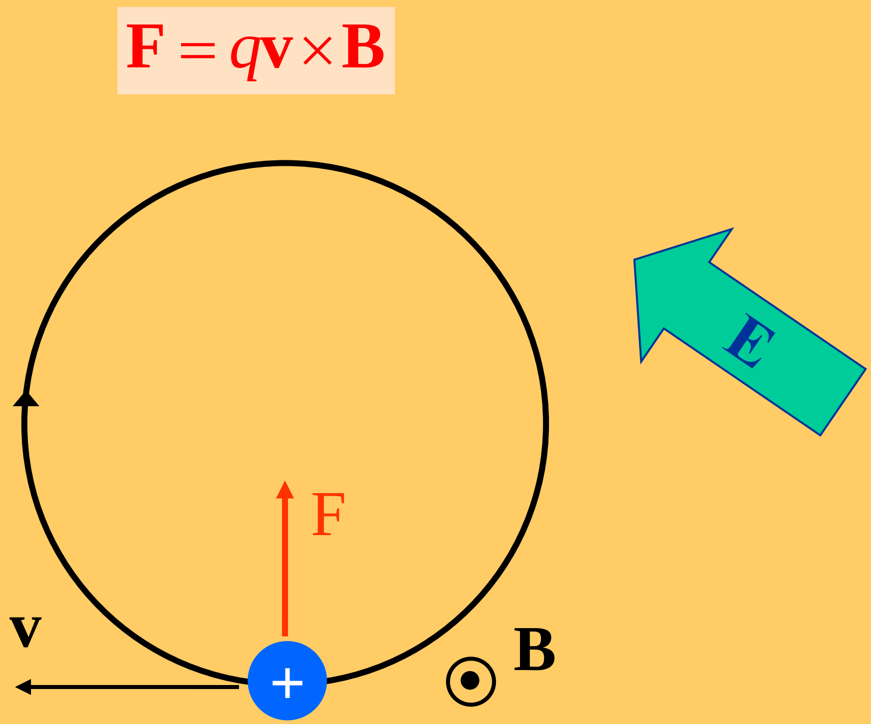
Think about this:



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

Last lecture (3)

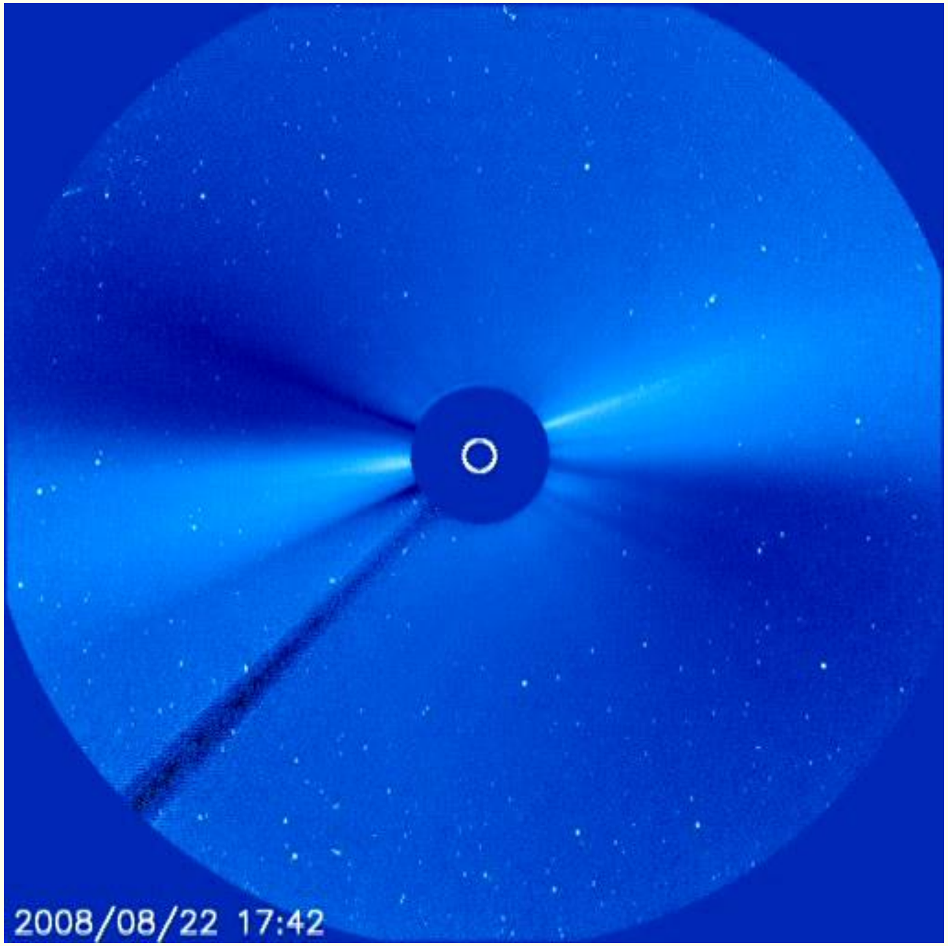
- Solar activity

Today's lecture (4)

- Solar wind – basic facts
- Solar wind – magnetic structure
- Ionosphere
  - layers
  - radio wave reflection

Solar wind

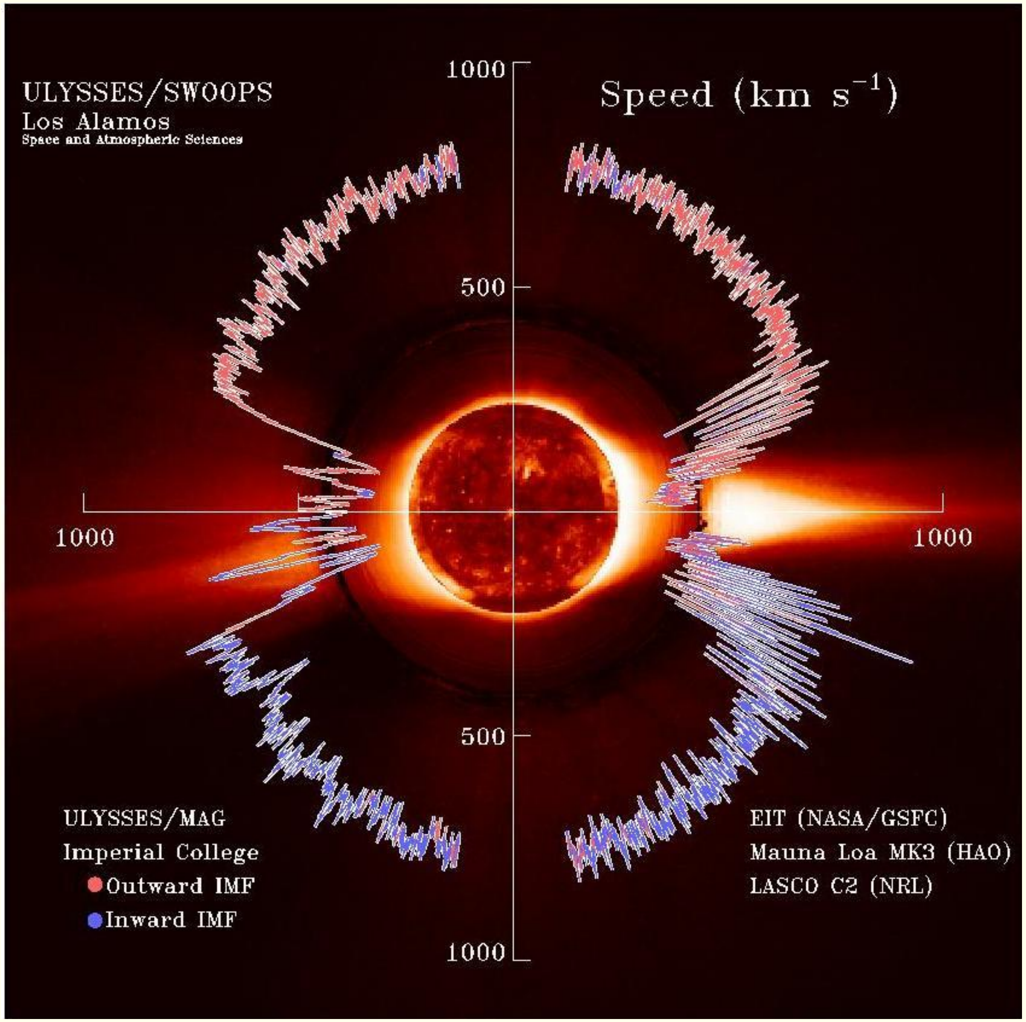
Corona continuously merges into solar wind



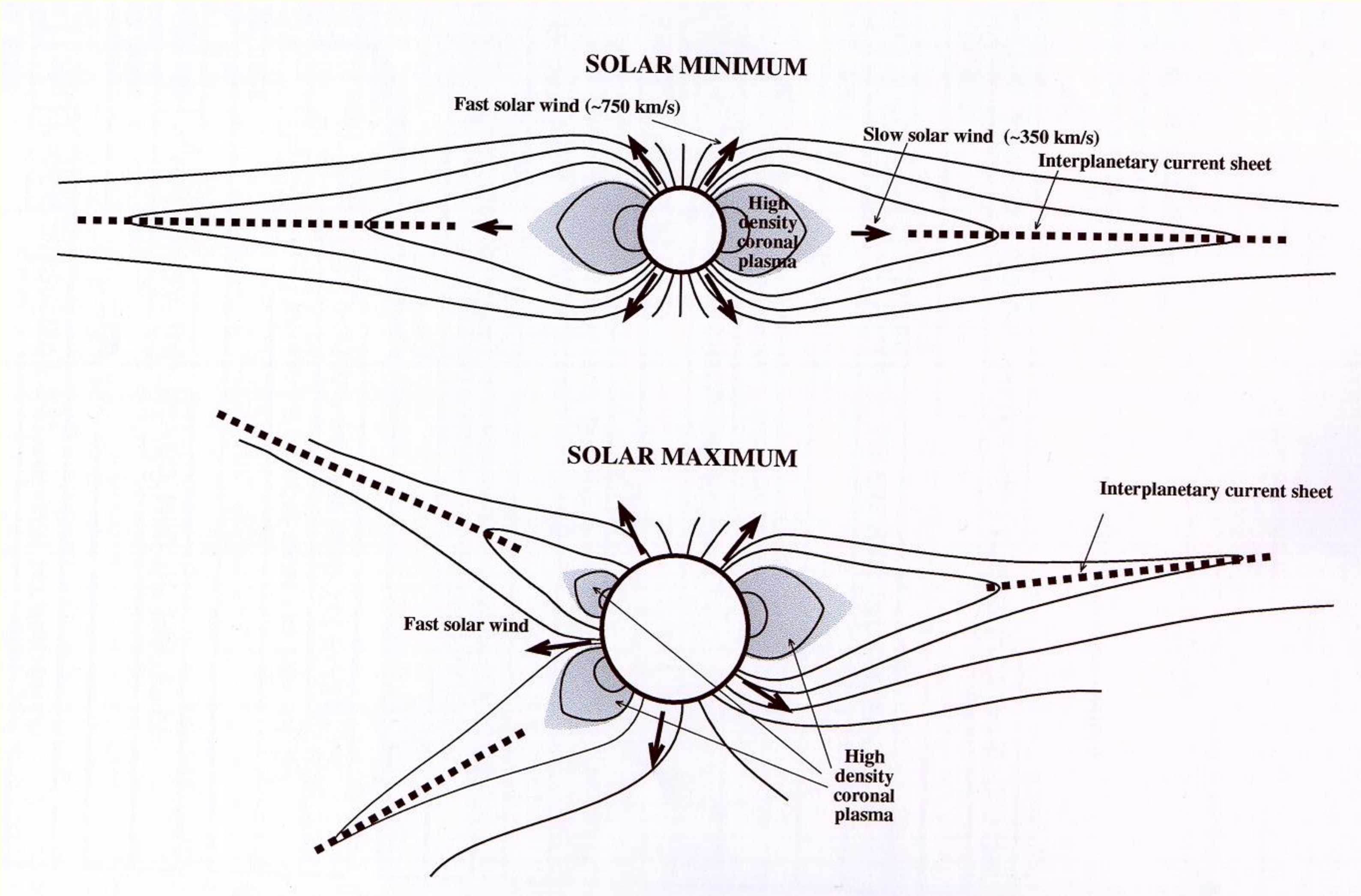
Solar and Heliospheric Observatory (SOHO)
LASCO C3 Coronagraph Movie

Solar wind

- **Fast solar wind in regions closer to poles**
- **Slow solar wind closer to equatorial plane**

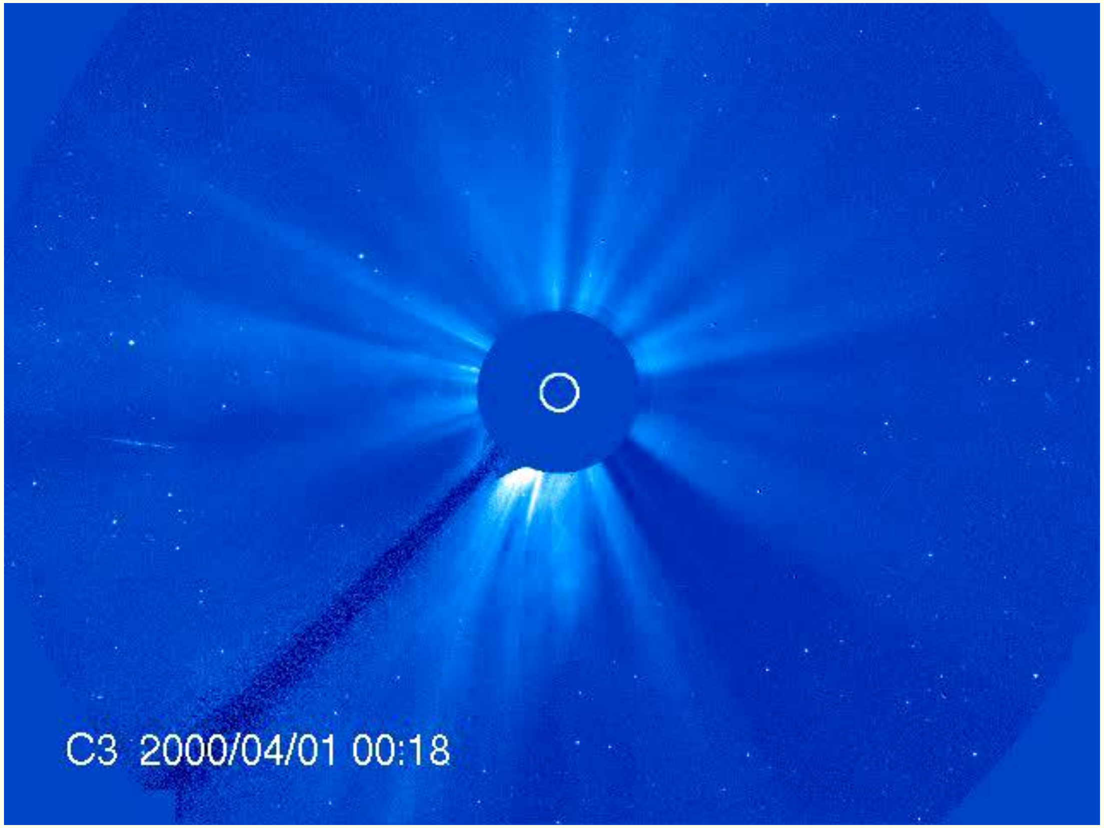


Solar wind



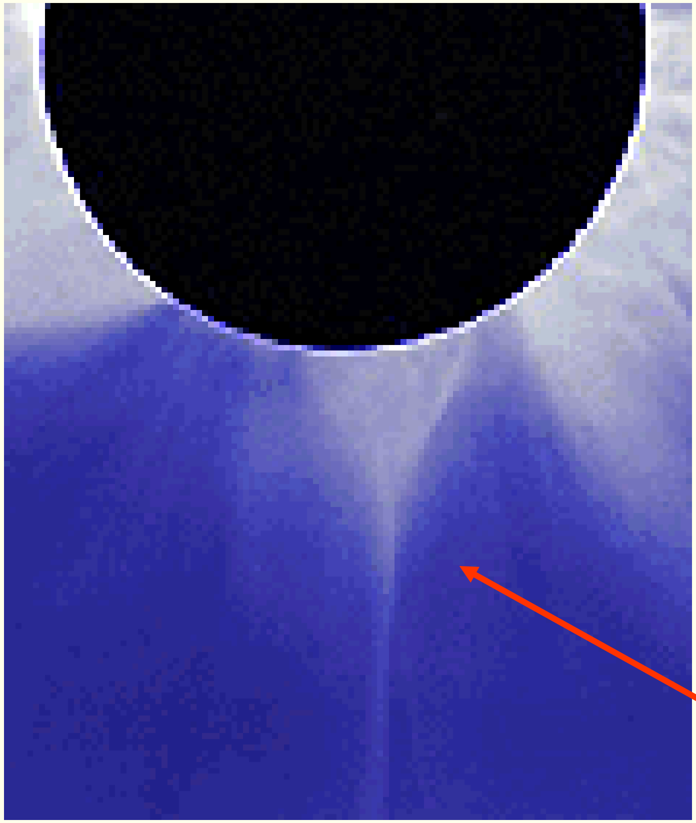
SOLAR MINIMUM
Fast solar wind (~750 km/s)
Slow solar wind (~350 km/s)
Interplanetary current sheet
High density coronal plasma
SOLAR MAXIMUM
Interplanetary current sheet
Fast solar wind
High density coronal plasma

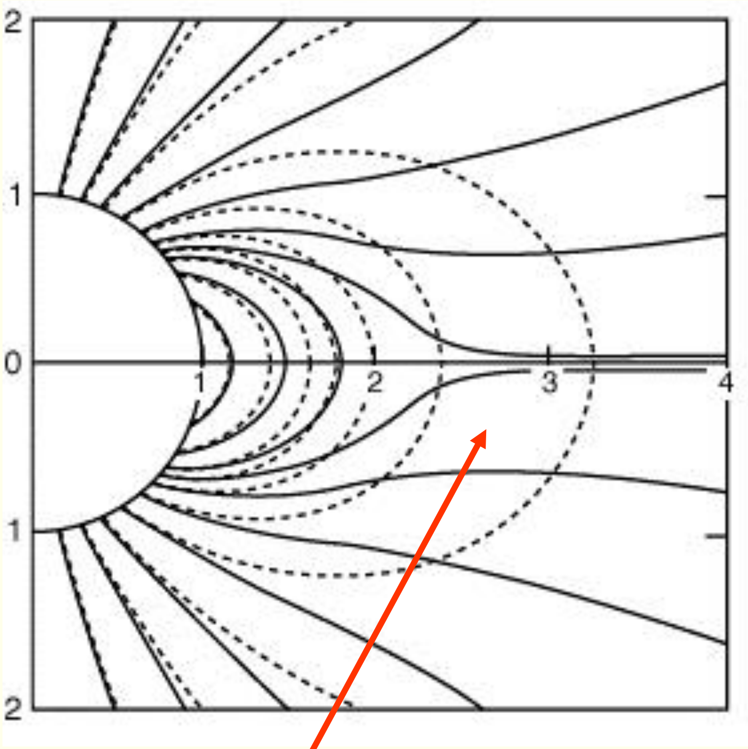
More active solar wind



Solar and Heliospheric Observatory (SOHO)
LASCO C3 Coronagraph Movie

Helmet streamers

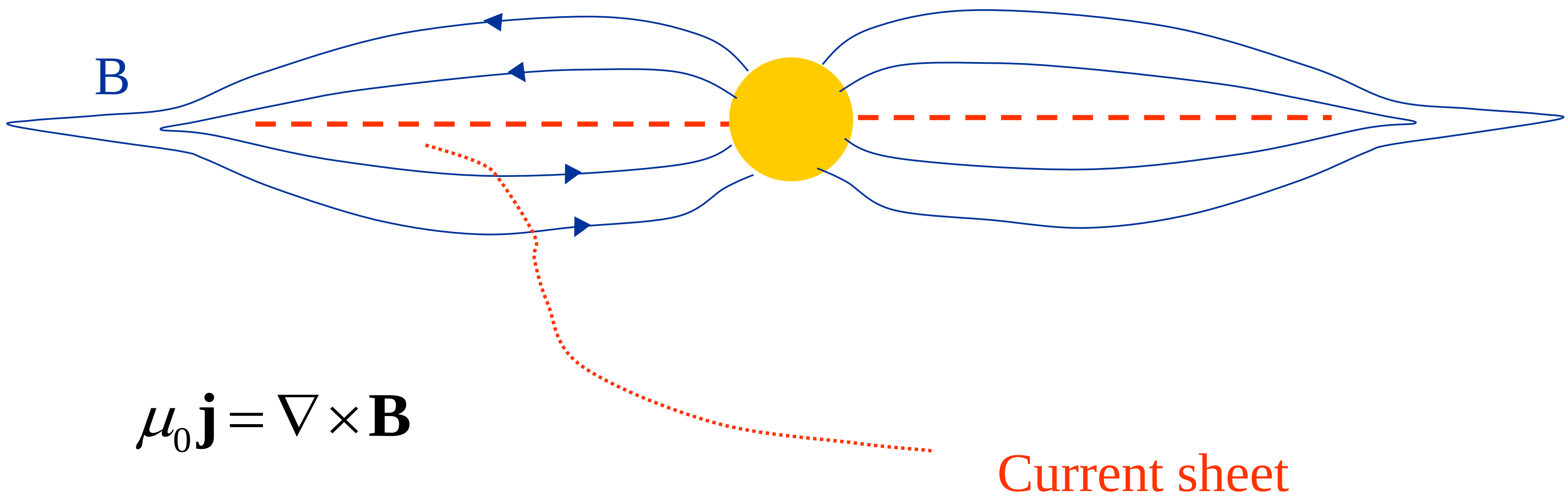




Magnetic field drawn out by solar wind.
This also brakes the solar wind.

Solar wind

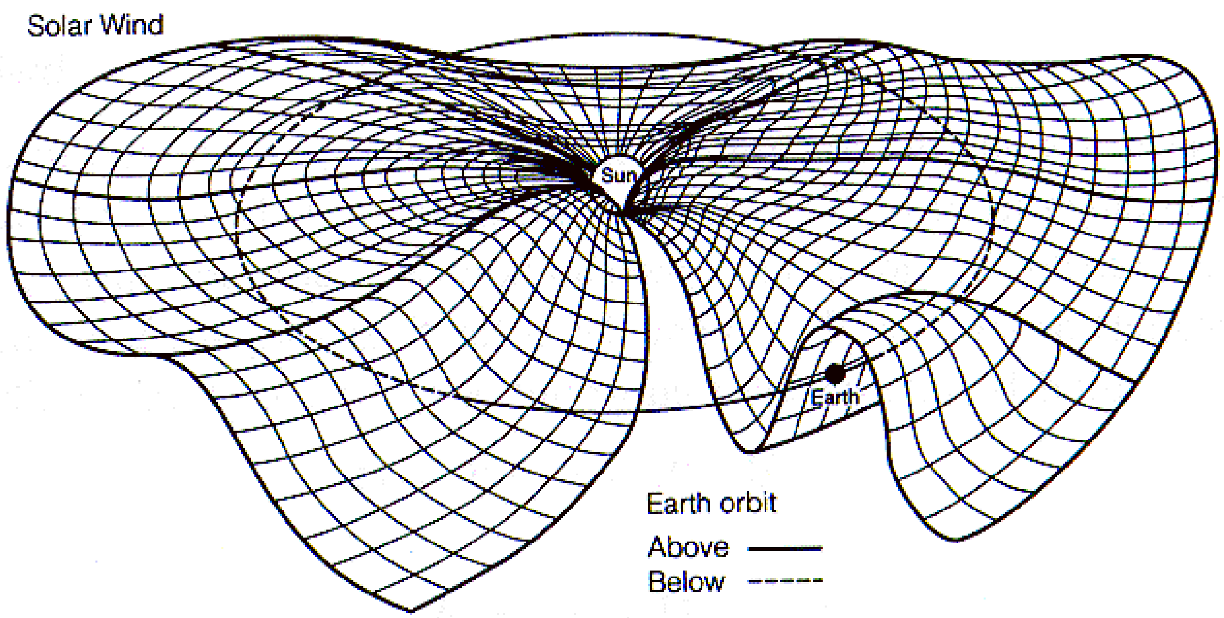
Interplanetary current sheet



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

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

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

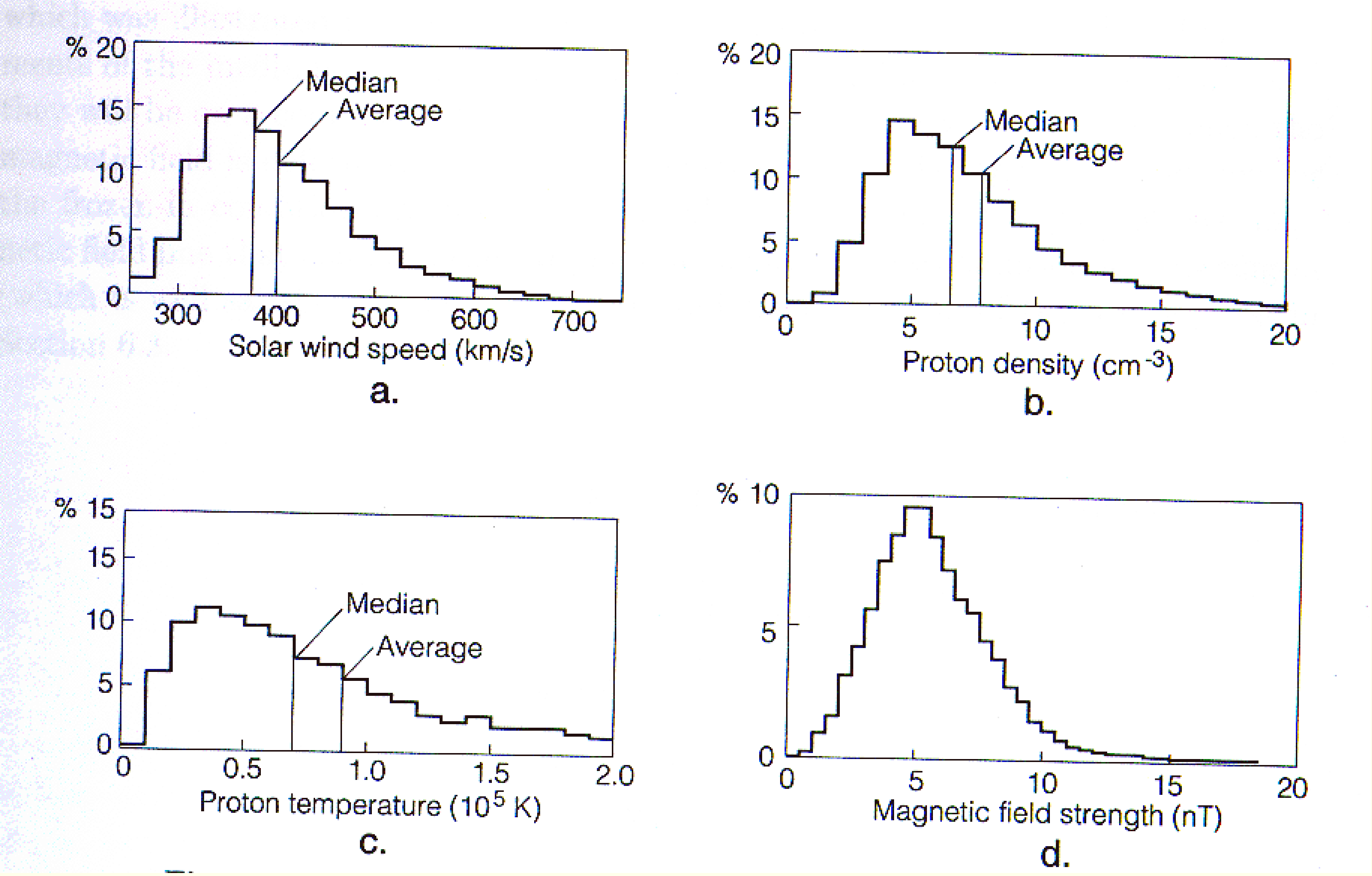
$v = 320\ km/s$

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

$T_e = 10^5\ K$

$B = 5\ nT$

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



The solar wind today

Average values

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

$v = 320\ km/s$

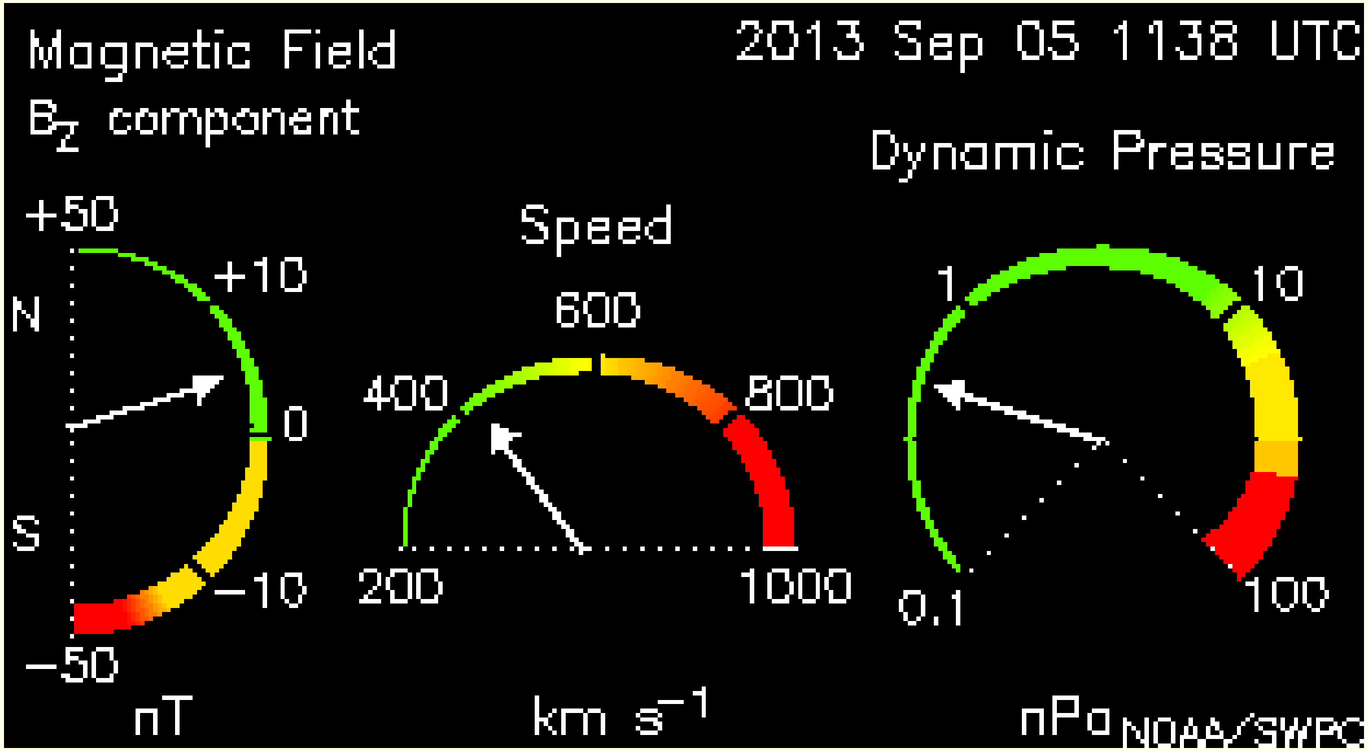
$T_p = 4 \cdot 10^4\ K$

$T_e = 10^5\ K$

$B = 5\ nT$

$p_D = \rho v^2/2 =$
$0.7\ nPa$

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



Measurements from ACE spacecraft
http://www.swpc.noaa.gov/SWN/
Space Weather Prediction Centre

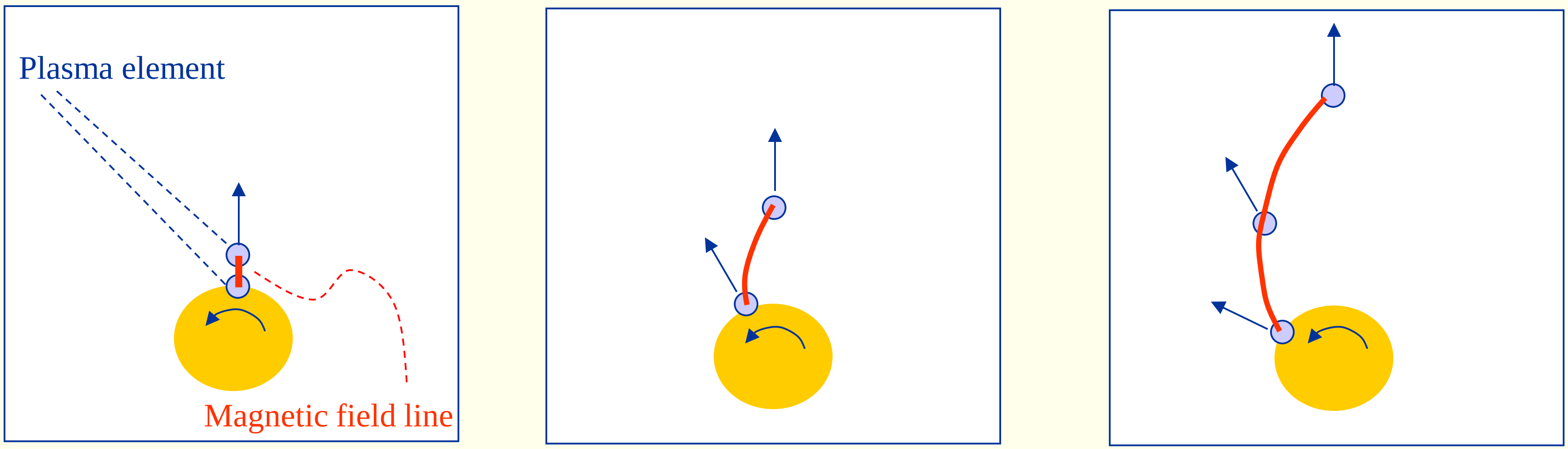
Guess how long does it take the solar wind to flow from the Sun to the Earth?

Blue	8 min	Yellow	1.5 days
Green	5 hours	Red	5 days

Does anyone happen to know the mathematical formula for the spiral caused by a rotating garden sprinkler?

Solar wind

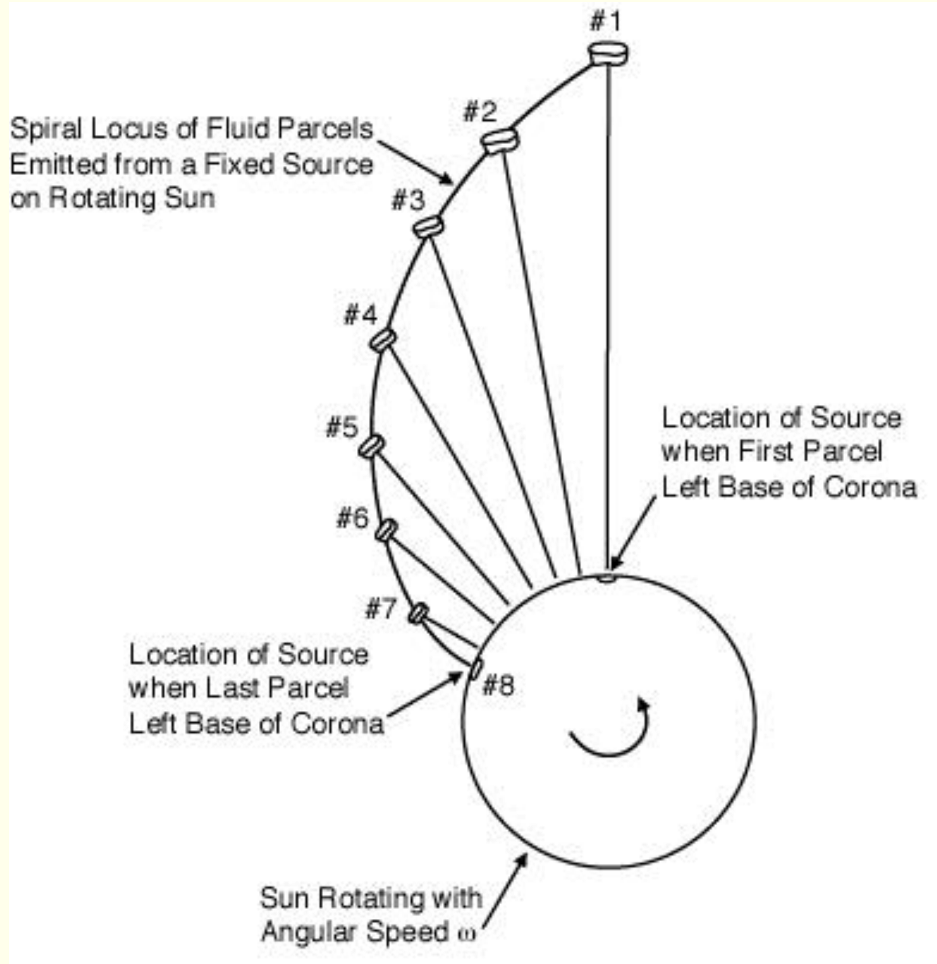
Magnetic field frozen into solar wind



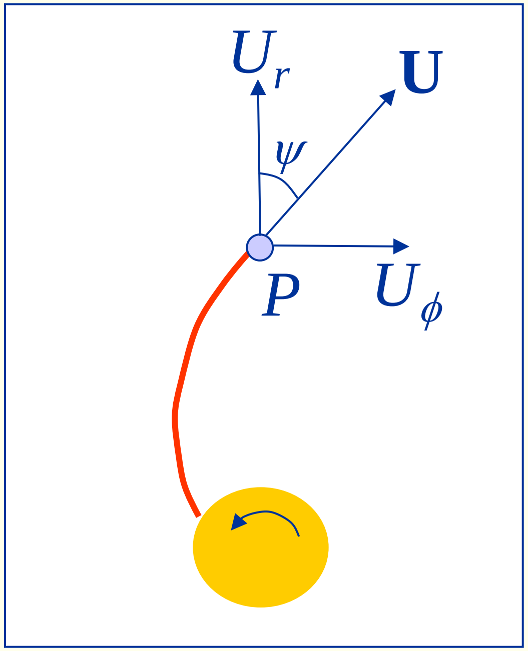
This is now seen from ”above”! (Looking down on the ecliptic plane from the pole.)

Solar wind

Parker spiral



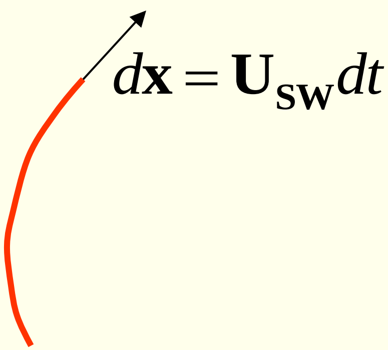
Parker spiral



Derivation of Ψ (Parker angle)

Consider a coordinate system rotating with the sun. The plasma element P in this coordinate system has two velocity components: U_r and U_ϕ .

Since the magnetic field is frozen into the solar wind, and follows the orbit of the plasma element P, at any time B has to be parallel to U. Then we have:



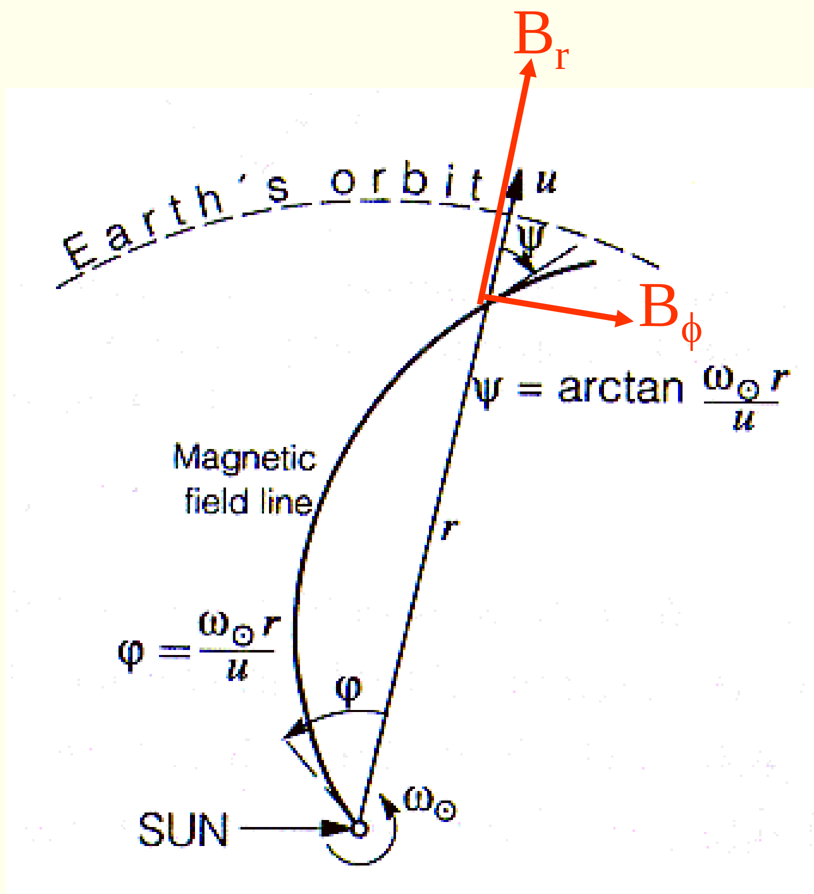
$$\tan\psi = \frac{B_\phi}{B_r} = \frac{U_\phi}{U_r} = \left(\frac{\omega r}{u_{SW}}\right)$$

Solar wind

Parker spiral

Archimedean spiral:

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



Archimedean spiral

An Archimedean spiral (also arithmetic spiral), is a spiral named after the 3rd-century-BC Greek mathematician Archimedes; it is the locus of points corresponding to the locations over time of a point moving away from a fixed point with a constant speed along a line which rotates with constant angular velocity. Equivalently, in polar coordinates (r,ϕ) it can be described by the equation (*Wikipedia*)

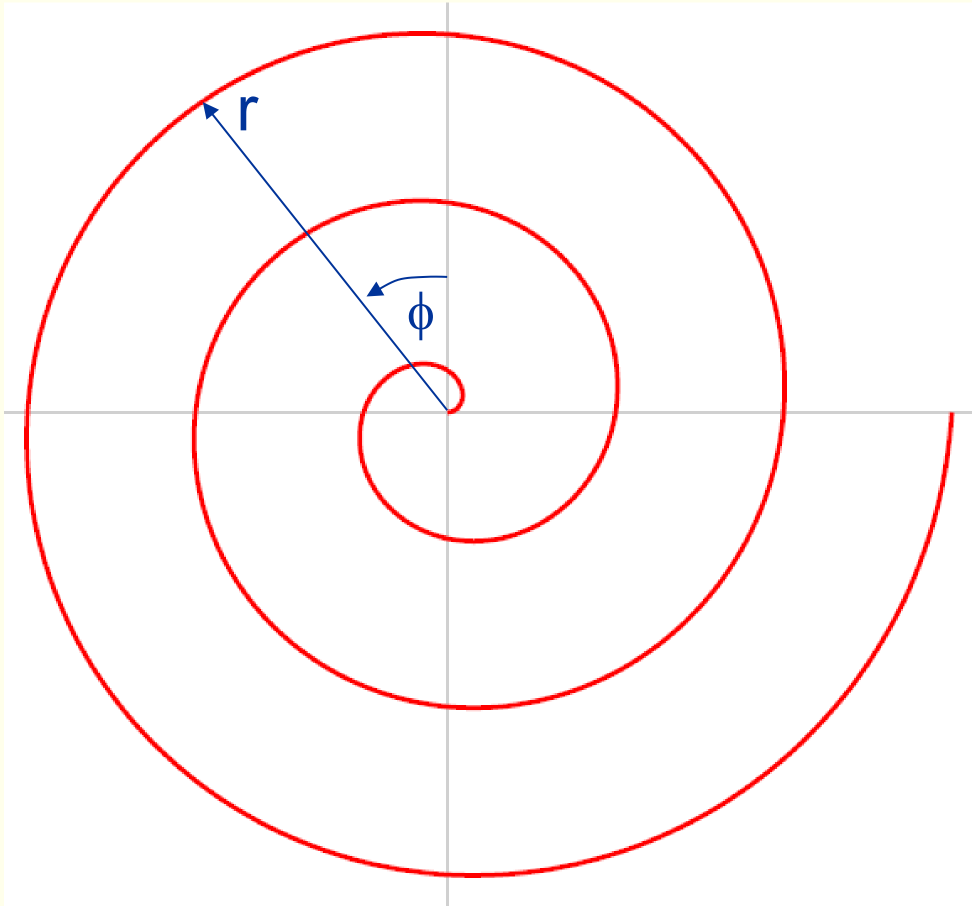
$$r = a + b\phi$$

$$r = a + b\omega t$$

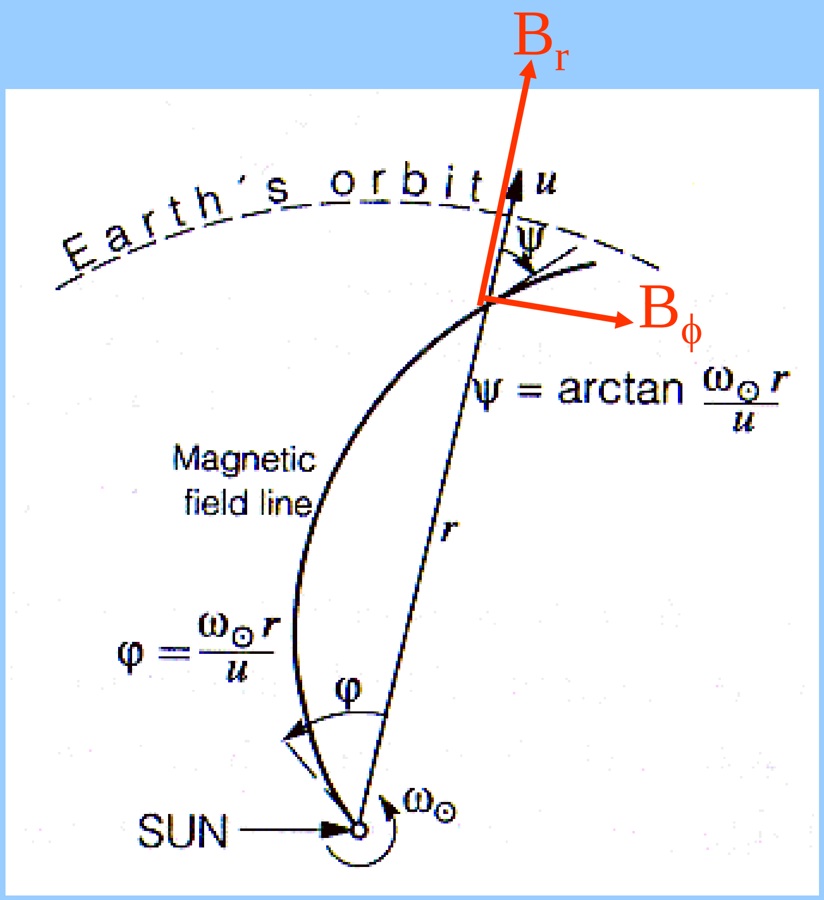
$$\frac{dr}{dt} = b\omega = u_{SW}$$

$$b = \frac{u_{SW}}{\omega}$$

$$r = R_{sun} + \frac{u_{SW}}{\omega}\phi$$



Use rotation period T of sun: T = 27 days



r = 1 A.U.

What is the angle Ψ at Earth's orbit for a typical solar wind speed?

Yellow	≈ 50 °
Red	≈ 80 °
Blue	≈ 1 °
Green	≈ 10 °

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*

ρ: *gyro radius*

λ: *mean free path*

l_c: *dimension of the plasma*

Plasma models/descriptions

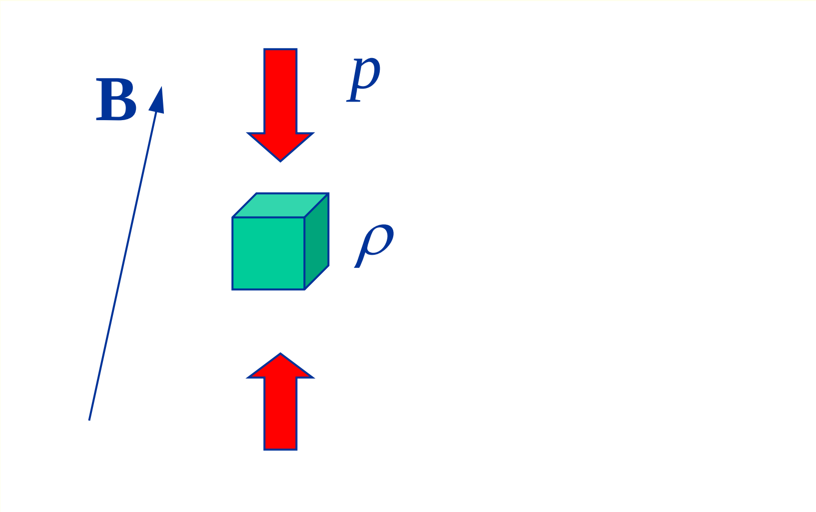
- Single particle motion
- Computer simulations of many-particle dynamics
- Generalization of statistical mechanics (kinetic theory)
- Generalization of fluid mechanics: *Magneto-hydrodynamics (MHD)*

Plasma physics
Magnetohydrodynamics (MHD)

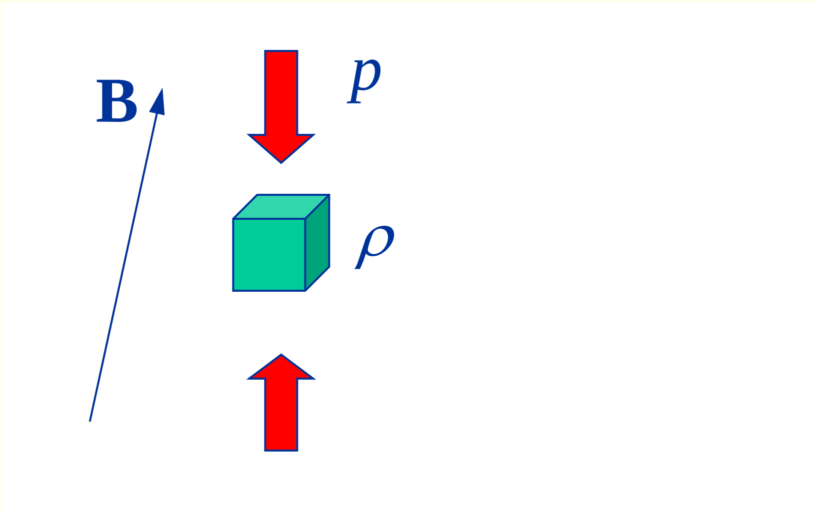
MHD is a combination of

- *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

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

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

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

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:

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

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

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

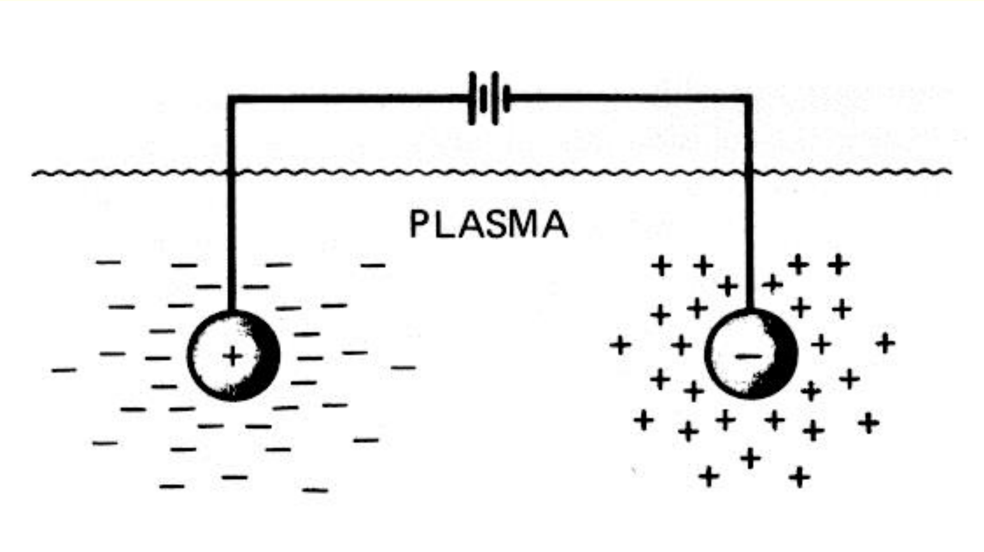
Represents tension in magnetic field

If magnetic tension = 0

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

Magnetic pressure

Quasineutrality



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

Debye length

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

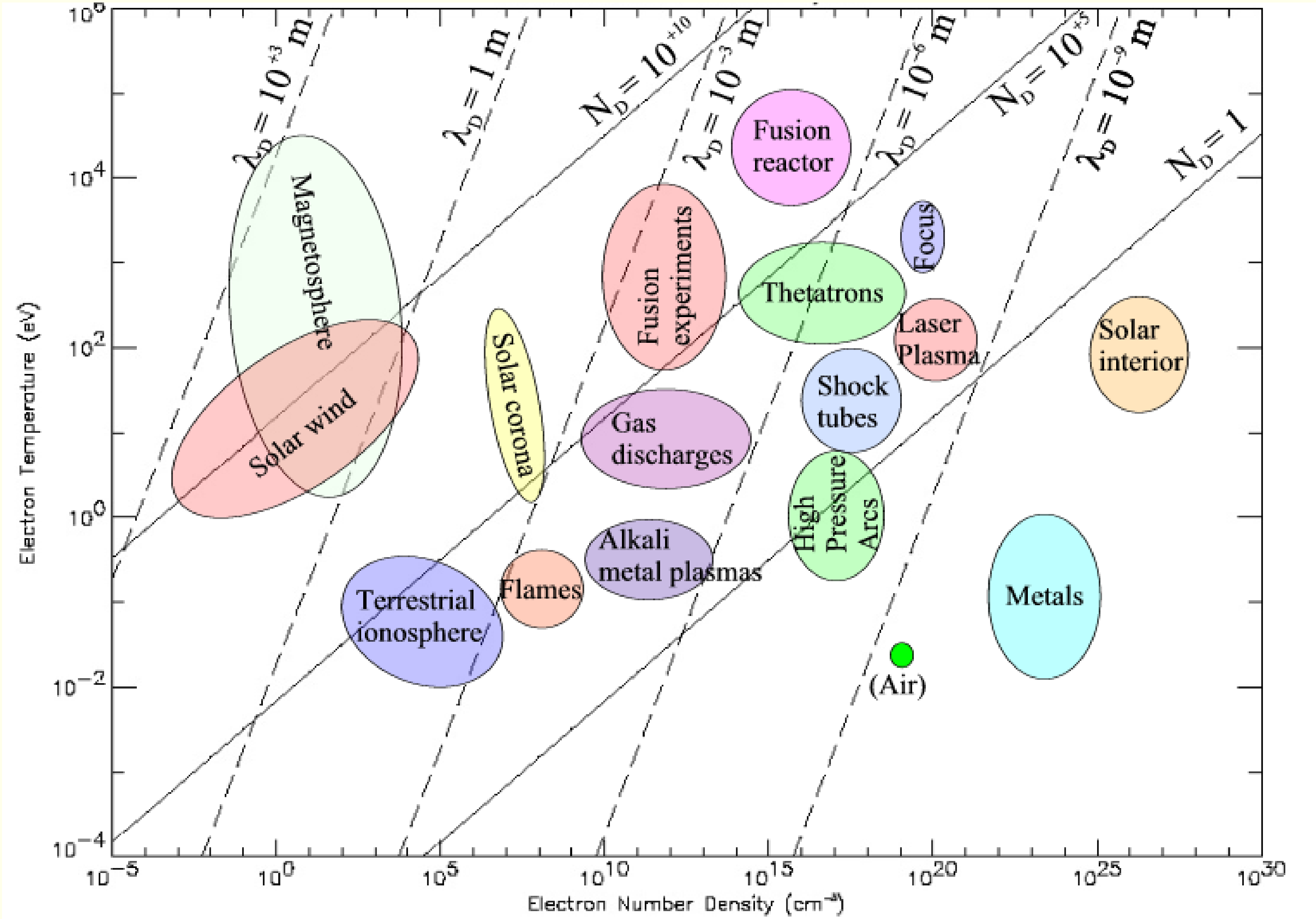
$$\frac{\Delta n}{n} = \frac{(n_e - n_i)}{n_e} < \left(\frac{\lambda_D}{l_c}\right)^2$$

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

Plasma close to neutral:

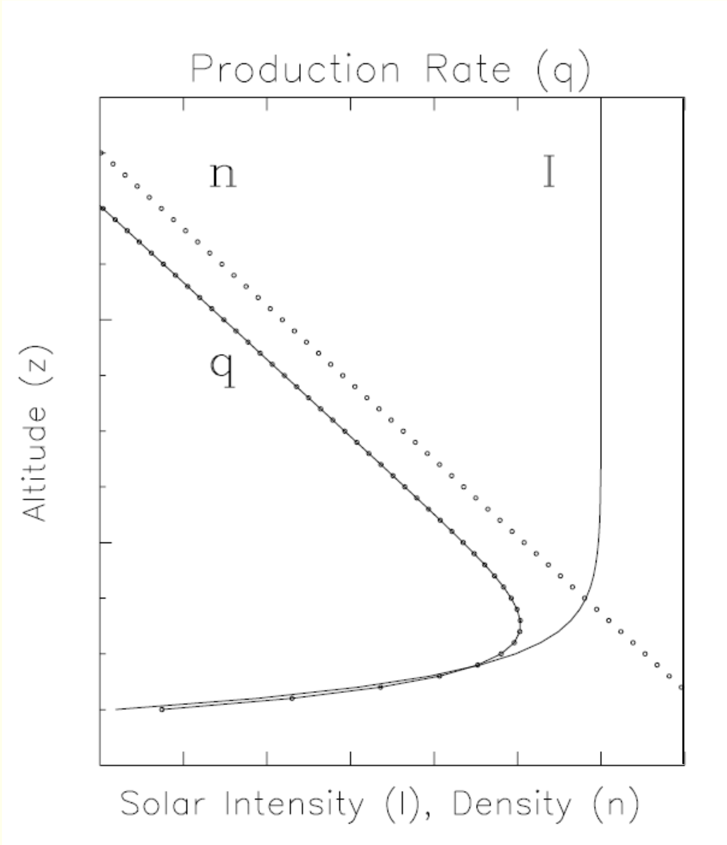
$$n_e \approx n_i$$

Debye lengths

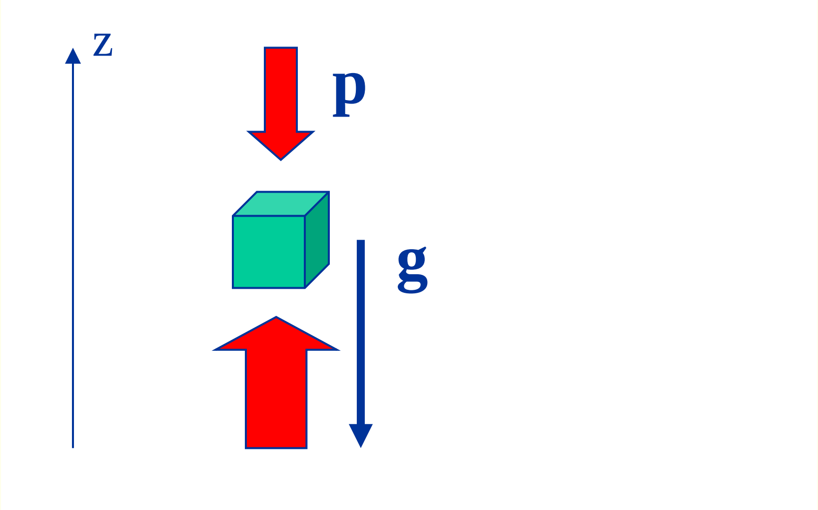


The ionosphere

Basic principle for creation of ionospheric layer



Atmospheric scale height



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

$$p = nk_BT = \frac{\rho k_B T}{m}$$ 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

$H = k_BT/gm$

Scale height

$$H = k_B T/gm$$

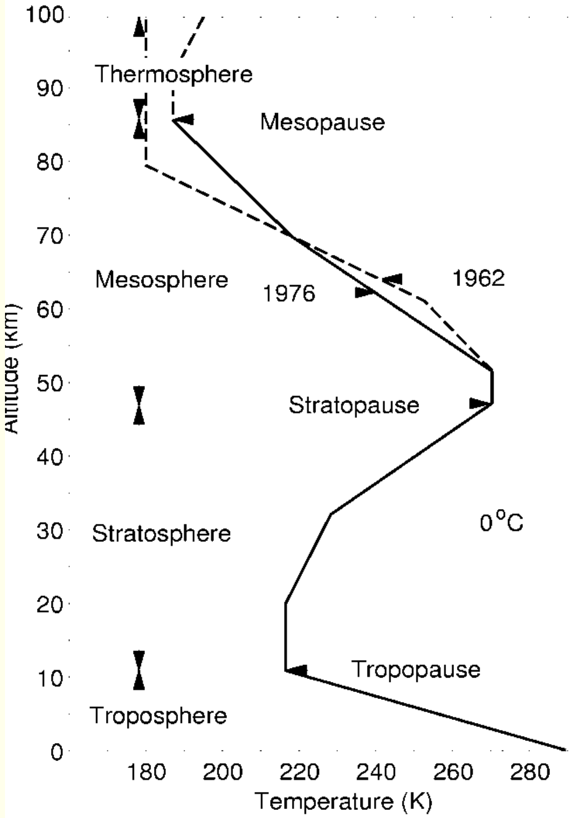
What is the approximate scale height in the atmosphere right here, right now?

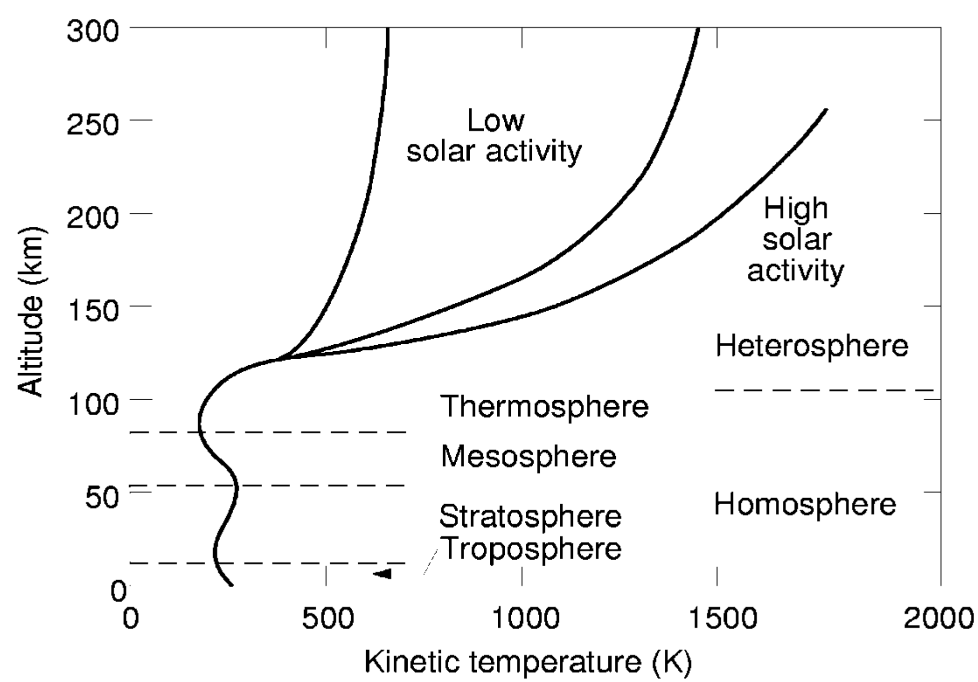
(0° C = 273 K)

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

What did we neglect when we derived the scale height?

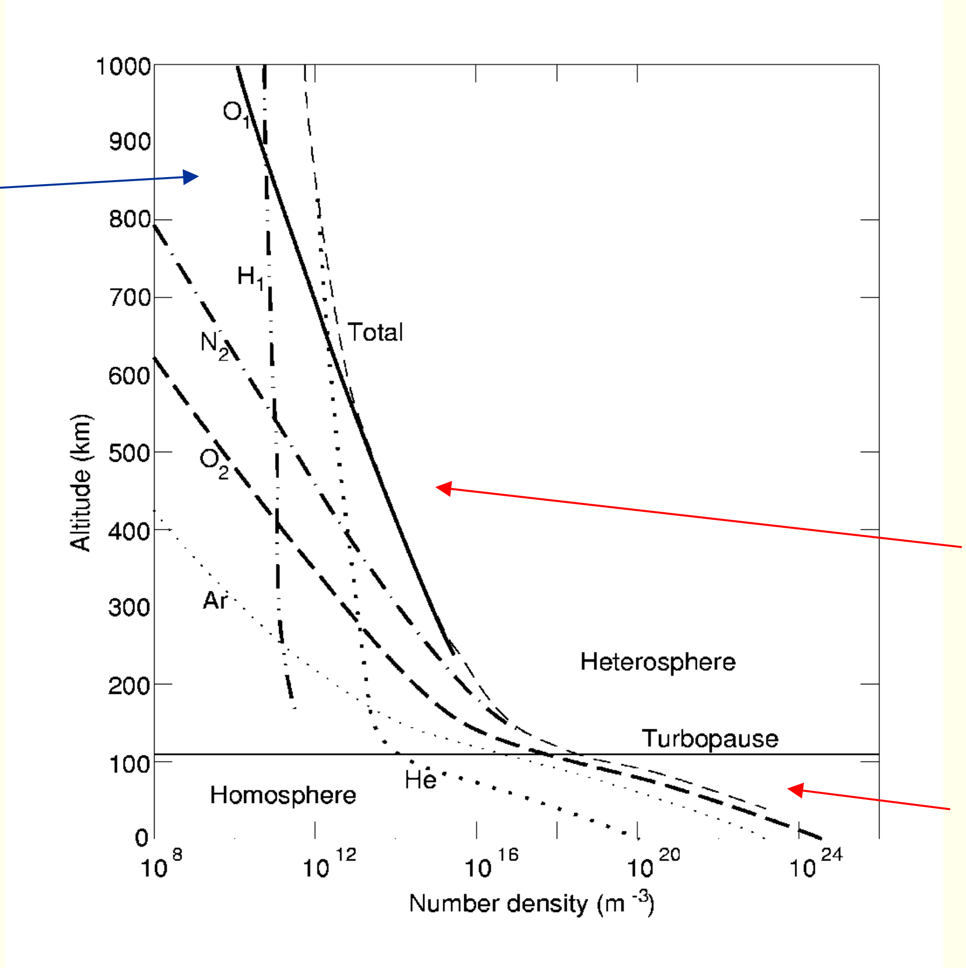
Temperature profile





Atmospheric composition

Longer scale height due to higher temperature



Separate scale heights for different components

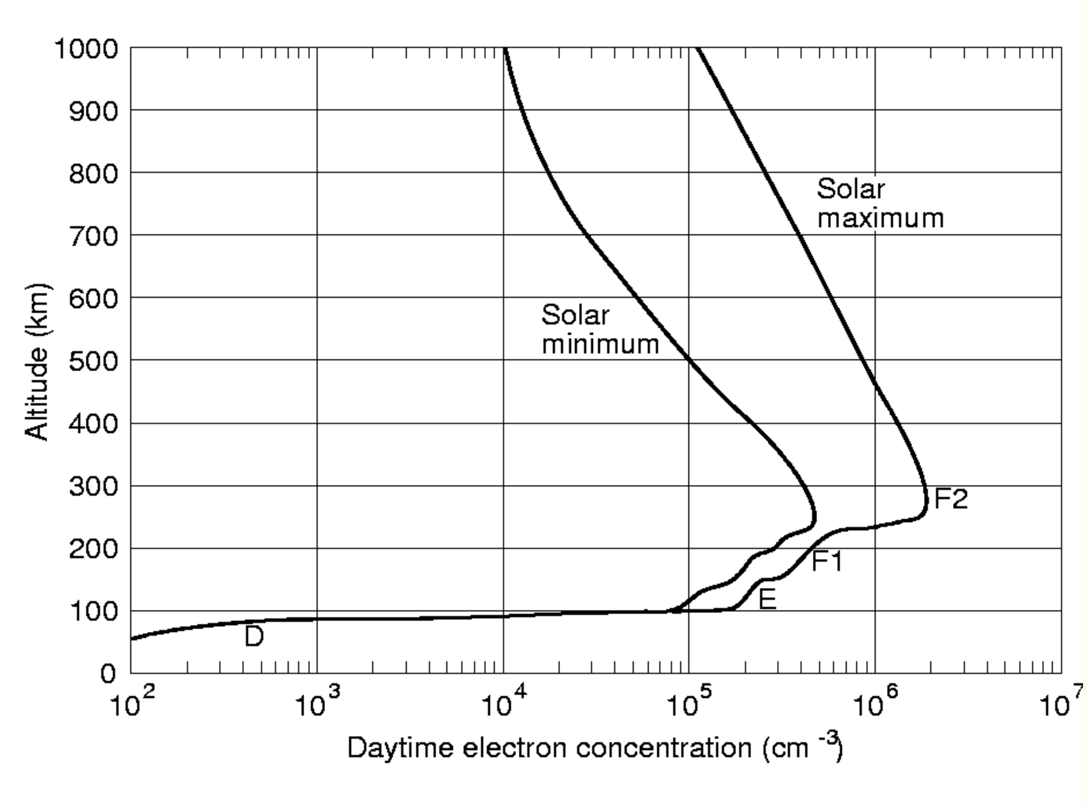
Turbulent mixing – one scale height

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 ?

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

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

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

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

Continuity equation

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

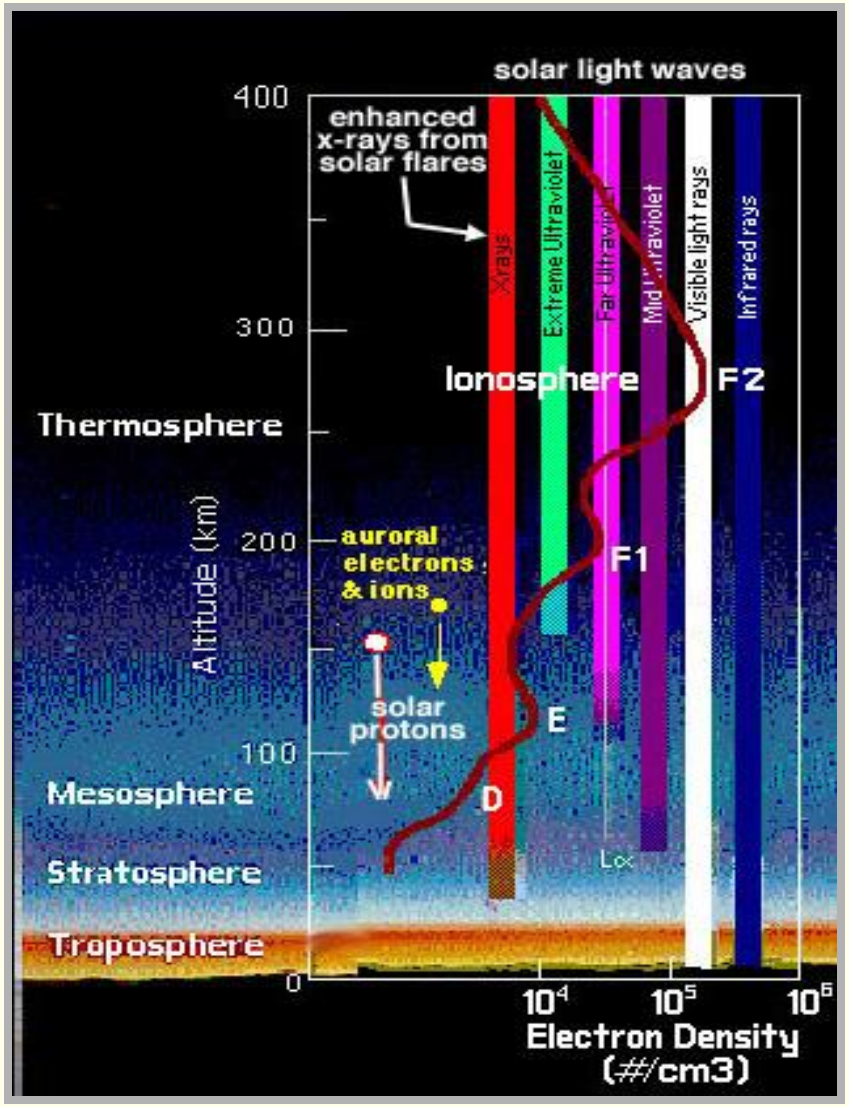
$$q = a_i I n_n$$

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)



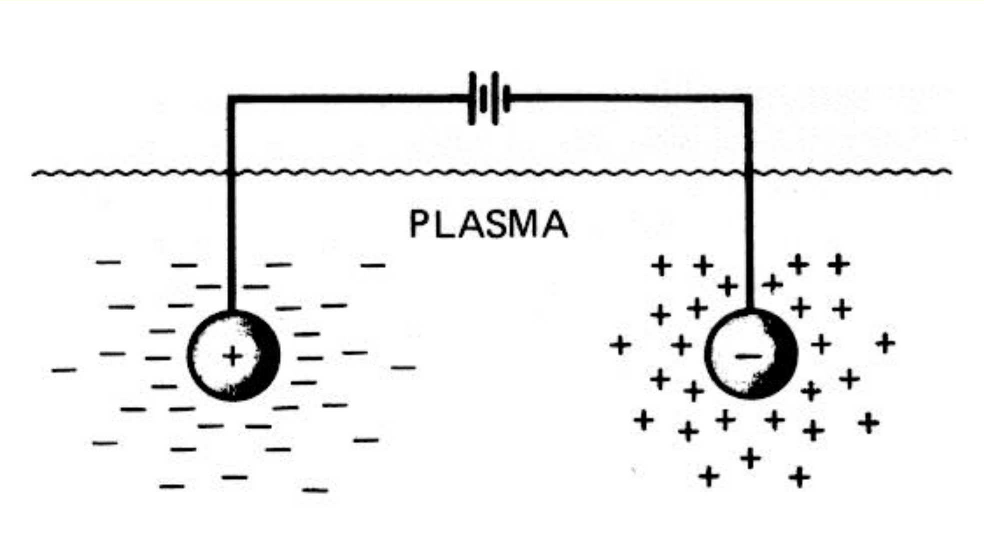
UV and X–ray radiation

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

Derive Chapman layer

Last Minute!

Quasineutrality



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

Debye length

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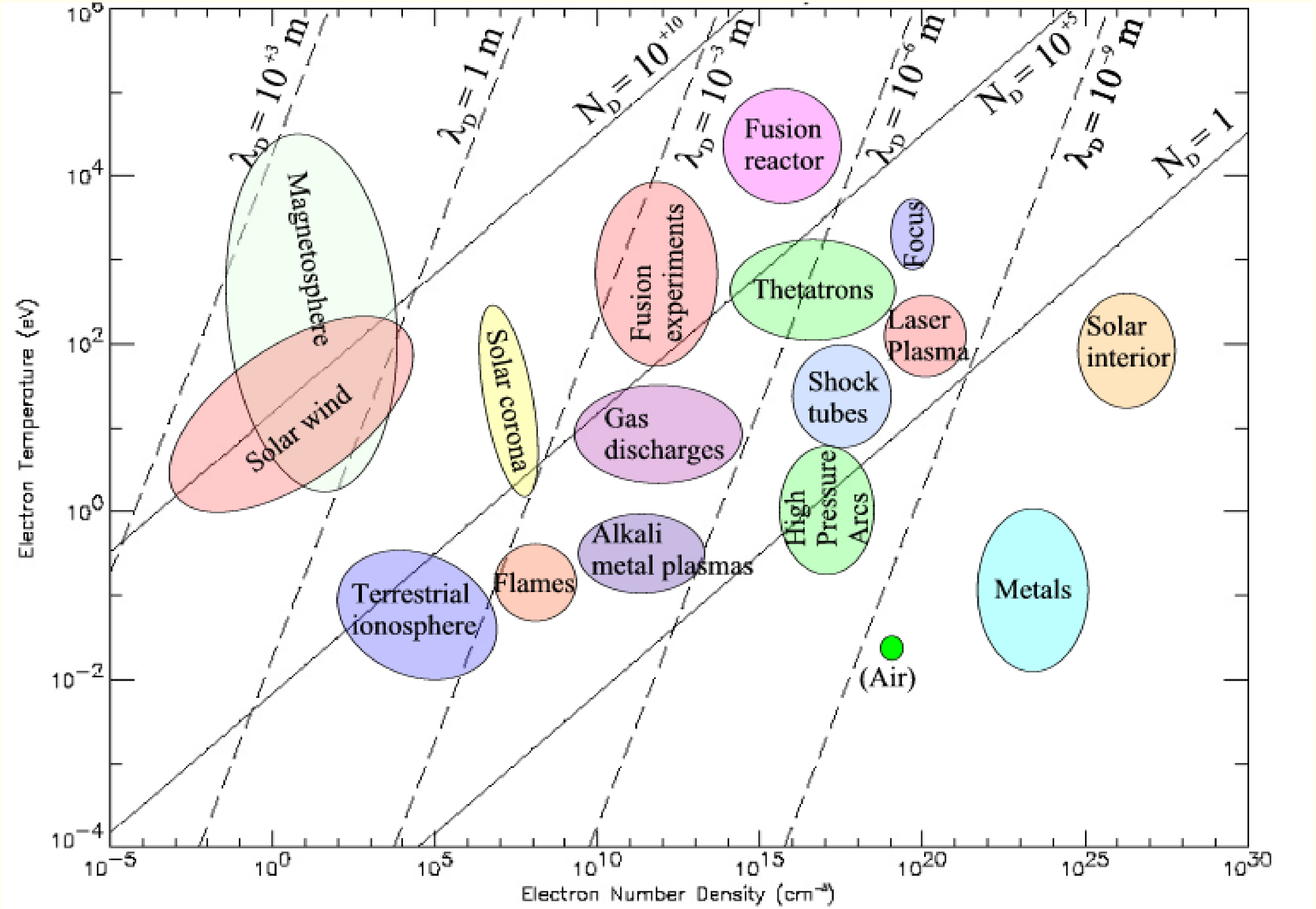
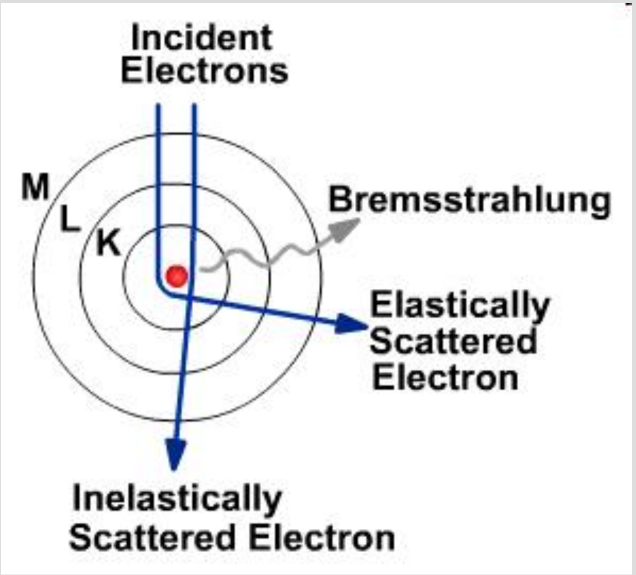
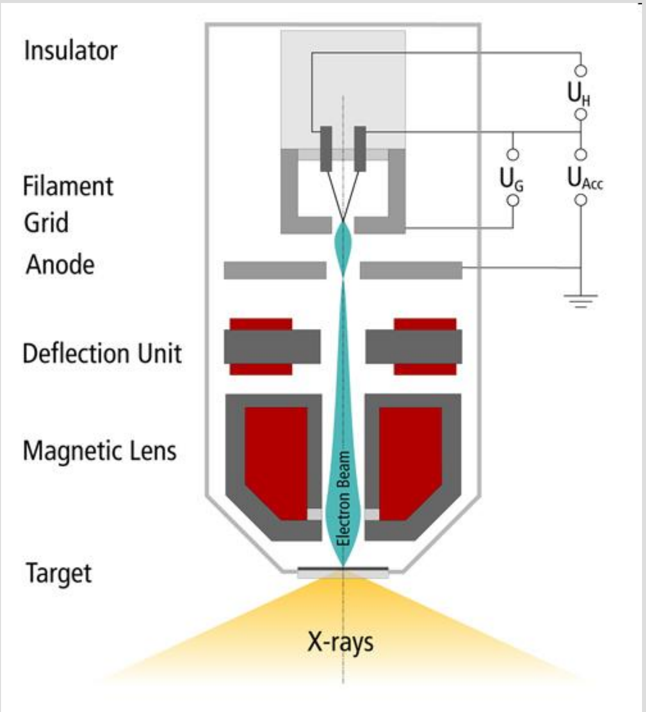
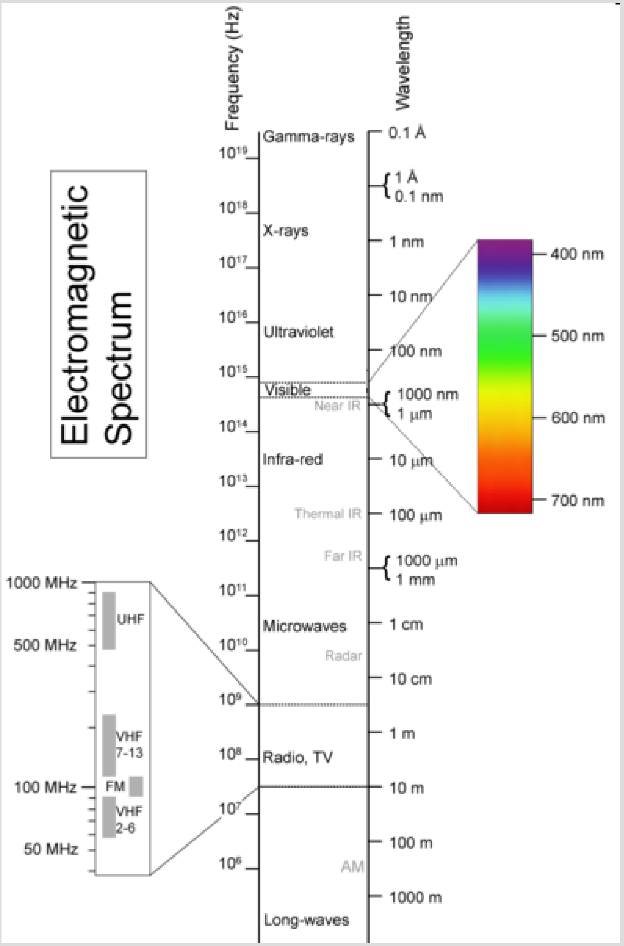


KTH
VETENSKAP
OCH KONST

X-rays, Bremsstrahlung







$$U_{acc} = hf = \frac{hc}{\lambda} \quad \Rightarrow$$

$$\lambda = \frac{hc}{U_{acc}} = \frac{6.62 \cdot 10^{-34} \cdot 3 \cdot 10^{8}}{100 \cdot 10^{3} \cdot 1.6 \cdot 10^{-19}} = 1.2 \cdot 10^{-11}\,\mathrm{m} = 0.012\,\mathrm{nm}$$