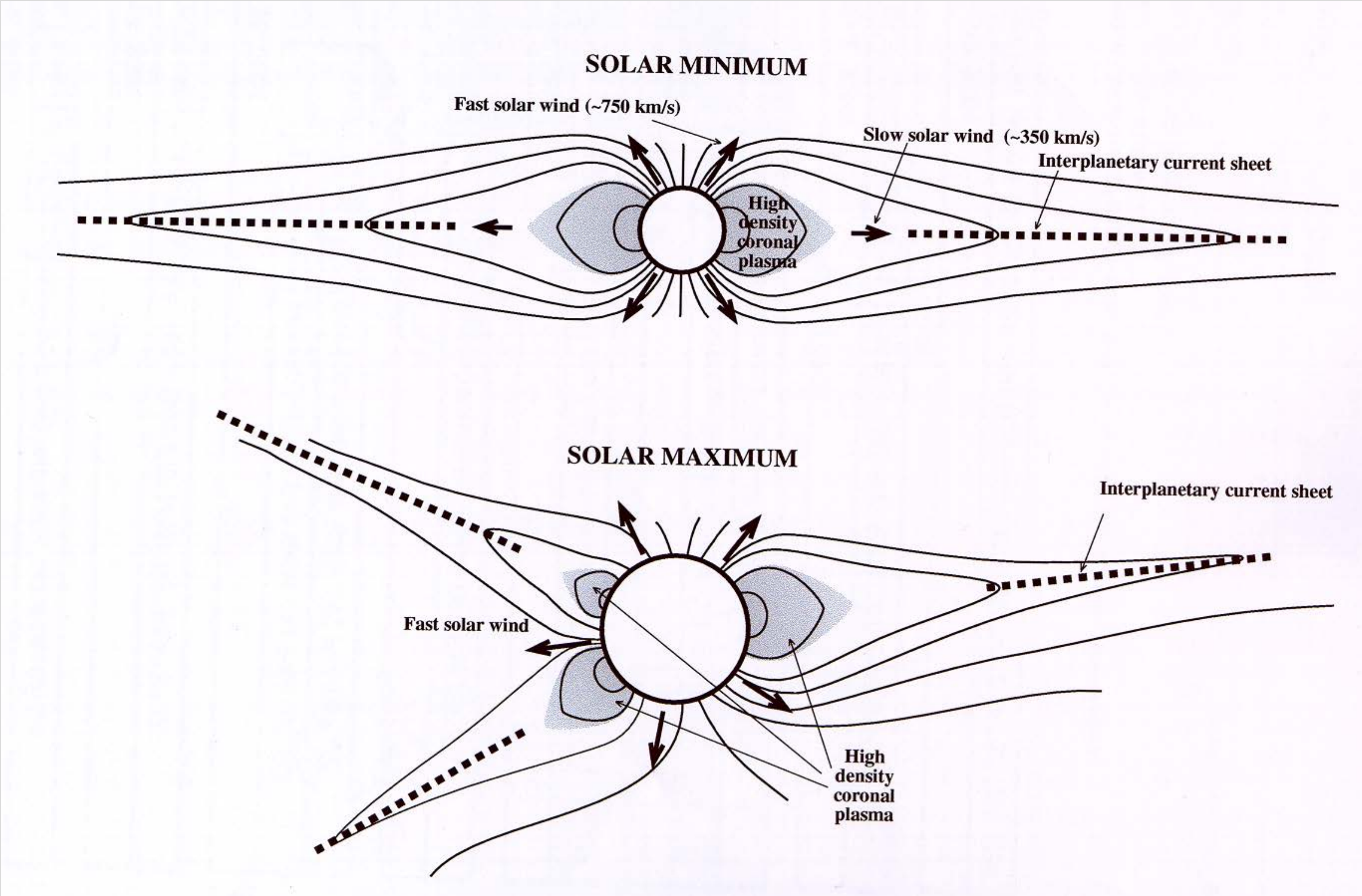
# Solar wind

*Corona continuously merges into solar wind*




**Solar and Heliospheric Observatory (SOHO)**
*LASCO C3 Coronagraph Movie*

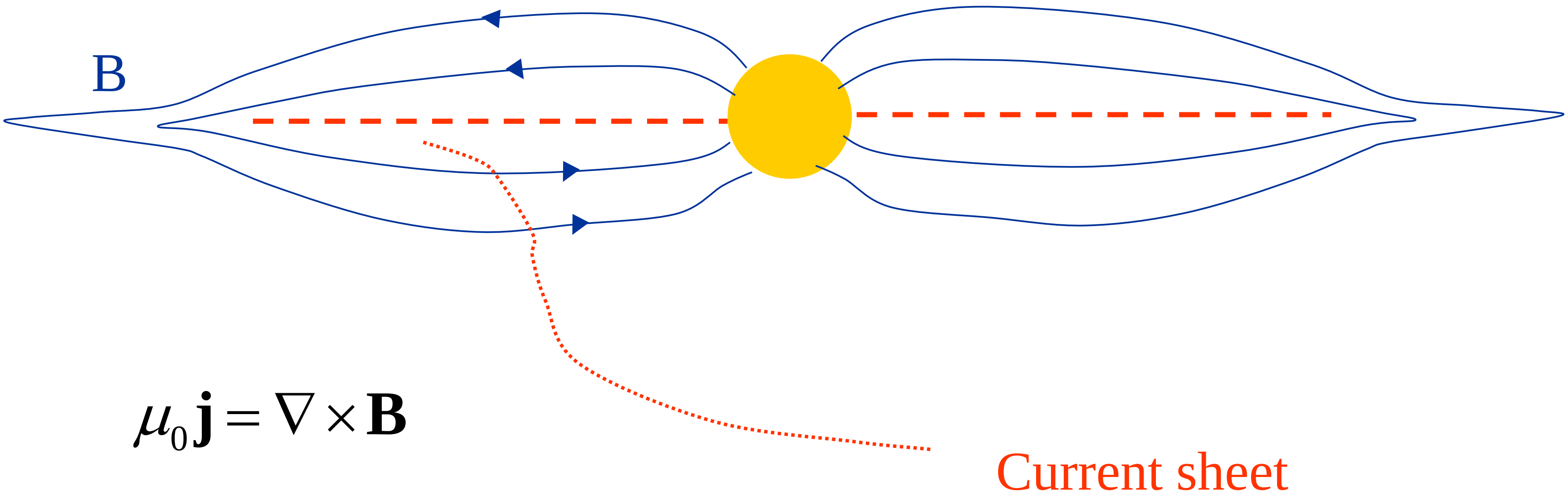
# Solar wind



SOLAR MINIMUM
Fast solar wind (~750 km/s)
Slow solar wind (~350 km/s)
Interplanetary current sheet
High density coronal plasma
SOLAR MAXIMUM
Interplanetary current sheet
Fast solar wind
High density coronal plasma

# Solar wind

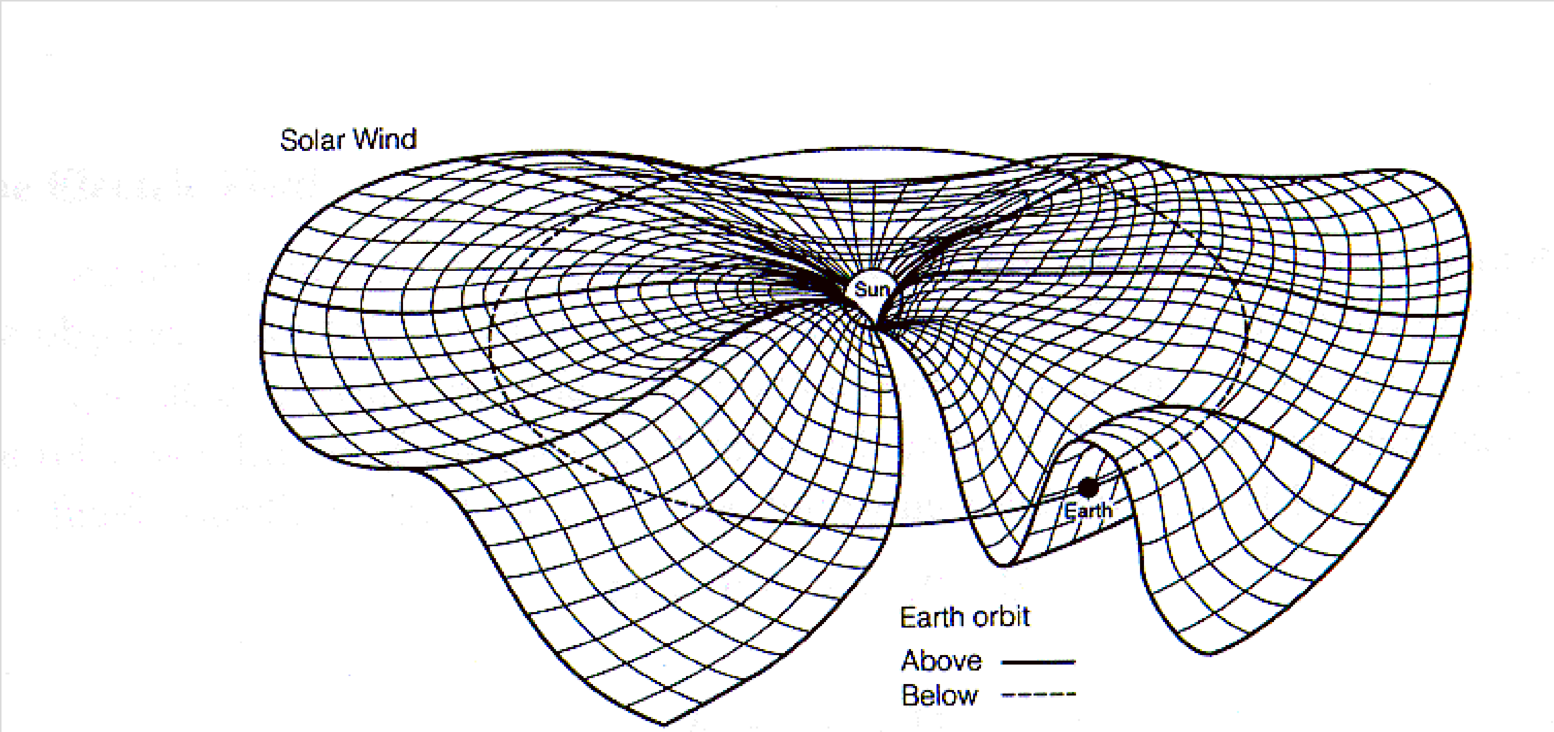
Interplanetary current sheet




$$\mu_0 \mathbf{j} = \nabla \times \mathbf{B}$$

# Solar wind

***Interplanetary current sheet***




**Later we will see that the N-S component of the interplanetary magnetic field (IMF is important for the coupling between solar wind and magnetosphere)**

# Solar wind

## *Some basic facts*

## Average values

$n_p = 8\ cm^{-3}$

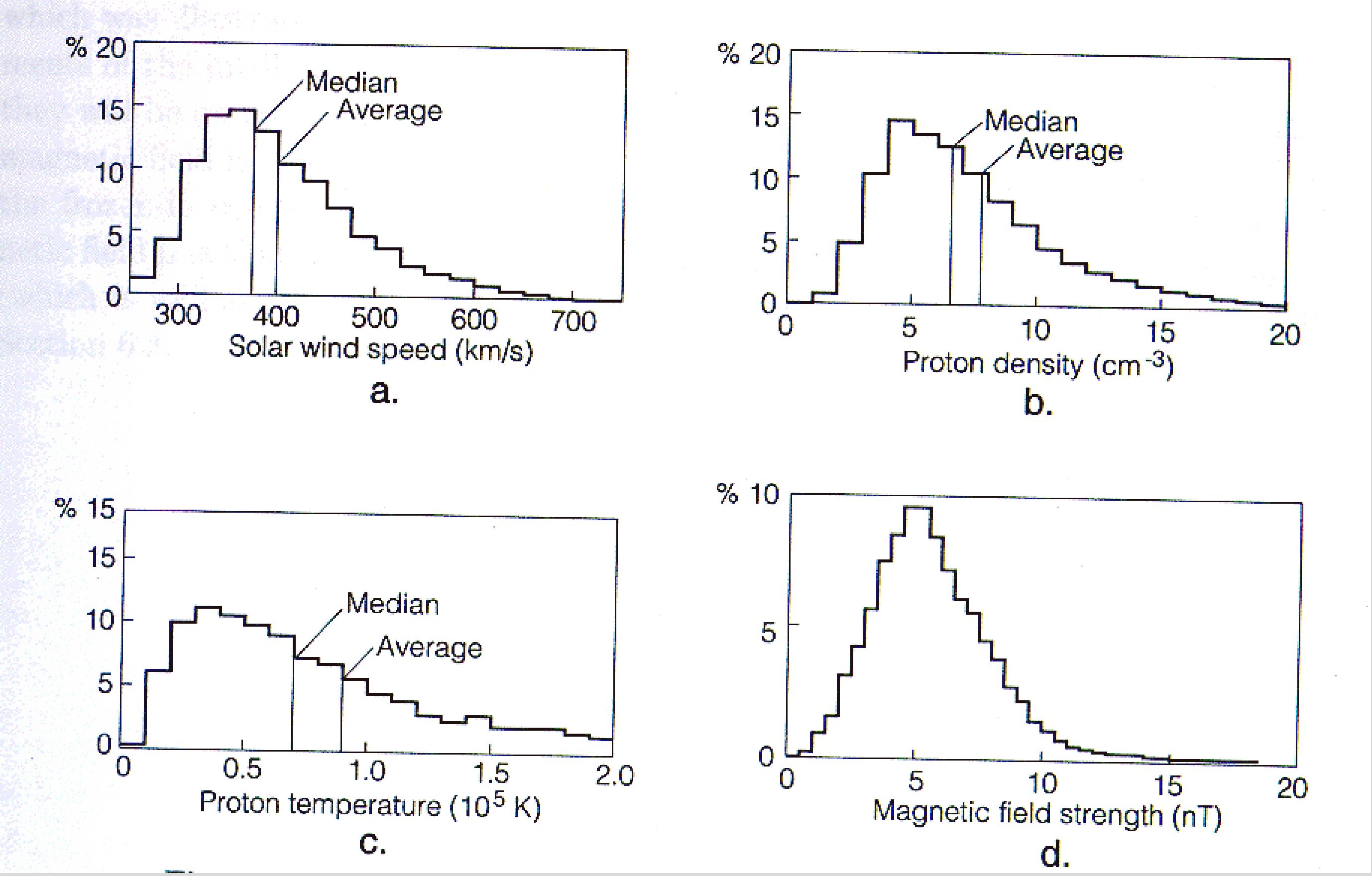
$v = 320\ km/s$

$T_p = 4 \cdot 10^4\ K$

$T_e = 10^5\ K$

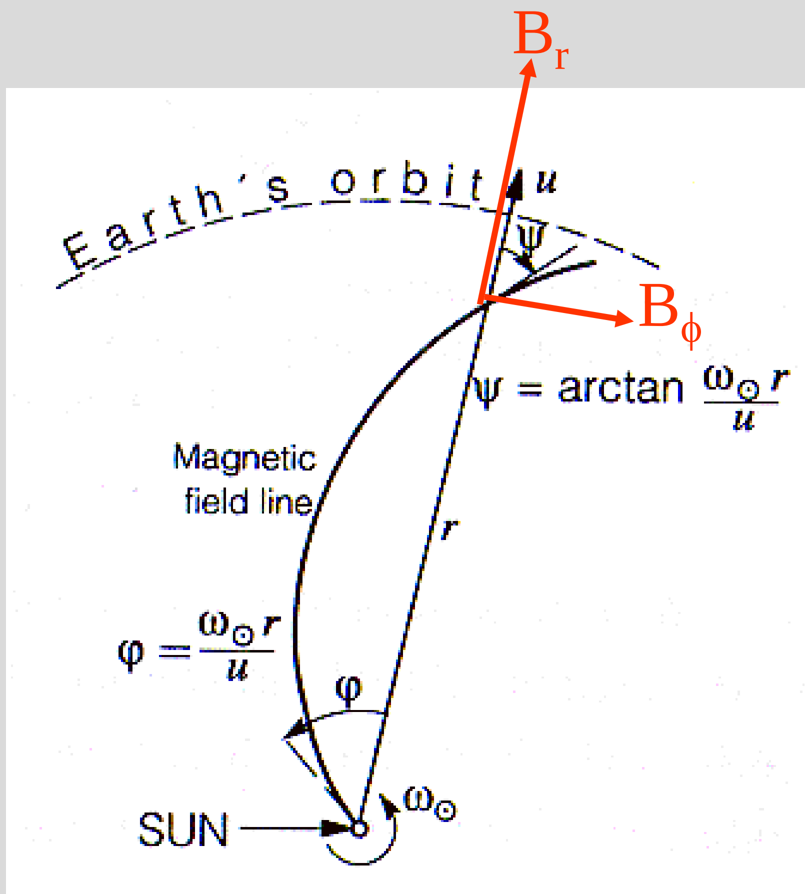
$B = 5\ nT$

$\Phi_K = \rho v^3/2 = 0.22\ mW/m^2$



# Solar wind

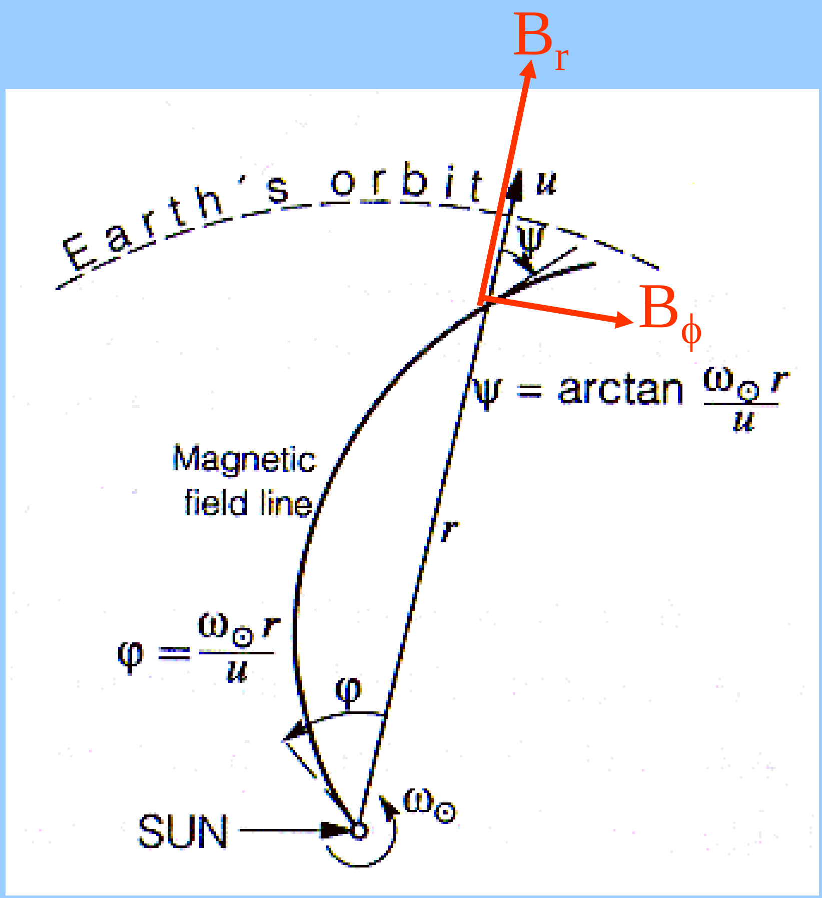
### *Parker spiral*




Archimedean spiral:

$$\frac{B_\phi}{B_r} = \tan\psi = \left(\frac{\omega r}{u_{SW}}\right)$$

Use rotation period $T$ of sun: $T = 27$ days




$r = 1$ A.U.

# What is the angle $\Psi$ at Earth's orbit for a typical solar wind speed?

Yellow ≈ 50 °

Red ≈ 80 °

Blue ≈ 1 °

Green ≈ 10 °

$$\Psi = \arctan\left(\frac{\omega r}{u}\right)$$

What is ω?

$$\omega = 2\pi f = \frac{2\pi}{T} = \frac{2\pi}{27 \cdot 24 \cdot 60 \cdot 60} = 2.7 \cdot 10^{-6} s^{-1}$$

$$\Psi = \arctan\left(\frac{\omega r}{u}\right) = \arctan\left(\frac{2.7 \cdot 10^{-6} \cdot 1.5 \cdot 10^{11}}{320 \cdot 10^{3}}\right) = \arctan(1.27) = 52^{\circ}$$

Yellow

# Classification of plasmas

- **High density plasmas**
  - $\lambda << \rho$
  - *magnetic field not important, collisions dominate, isotropic.*
- **Medium density plasmas**
  - $\rho << \lambda << l_c$
  - *magnetic field important, collisions important, anisotropies.*
- **Low density plasmas**
  - $l_c << \lambda$
  - *magnetic field important, anisotropies, uninhibited motion along magnetic field*

$\rho$: *gyro radius*

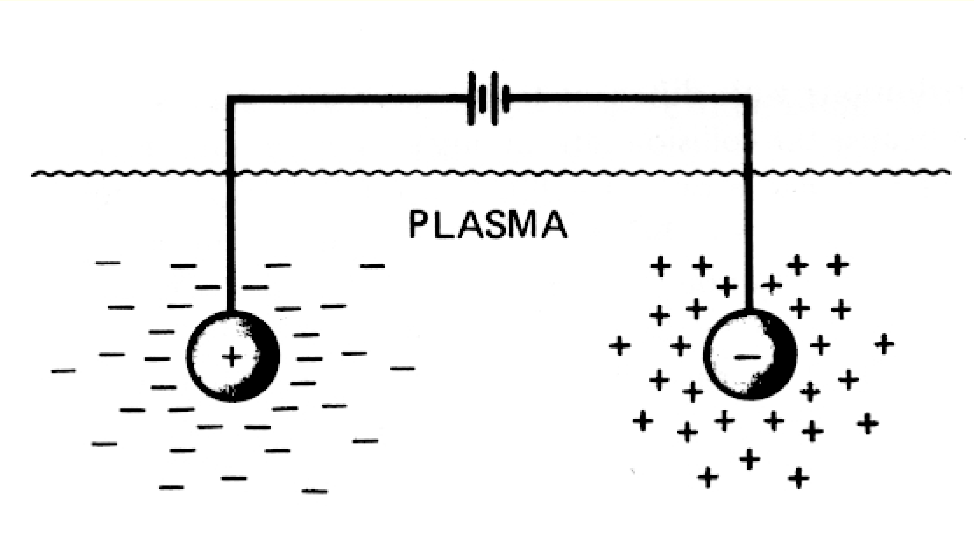
$\lambda$: *mean free path*

$l_c$: *dimension of the plasma*

# Plasma models/descriptions

- Single particle motion
- Computer simulations of many-particle dynamics
- Generalization of statistical mechanics (kinetic theory)
- Generalization of fluid mechanics: *Magneto-hydrodynamics (MHD)*

# Quasineutrality




$$\frac{\Delta n}{n} = \frac{(n_e - n_i)}{n_e} < \left(\frac{\lambda_D}{l_c}\right)^2$$

$$\Phi = \Phi_0 e^{-x/\lambda_D}$$

Debye length

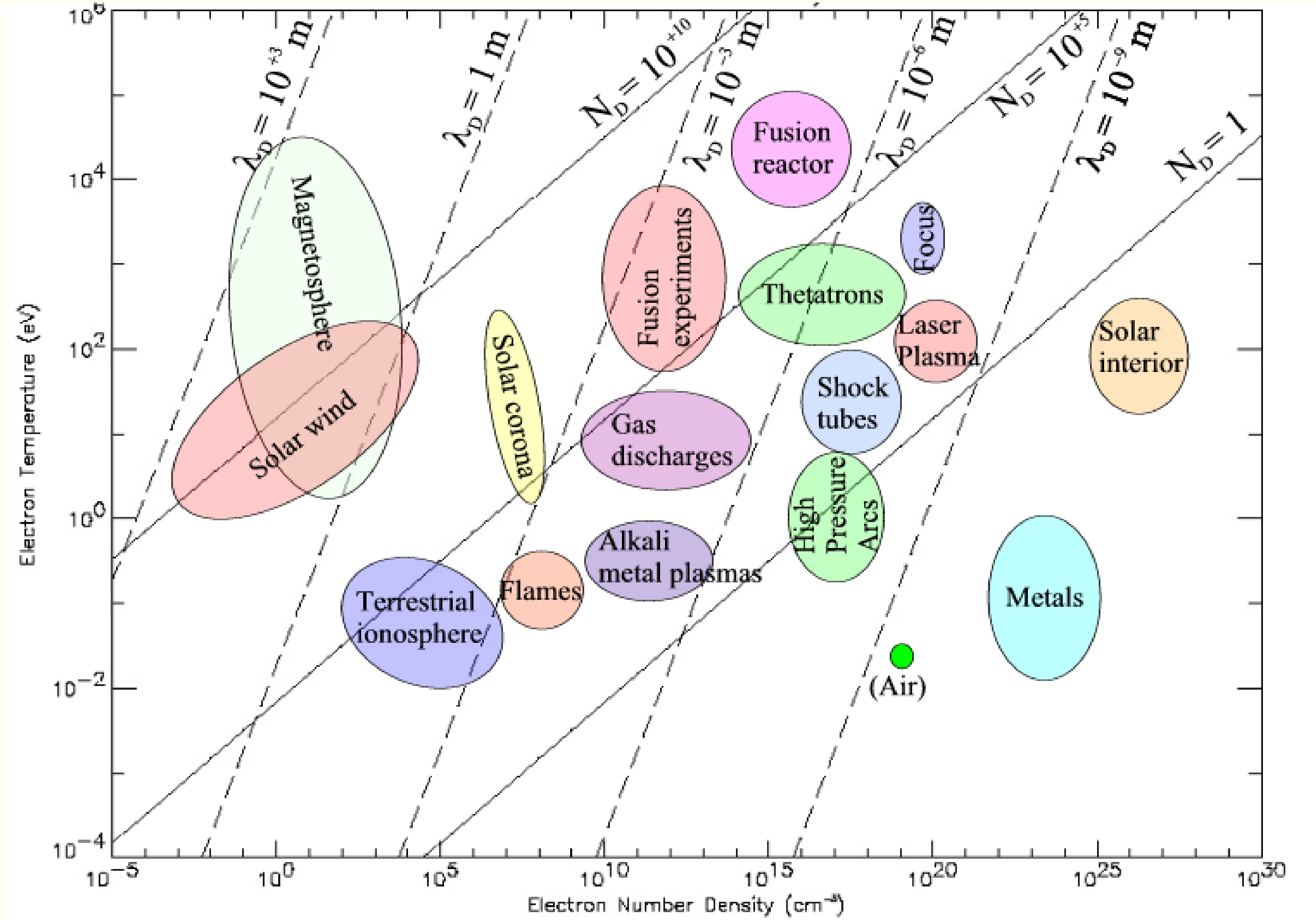
$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{n_e e^2}}$$

$$l_C >> \lambda_D \quad \Rightarrow$$

Plasma close to neutral:

$$n_e \approx n_i$$

# Debye lengths



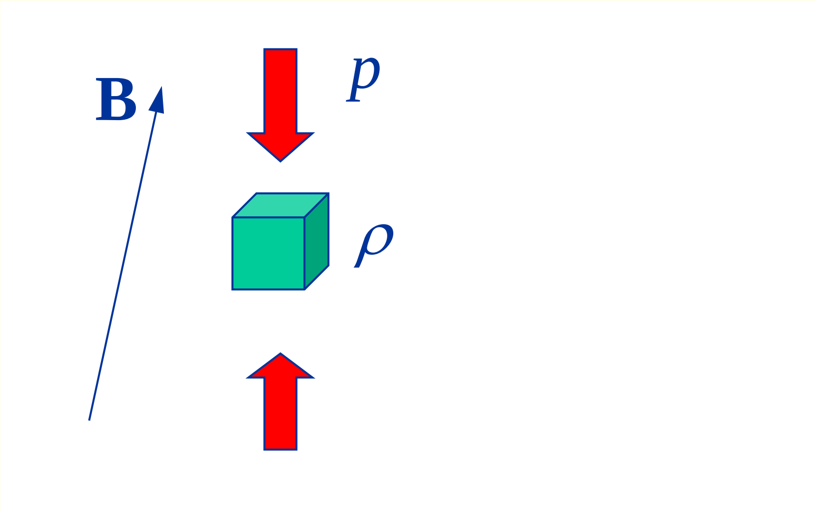
# Plasma physics

# *Magnetohydrodynamics (MHD)*

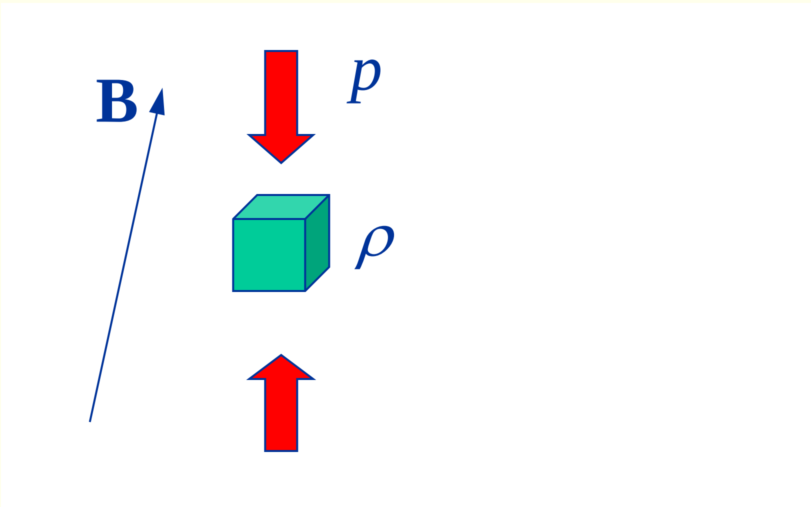
MHD is a combination of

- *fluid-/hydrodynamics* (which is based on Newton's laws of motion)
- *Maxwell's equations* (electrodynamics)

applied on a plasma volume element.



# Magnetohydrodynamics (MHD)




For a volume element of plasma:

$$\mathbf{F} = m\mathbf{a} \quad \Rightarrow$$

quasineutrality

$$-\nabla p + n_e q \mathbf{v}_e \times \mathbf{B} + \cancel{\rho_e \mathbf{E}} = \rho \frac{d\mathbf{v}}{dt} \quad \Rightarrow$$

$$(1) \qquad \rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B}$$

# Magnetohydrodynamics (MHD)

(1) $$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B}$$

This together with two of Maxwell's equations and Ohm's law make up the most common MHD equations:

(2) $$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

(3) $$\nabla \times \mathbf{B} = \mu_0 \left( \mathbf{j} + \cancel{\varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}} \right)$$

Only consider slow variations

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

# Magnetohydrodynamics (MHD)

(1) $$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B}$$

In equilibrium:

$$0 = -\nabla p + \mathbf{j} \times \mathbf{B} \quad \Longleftrightarrow$$

$$-\nabla p + \frac{1}{\mu_0}(\nabla \times \mathbf{B}) \times \mathbf{B} = 0$$

$$-\nabla p - \nabla\left(\frac{B^2}{2\mu_0}\right) + \frac{1}{\mu_0}(\mathbf{B} \cdot \nabla)\mathbf{B} = 0$$

Represents tension in magnetic field

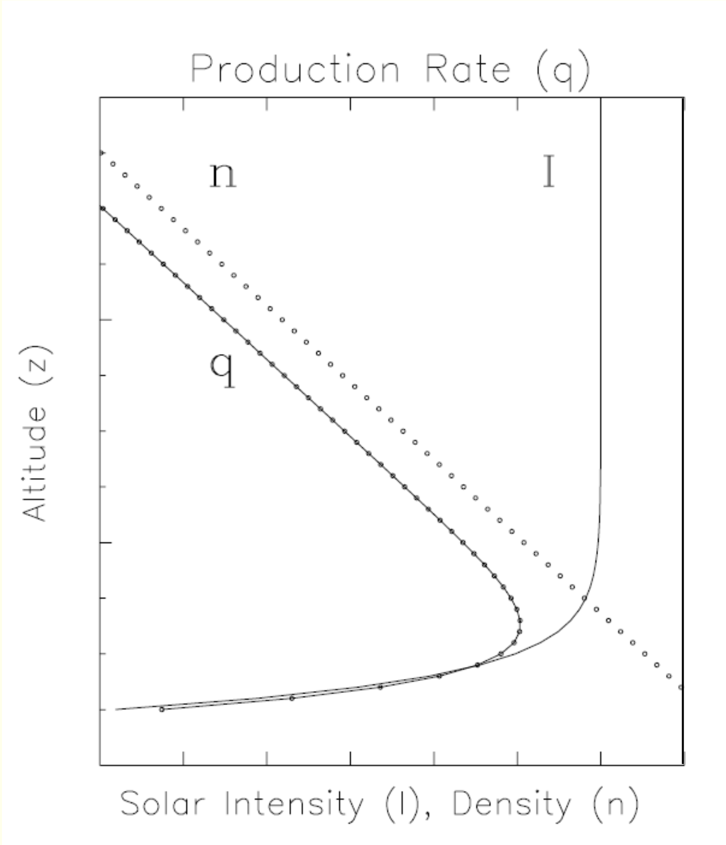
If magnetic tension = 0

$$p + \frac{B^2}{2\mu_0} = konst$$

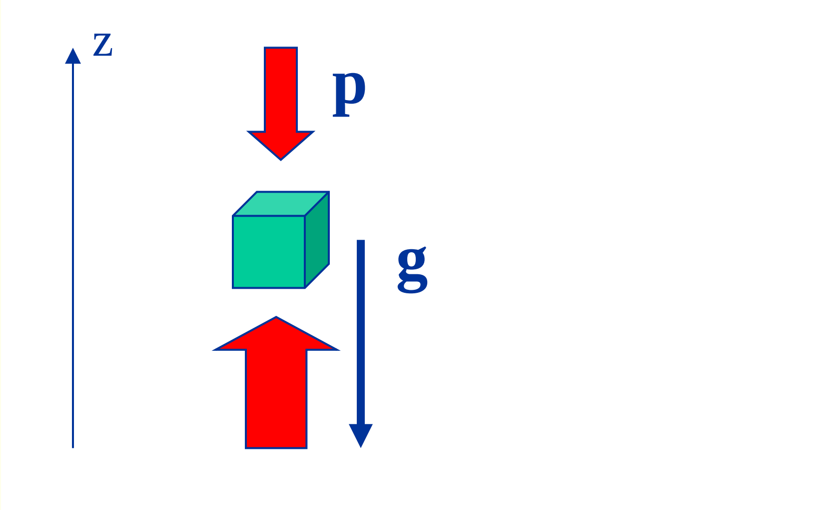
Magnetic pressure

# The ionosphere

# Basic principle for creation of ionospheric layer



# Atmospheric scale height




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

$$p = nk_B T = \frac{\rho k_B T}{m}$$ ideal gas law

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

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

Scale height

$H = k_B T/gm$

# Scale height

$$H = k_B T/gm$$

What is the approximate scale height in the atmosphere right here, right now?

*(0° C = 273 K)*

| | | | |
|---|---|---|---|
| Blue | 1 km | Yellow | 30 km |
| Green | 9 km | Red | 100 km |

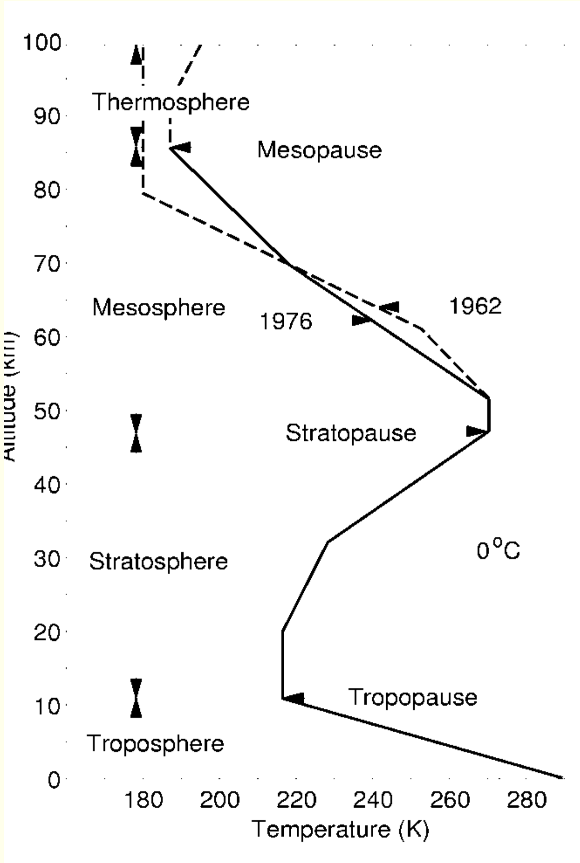
$$H = k_B T/gm = (1.38\cdot10^{-23} \cdot 290)/(9.81 \cdot 14 \cdot 2 \cdot 1.67\cdot10^{-27}) =$$

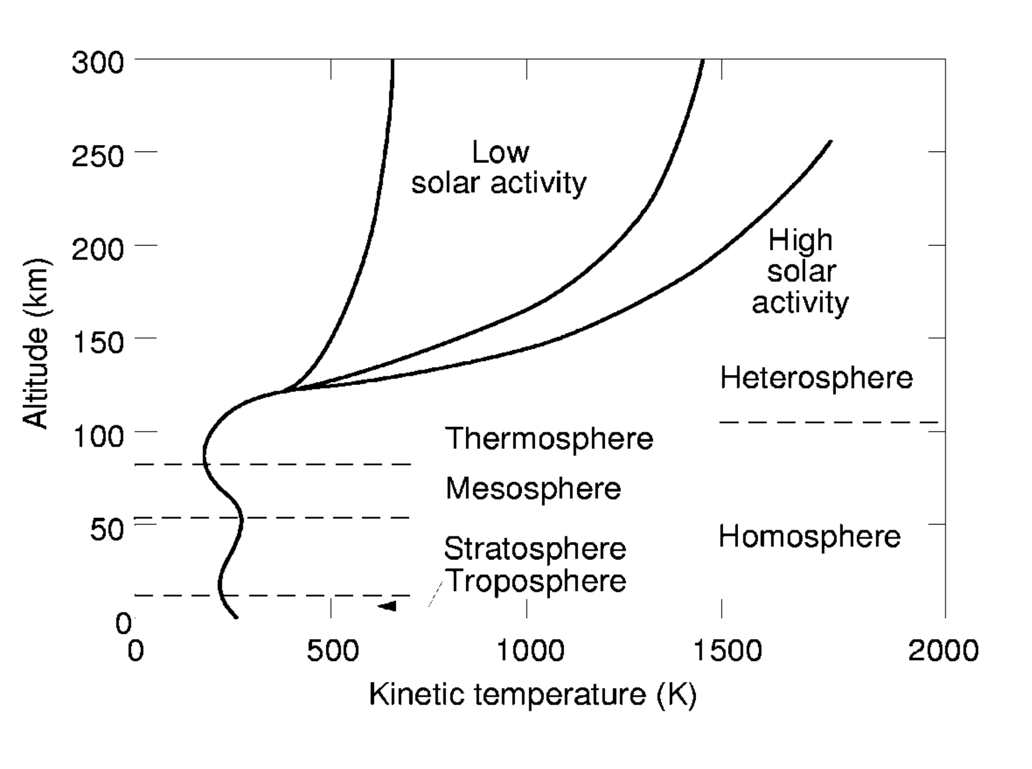
$$= 8724 \text{ m} \approx 9 \text{ km}$$

Green

What did we neglect when we derived the scale height?

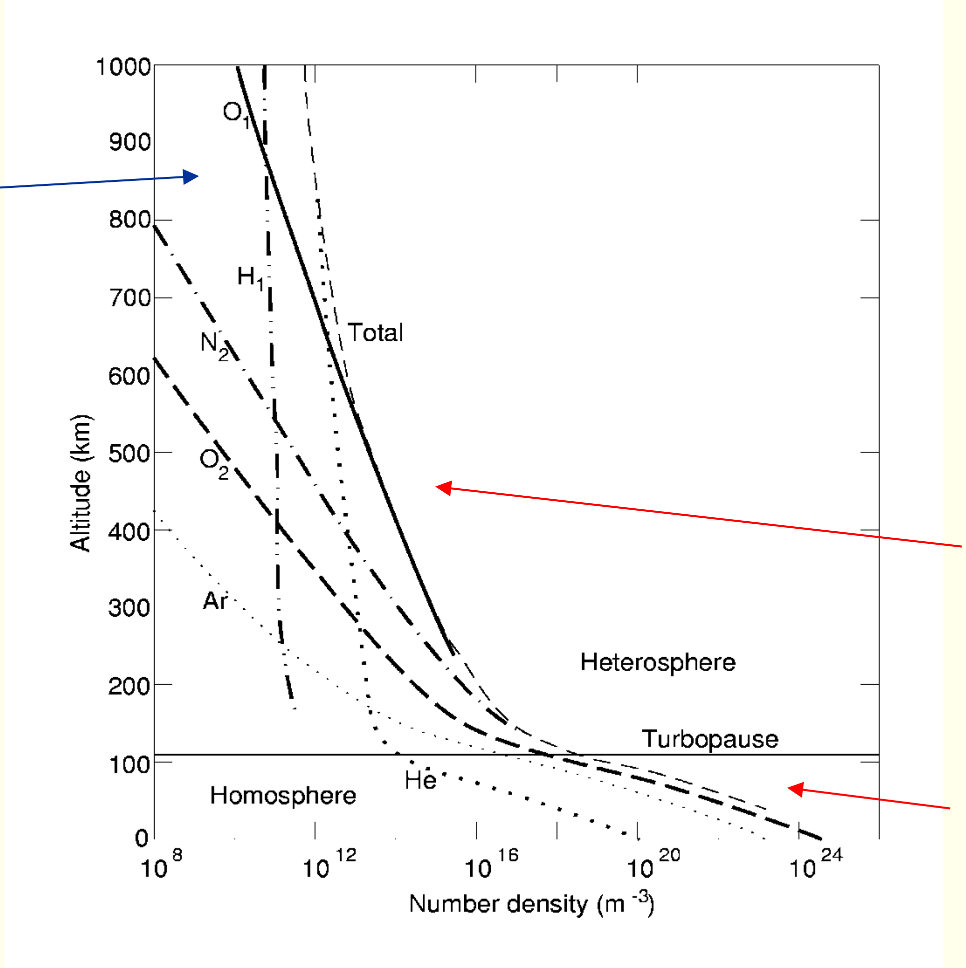
# Temperature profile



# Atmospheric composition

Longer scale height due to higher temperature




Separate scale heights for different components

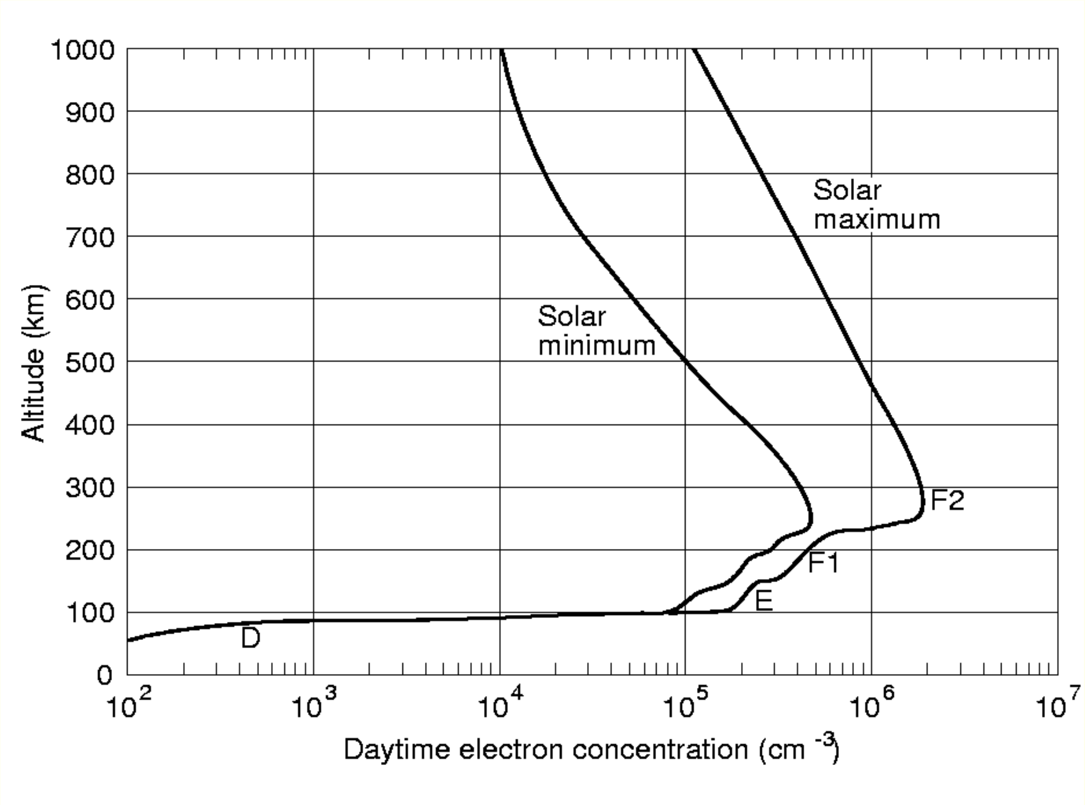
Turbulent mixing – one scale height

# Ionosphere History

- The ionized, electrically conducting part of the upper atmosphere
- The ionosphere is a **plasma**

- Stewart, 1882: Explained variations in the geomagnetic field
- Kenelly & Heavyside, 1902: explained Marconis transatlantic radio communication experiments
- Appleton & Barnett: experimental proof

# Altitude distribution of electron density ($n_e$)



# Continuity equation = conservation of ?

$$\frac{\partial n_e}{\partial t} = q - r - \cancel{\nabla \cdot (n_e \mathbf{v}_e)}$$

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

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

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

# Ionization and recombination

# Continuity equation

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

$$q = a_i I n_n$$

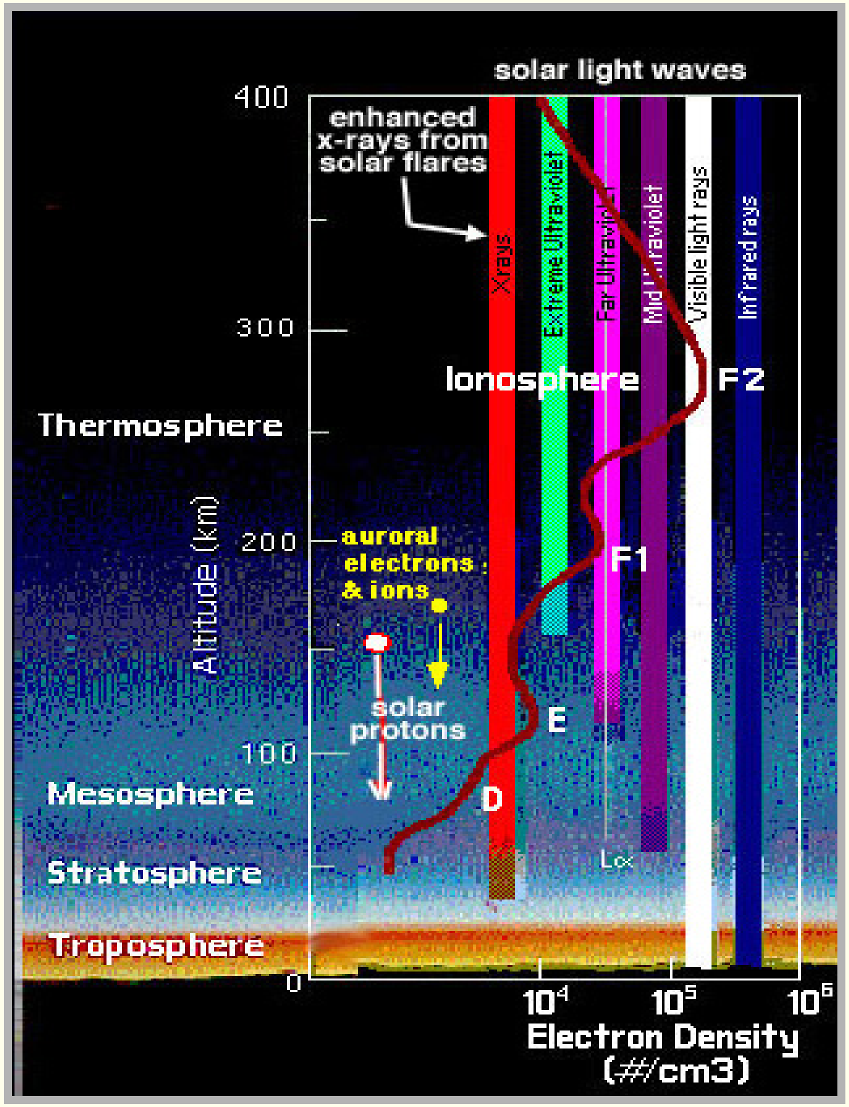
Ionization ($m^{-3}s^{-1}$)

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




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

# Derive Chapman layer

# Electron density in Chapman layer

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

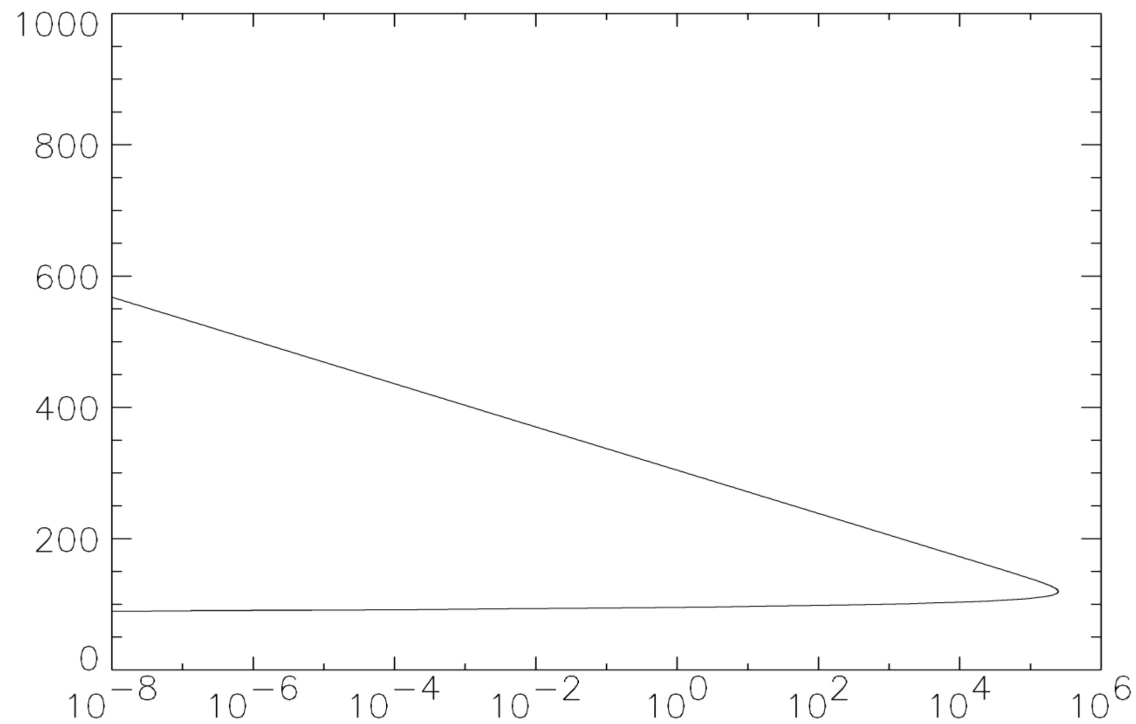
# What does it look like in reality?

- 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

$a_a = 9.3\times10^{-23}$ m$^2$
$a_i = 9.3\times10^{-23}$ m$^2$
$a_r = 3.0\times10^{-14}$ m$^3$s$^{-1}$
T = 270 K
$m = 16*2*m_p$
$n_0 = 2.7\times10^{25}$ m$^{-3}$
$I_0 = 3.6\times10^{13}$ photons m$^2$s$^{-1}$

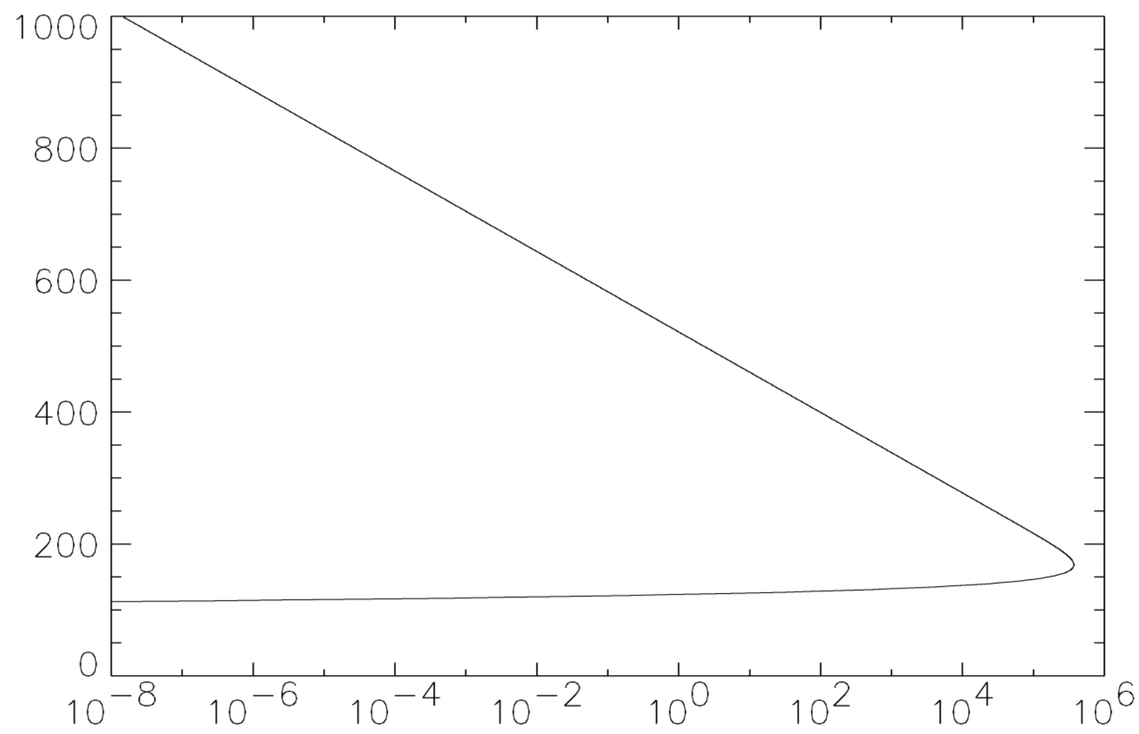



$N_2^+$ produced, but rapidly lost through charge exchange: $N_2^+ + O_2 \rightarrow N_2 + O_2^+$

## "F1-region" - simple model calculation

## $O_2$ dominating species, 30 nm UV radiation

$a_a = 9.3\times10^{-23}$ m$^2$
$a_i = 9.3\times10^{-23}$ m$^2$
$a_r = 3.0\times10^{-14}$ m$^3$s$^{-1}$
$T = 500$ K
$m = 16*2*m_p$
$n_0 = 2.7\times10^{25}$ m$^{-3}$
$I_0 = 1.5\times10^{14}$ photons/m$^2$/s



# ”F2-region” - simple model calculation

## O dominating species, 30 nm UV radiation

$a_a = 9.3\times10^{-23}$ m$^2$

$a_i = 9.3\times10^{-23}$ m$^2$

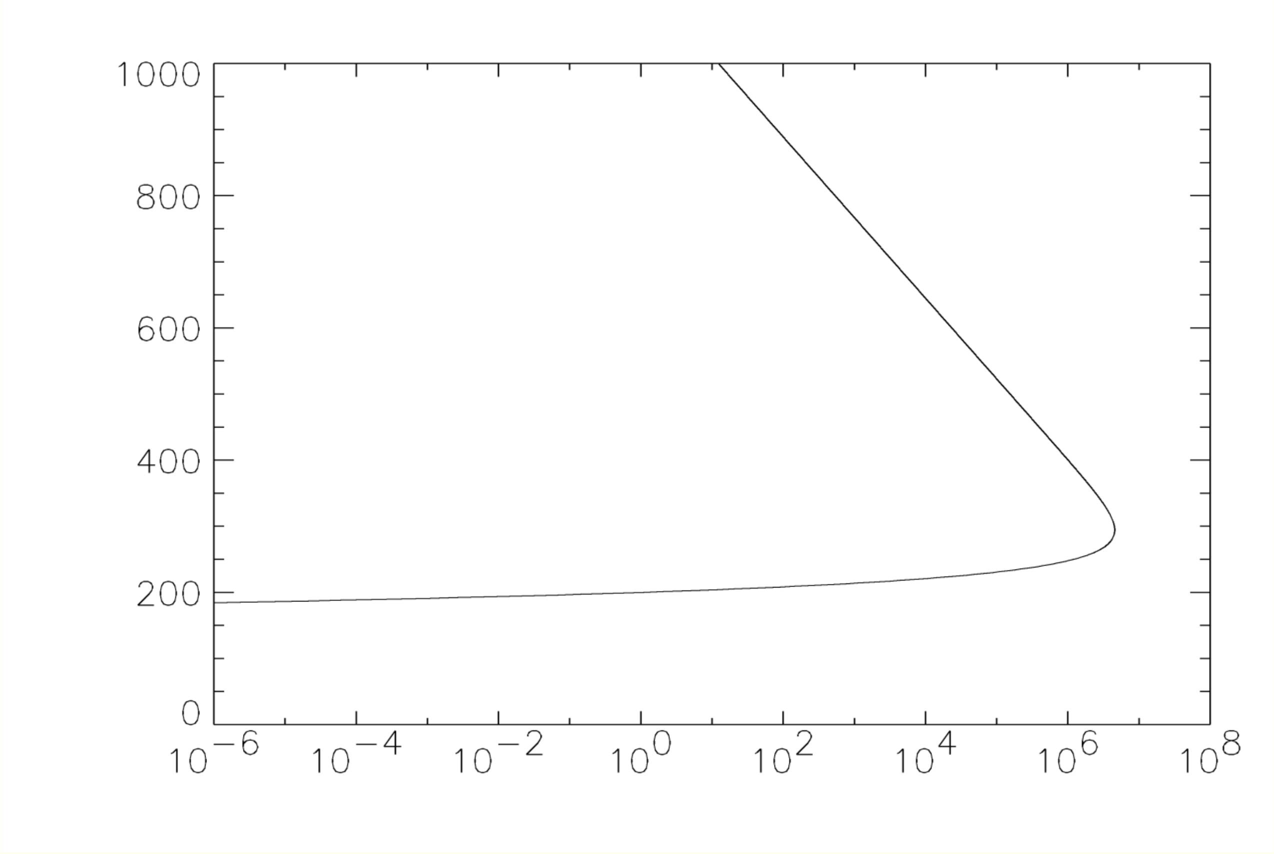
$a_r = 1.0\times10^{-16}$ m$^3$s$^{-1}$

T=500 K

$m = 16*m_p$

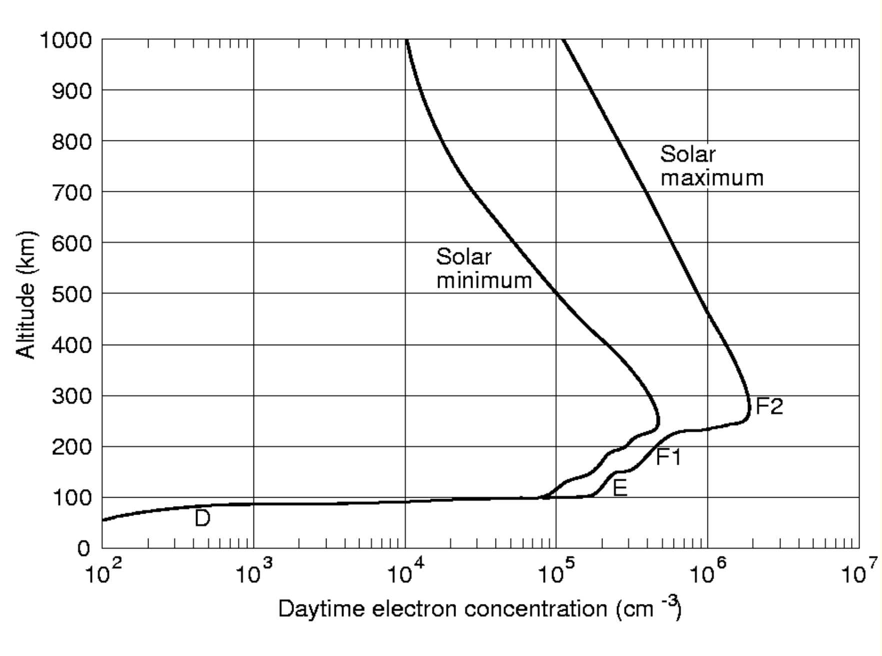
$n_0 = 2.7\times10^{25}$ m$^{-3}$

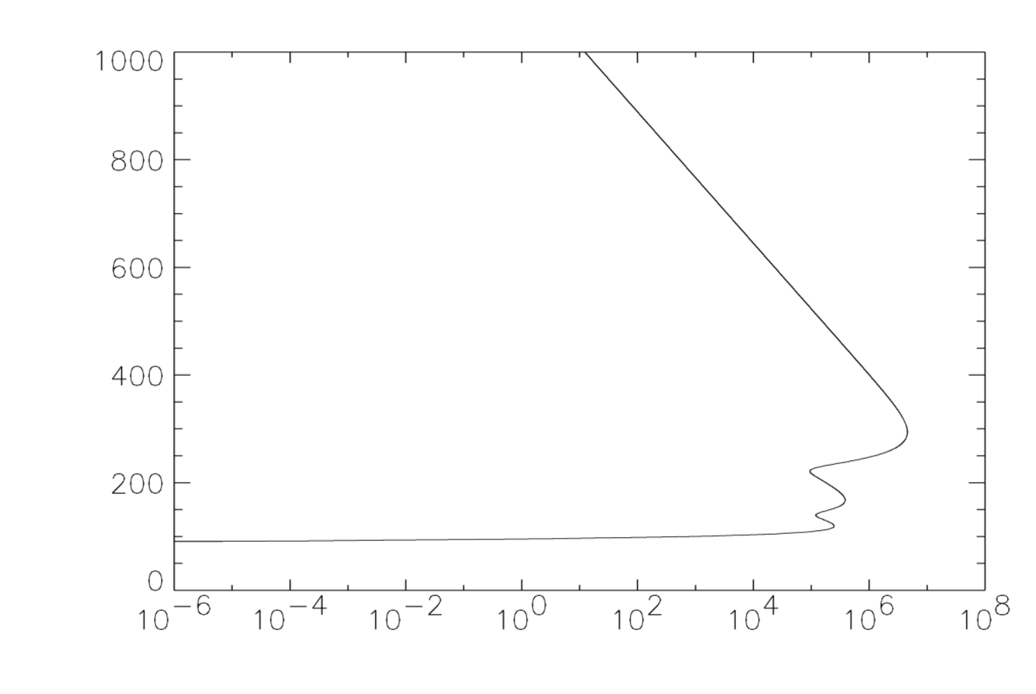
$I_0 = 1.5 \times10^{14}$ photons/m$^2$/s



# 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 $\alpha$ (1215 Å) + cosmic radiation | Lyman $\beta$ (1025 Å) X-rays | UV | UV |

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

# Last Minute!