Introduction to space plasmas

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Outline of the course

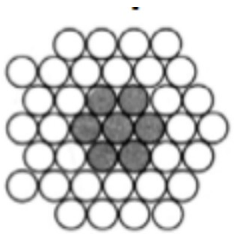
- 3 first lectures by Arnaud Zaslavsky: an introduction to plasma physics, collective behaviour in a plasma, macroscopic object in a plasma, particle dynamics in electromagnetic fields.
- 5 next lectures by Olga Alexandrova: MHD description of plasmas
- 2 last lectures by Arnaud Zaslavsky: Kinetic description of plasmas / Waves if enough time

Some bibliography:

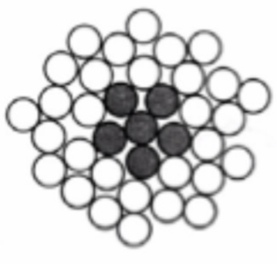
- F. Chen*, Introduction to Plasma Physics and Controled Fusion*
- W. Baumjohann & R.A. Treumann, *Basic Space Plasmas Physics*
- N. Meyer-Vernet, *Basics of the Solar Wind*
- J.-M. Rax, *Physique des Plasmas*
- G. Belmont, L. Rezeau, C. Riconda & A. Zaslavsky, *Introduction to Plasma Physics / Introduction à la physique des plasmas.*

The fourth state of matter (?)

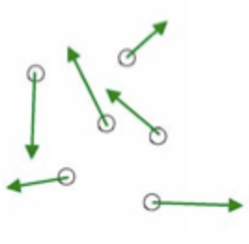
Internal energy



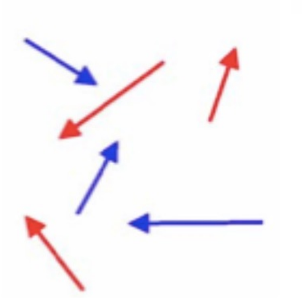
- Solid : atoms have fixed position with respect to each other + vibrations



- Liquid : atoms do not have fixed position, but strong interactions with neighbors (incompressibility) still prevail



- *Gas : free atoms (compressible) + short interactions (collisions)*



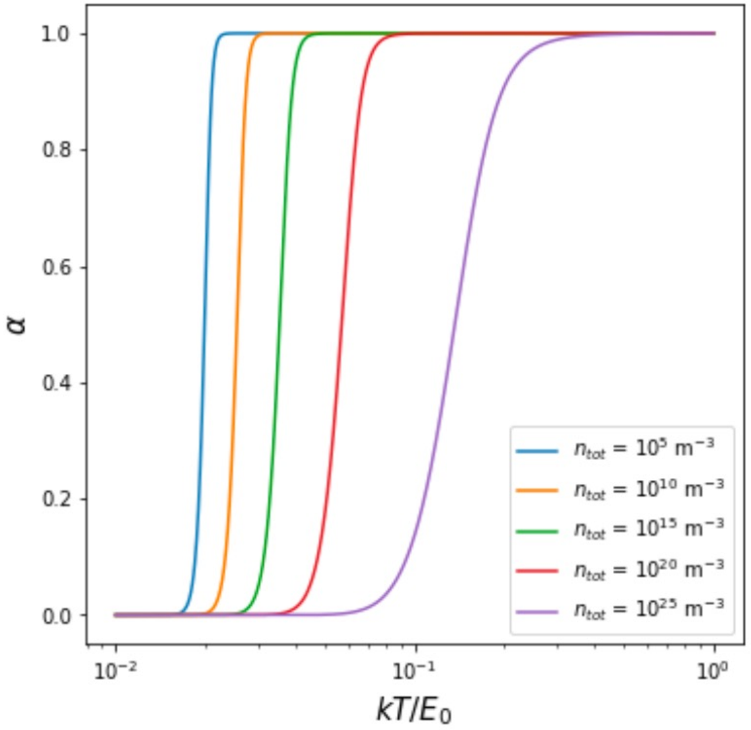
- *Plasma : Free electrons + ions (+ neutrals…). Collisions + long range interaction (Lorentz force) induce collective behaviours.*

(not strictly speaking a « phase » since no phase transition from gas to plasma, but a continuous increase of the degree of ionization with increase of T)

Thermal equilibrium: Saha's equation

- In thermal equilibrium, the ionization degree is given by Saha's equation (here for hydrogen atoms)

$$\frac{n_e n_{X^{n+1}}}{n_{X^n}} = \frac{2 g_{X^{n+1}}}{g_{X^n}} \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-W/kT}$$



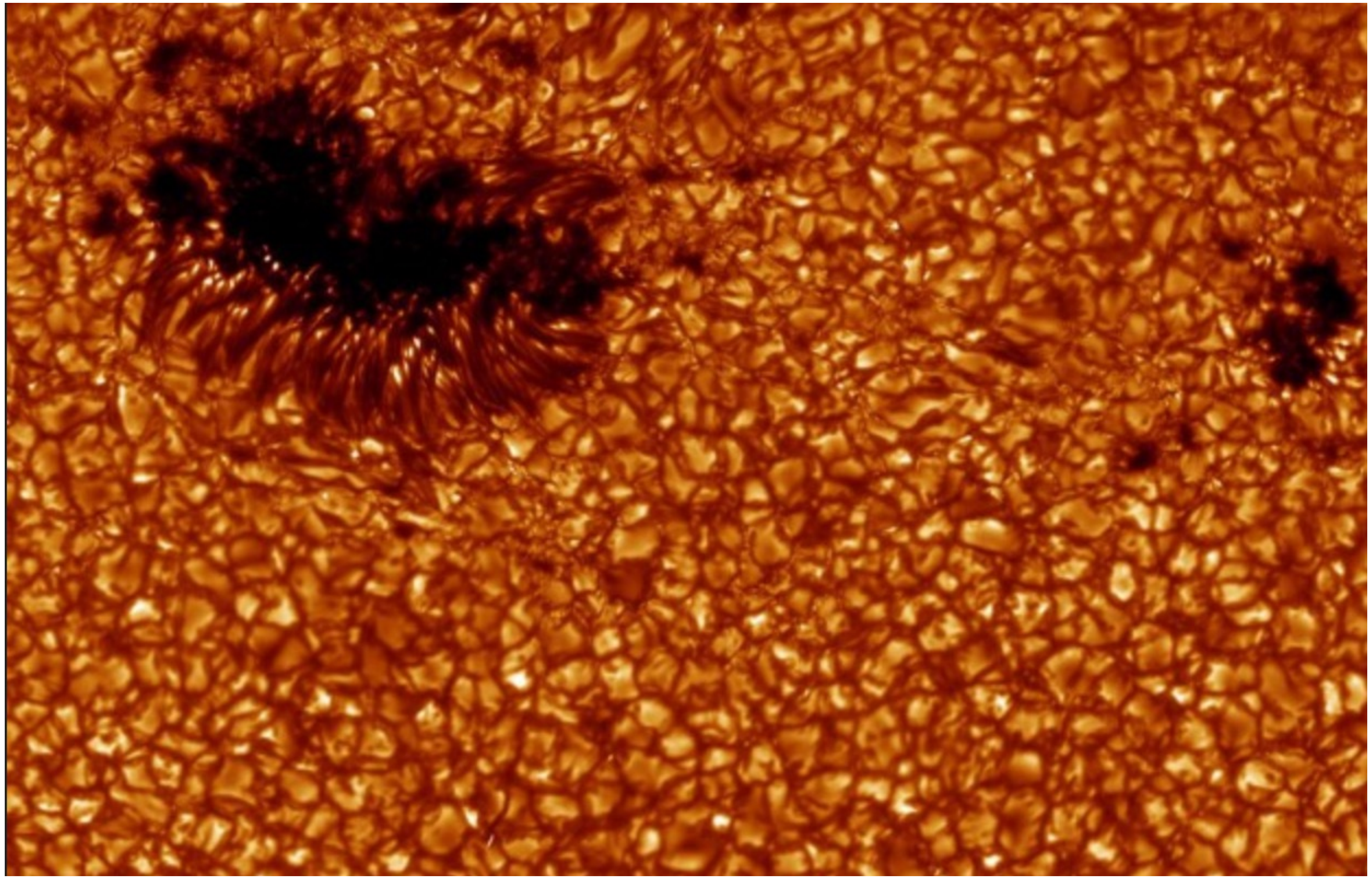
Calculate $\alpha(T, n_{tot}) = n_{e^-}/(n_{e^-} + n_{H^0})$ for a gas of hydrogen.

The degree of ionization gets important at temperature relatively lower than the ionization energy, at least for sparse media (because recombination is not efficient)

Efficient for studying stellar surfaces / external parts

Not usueful for most dilute plasma environment, which are not in thermal equilibrium

The Sun's photosphere



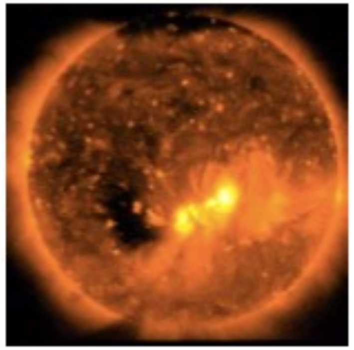
$$n \sim 2{\times}10^{23}\ \mathrm{m^{-3}}$$

$$T \sim 6400\ \mathrm{K} \sim 0.5\ \mathrm{eV}$$

$$\alpha \sim 4{\times}10^{-4}$$

Producing a plasma from a gas

- Heating: $kT \sim W_{ionization}$



- Photo-ionizing: $h\nu \sim W_{ionization}$

- Discharging: $eE\ell_{mfp} \sim W_{ionization}$

Plasmas in the universe

- Plasma state is an « electrified gas », that is, a gas in which a sufficient fraction of atoms or molcules are dissociated into positive ions and electrons for Lorentz forces to play a significant role in the dynamics.

- 99 % of the matter in the universe under plasma state: probably not a very accurate evaluation, but stellar interiors and atmospheres, and interstellar nebulae – and much of the interstellar hygrogen in general is under plasma state.

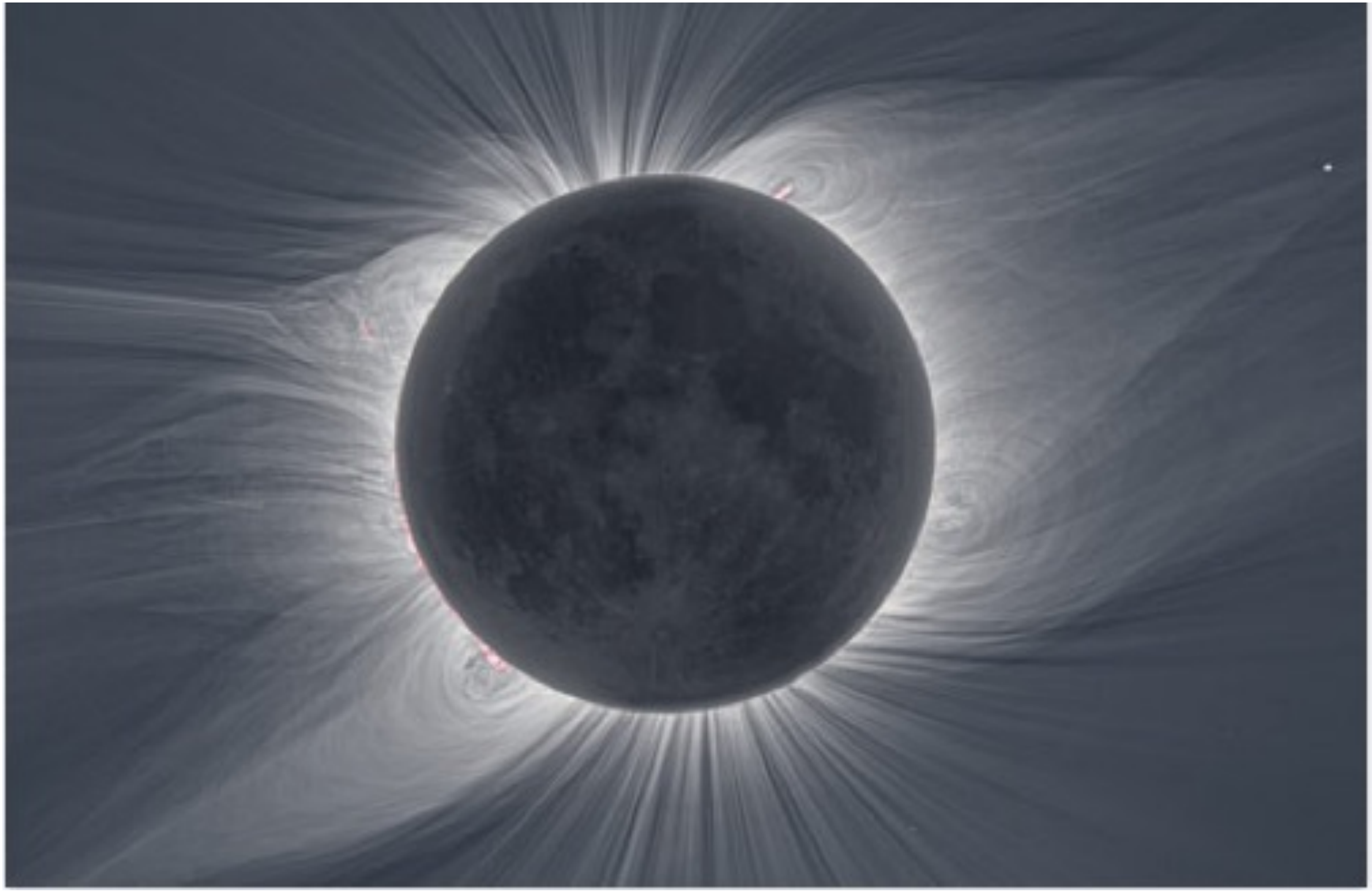
Table 1: An overview of parameters of ionised gases in the Universe (adapted from J.A. Irwin, Astrophysics - Decoding the Cosmos, Wiley 2007)

Location	n_e [m^{-3}]	$n_m + n_H$ [m^{-3}]	T [K]	Reference
Solar corona	10^{14}	$\simeq 0$	10^6	Koutchmy 1994, Adv. Space Res. 14(4), 29
Interplanetary space (1 AU)	$10^6 - 10^8$	$\simeq 0$	$10^4 - 10^5$	Schwenn 1991, dans "Physics of the Inner Heliosphere", Springer
Stellar interiors	10^{33}	$\simeq 0$	$10^{7.5}$	
Planetary nebulae	$10^9 - 10^{11}$	$\simeq 0$	10^4	Zhang et al. 2004, MNRAS 351, 935
H II regions	$10^8 - 10^9$	$\simeq 0$	$10^3 - 10^4$	Feng-Yao Zhu et al 2019, ApJ 881, 14
Interstellar medium	$10^3 - 10^7$	$10^4 - 10^{11}$	10^2	compare with lecture on the ISM
Intergalactic space	< 10	$\simeq 0$	$10^5 - 10^6$	

number densities: n_e free electrons, n_m molecules, n_H neutral hydrogen

HII region in the Large Magellanic Cloud

The Sun

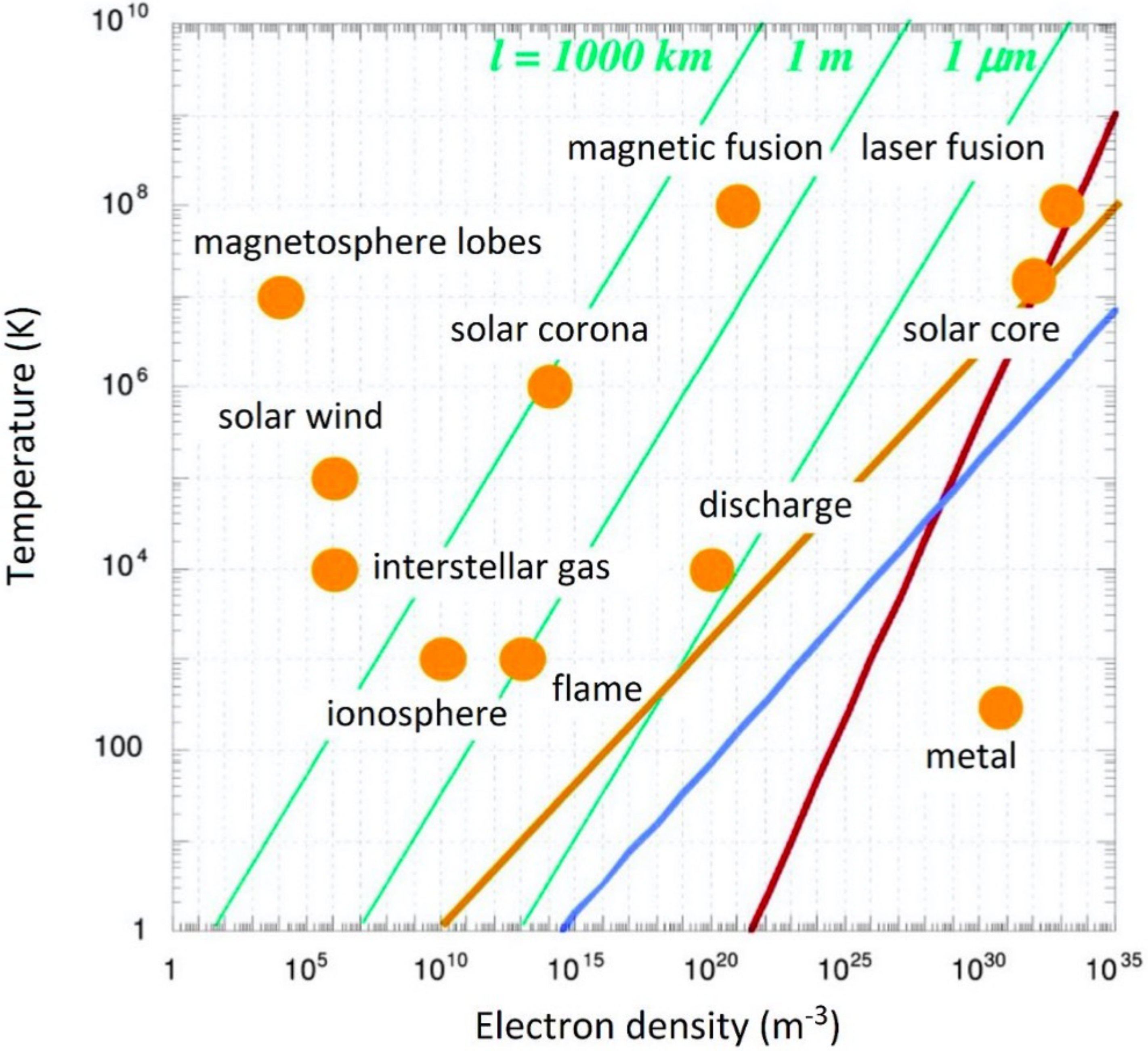


The solar corona in white-light during a total eclipse.

(Compton scattering)

A medium structured by the magnetic field.

Planetary environments



l = 1000 km
1 m
1 μm
magnetic fusion
laser fusion
magnetosphere lobes
solar corona
solar core
solar wind
discharge
interstellar gas
flame
ionosphere
metal
Temperature (K)
Electron density (m^-3)
10^10
10^8
10^6
10^4
100
1
10^5
10^15
10^20
10^25
10^30
10^35

Ionization and recombination

- Plasma state consists in a dynamic « chemical » equilibrium between ionization and recombination processes

$$A \rightleftarrows A^+ + e^-$$

- Two main agents to trigger this reaction: electrons, or photons

$$A + e^- \rightarrow A^+ + e^- + e^-$$

$$A + h\nu \rightleftarrows A^+ + e^- .$$

- Reactions quantifyed through the reaction cross-sections

Cross section and mean free path

Reaction : $A + B \rightarrow C + D.$

$$\dot{n}_{reac} = dn_C/dt = -dn_A/dt = n_A v_{A/B} n_B \sigma$$

Number of reaction per unit time proportionnal to the densities and relative speeds. The proportionnality coefficient is the cross section.

The mean-free path λ of the particle A evolving in a (steady) background of particles B is defined by $dp/ds = 1/\lambda$ with dp the probability to have a reaction occurring when A travels the distance ds.

$$n_A(s + ds) = n_A(s)(1 - dp) \Rightarrow dn_A/ds = -n_A/\lambda$$

So that $\boldsymbol{\lambda = 1/n_B \sigma}$

Ionisation processes : Electron impact

Electron impact :

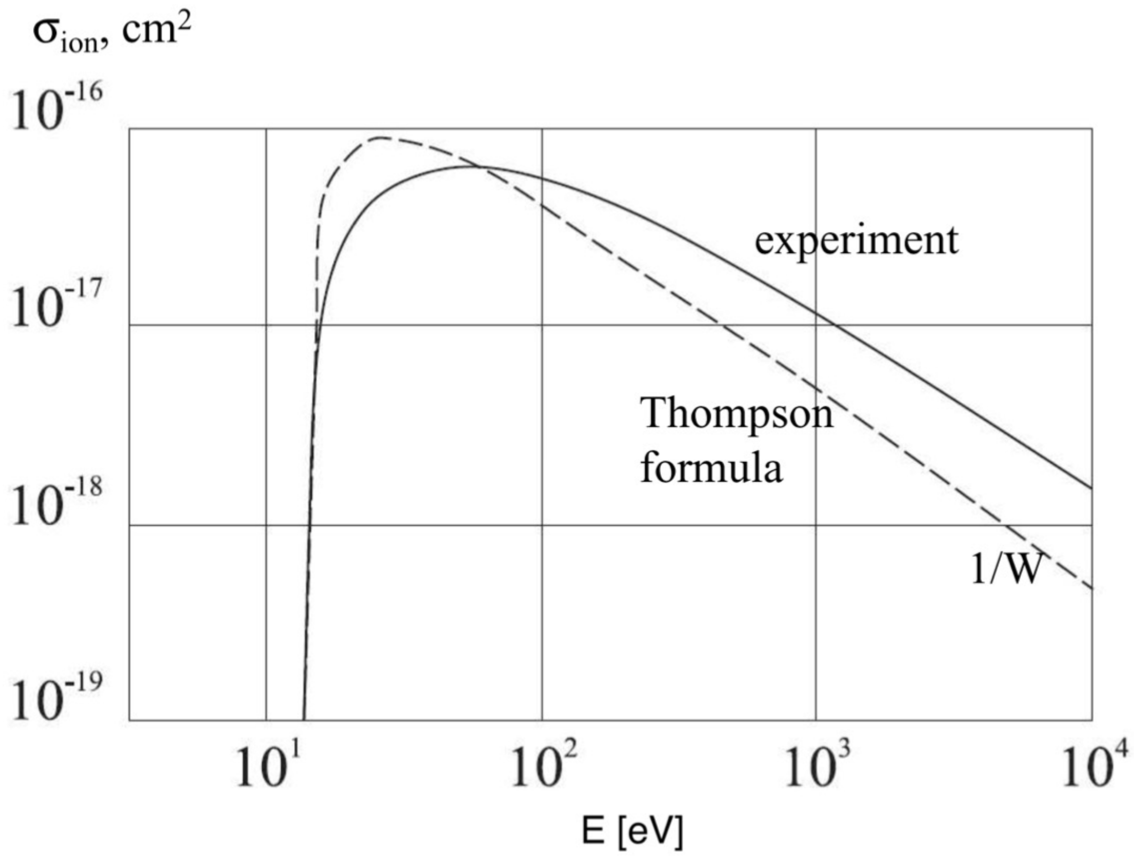
$$A + e^- \rightarrow A^+ + e^- + e^-$$

Cross-section given by the Thomson formula

$$\sigma_e(E) = \frac{\pi q_e^4 (E - W)}{W E^2}$$

Order of magnitude :

$$\sigma_e \sim 10^{-20}\ \mathrm{m}^2 \text{ for } W \sim 10 \text{ eV}$$



Ionisation processes : photoionisation

$$A + h\nu \rightarrow A^+ + e^- .$$

Order of magnitude of the cross section

$$\sigma_{ph} \simeq 5 \times 10^{-22} (E/W)^{-3} \text{ m}^2$$

Flux density of ionising photons

$$N_{ph} = \frac{1}{4\pi r^2} \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu$$

With $L_\nu(R,T) = 4\pi R^2 \frac{2\pi h \nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$

Recombination processes

2 main recombination processes:

- Radiative recombination $A^+ + e^- \to A + h\nu$

Cross section : $\sigma_{rad} \sim 10^{-24}\mathrm{m}^2.$

- Dissociative recombination $XY^+ + e^- \to X^* + Y^*$

Cross section : $\sigma_{dis} \sim 10^{-18}\ \mathrm{m}^2$

- In presence of diatomic molecules (terrestrial ionosphere…) the second dominates by far.

Case study : chapman's ionization layer

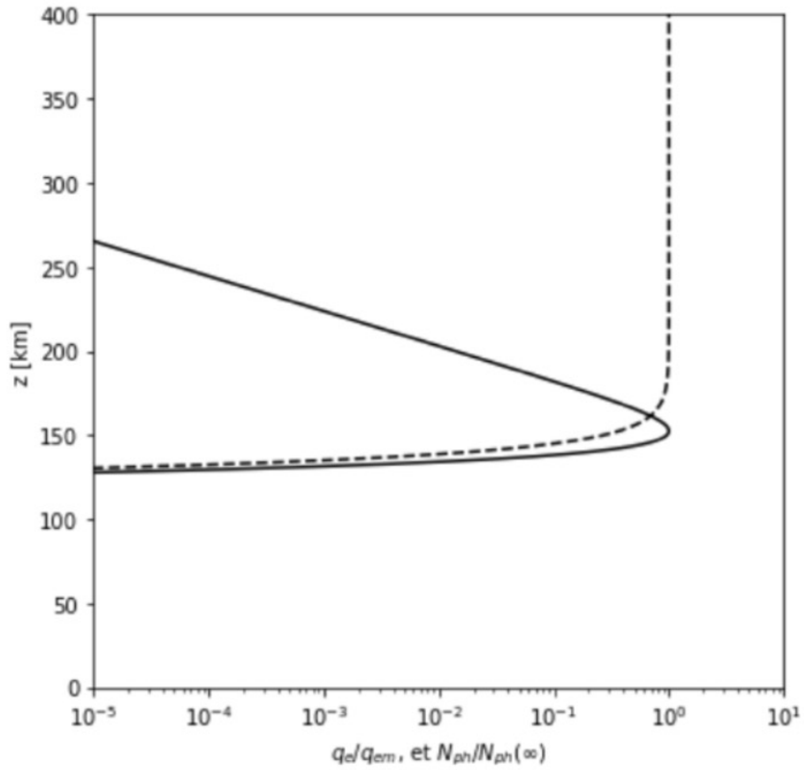
- We consider the photo-ionization reaction, caracterized by a cross section σ_{ph}

- We consider the gas to be illuminated by a photon flux density $N_{ph}(z)$

- Then $\frac{dN_{ph}}{dz} = n_A(z)\sigma_{ph}N_{ph}$ and $N_{ph} = N_\infty \exp - \int_z^\infty n_A(z)\sigma_{ph}dz$

- The electron production rate per unit volume is $Q_e = \frac{dN_{ph}}{dz} = n_A(z)\sigma_{ph}N_{ph}$ since one electron is produced per photon absorbed

- We obtain $Q_e = Q_{max} \exp\left(1 - y - \exp -y\right)$ with $y = \frac{z - z_m}{H}$, assuming the atmosphere is in hydrostatic isothermal equilibrium (H = kT/mg, $z_m = H \ln \sigma_{ph} H n(0)$)



Chapman's ionization layer : recombination

We can consider two main recombination processes:

- Radiative recombination $X + h\nu \rightleftarrows X^+ + e^-$

The cross section of these processes are $\sigma_{ph} \sim 10^{-22}\ \mathrm{m}^2, \qquad \sigma_{rad} \sim 10^{-24}\ \mathrm{m}^2$

- Dissociative recombination $XY^+ + e^- \rightarrow X^* + Y^*$

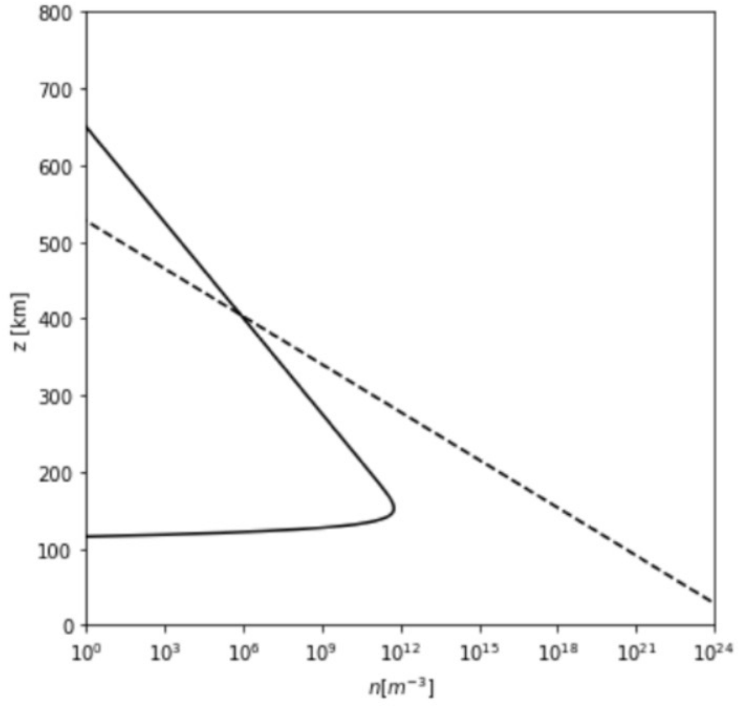
The cross section of this process is $\sigma_{dis} \sim 10^{-18}\ \mathrm{m}^2$

- In presence of diatomic molecules (terrestrial ionosphere…) the second dominates. We have a recombination rate $R = k_{dis} n_{XY^+} n_e = k_{dis} n_e^2$ with $k_{dis} \simeq \sigma_{dis} v_{the}$

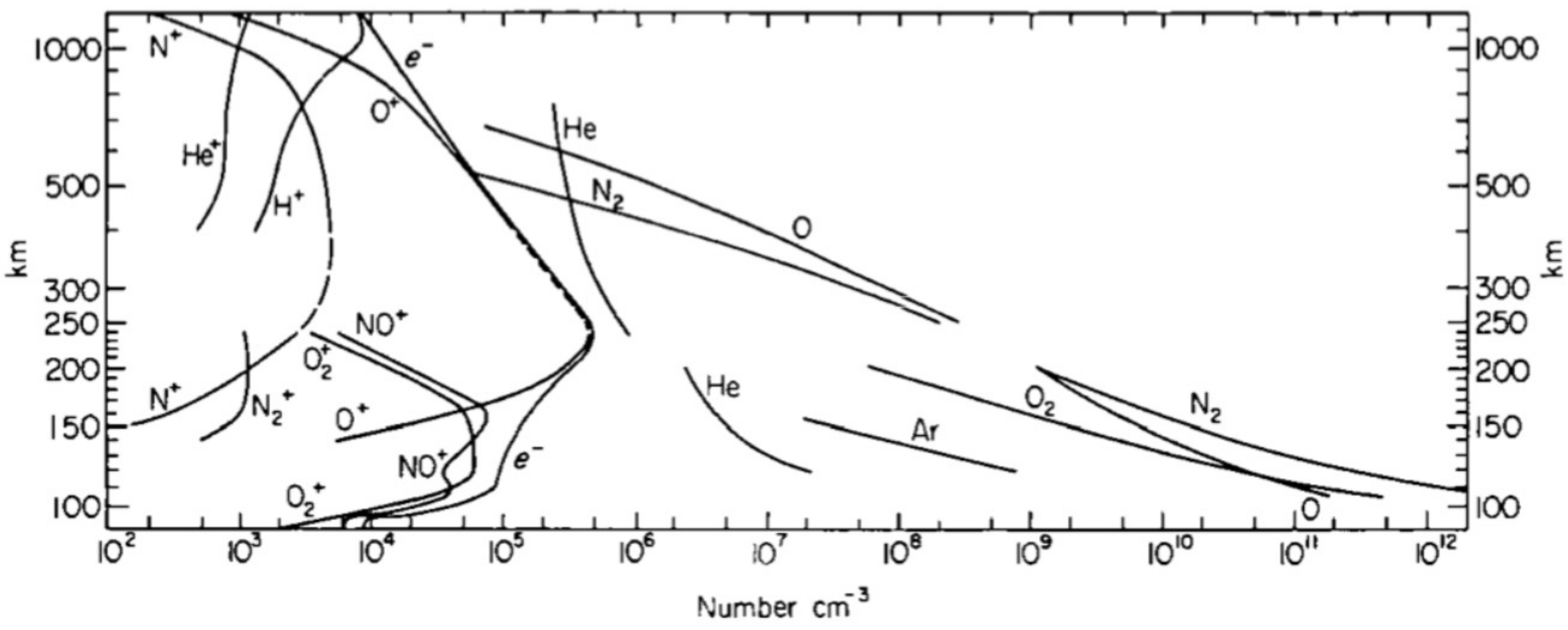
- The electron density in the ionization layer is then given by $n_e(z) = \sqrt{Q_e(z)/k_{dis}}$

Chapman's ionization layer : model vs observations

Our simple model:



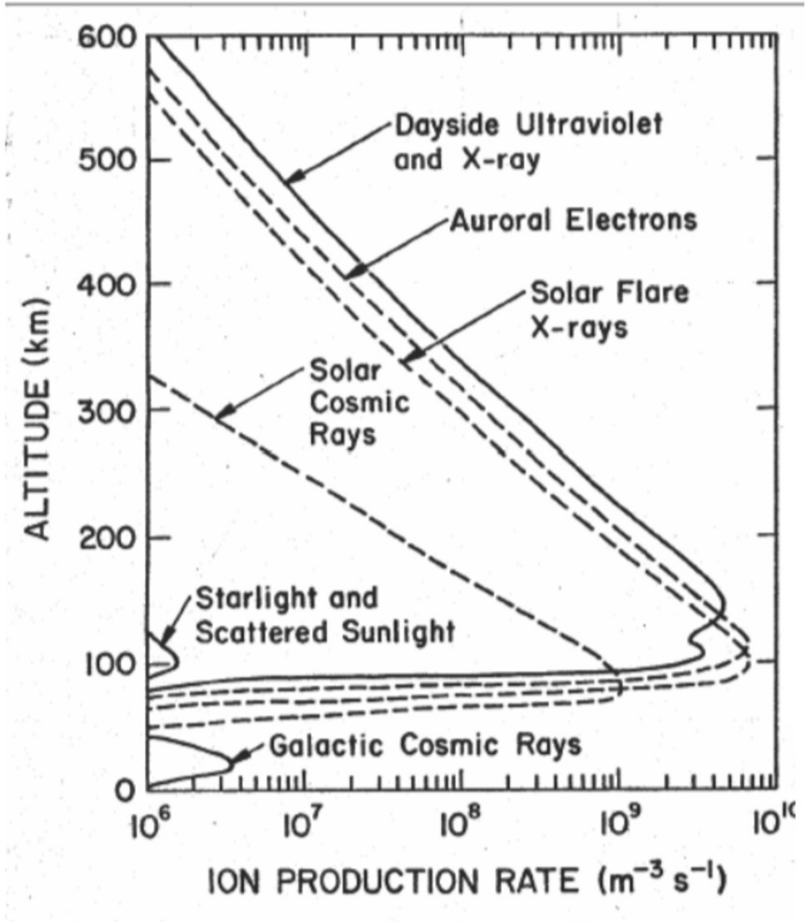
Measurements in the terrestrial ionosphere:



Origin of the airglow ?

Seen from the international space station

Other ionization processes in the ionosphere



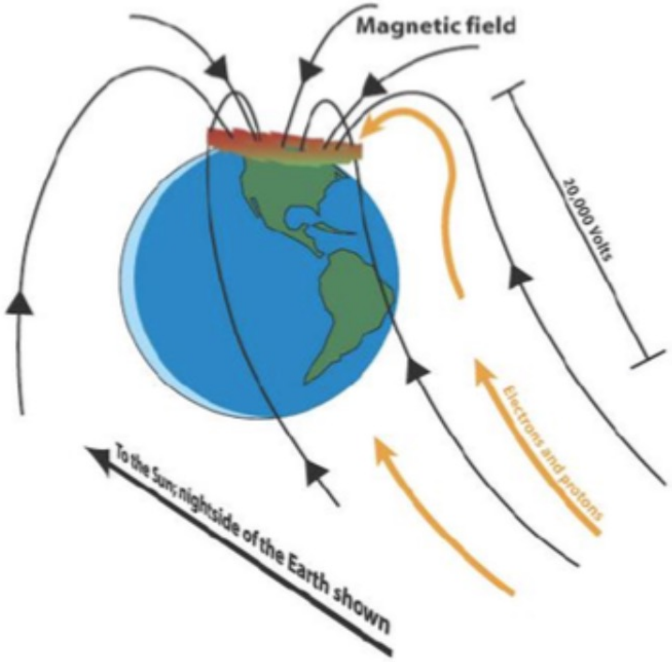
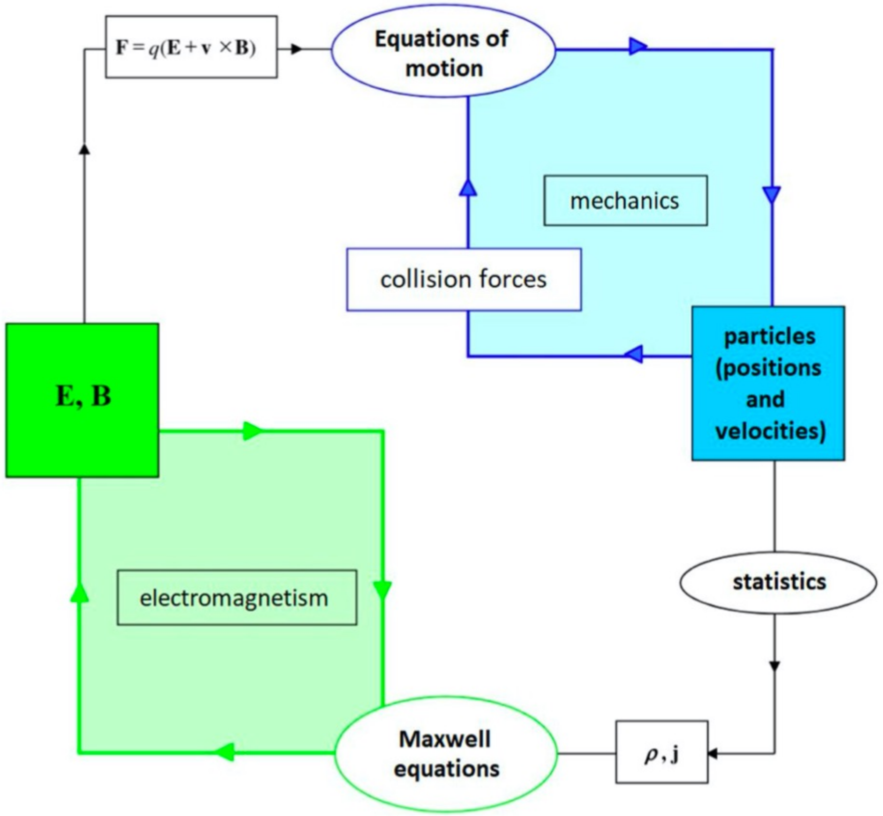


Photo credit: Fabrice Mottez

Plasma physics: collective phenomena

- As we shall see in a forthcoming lecture, collisions may not be very effective in a plasma, and the physics is not only controled by particle-particle interactions, but also by interactions of particles with a mean electromagnetic field.



Collective plasma phenomena, general scheme

Electrostatic plasma scales

- In a neutral gas, dimensionned parameters are m, n and T.

$\Rightarrow$ We can build two scales, $\ell = n^{-1/3}$ and $c = \sqrt{kT/m}$

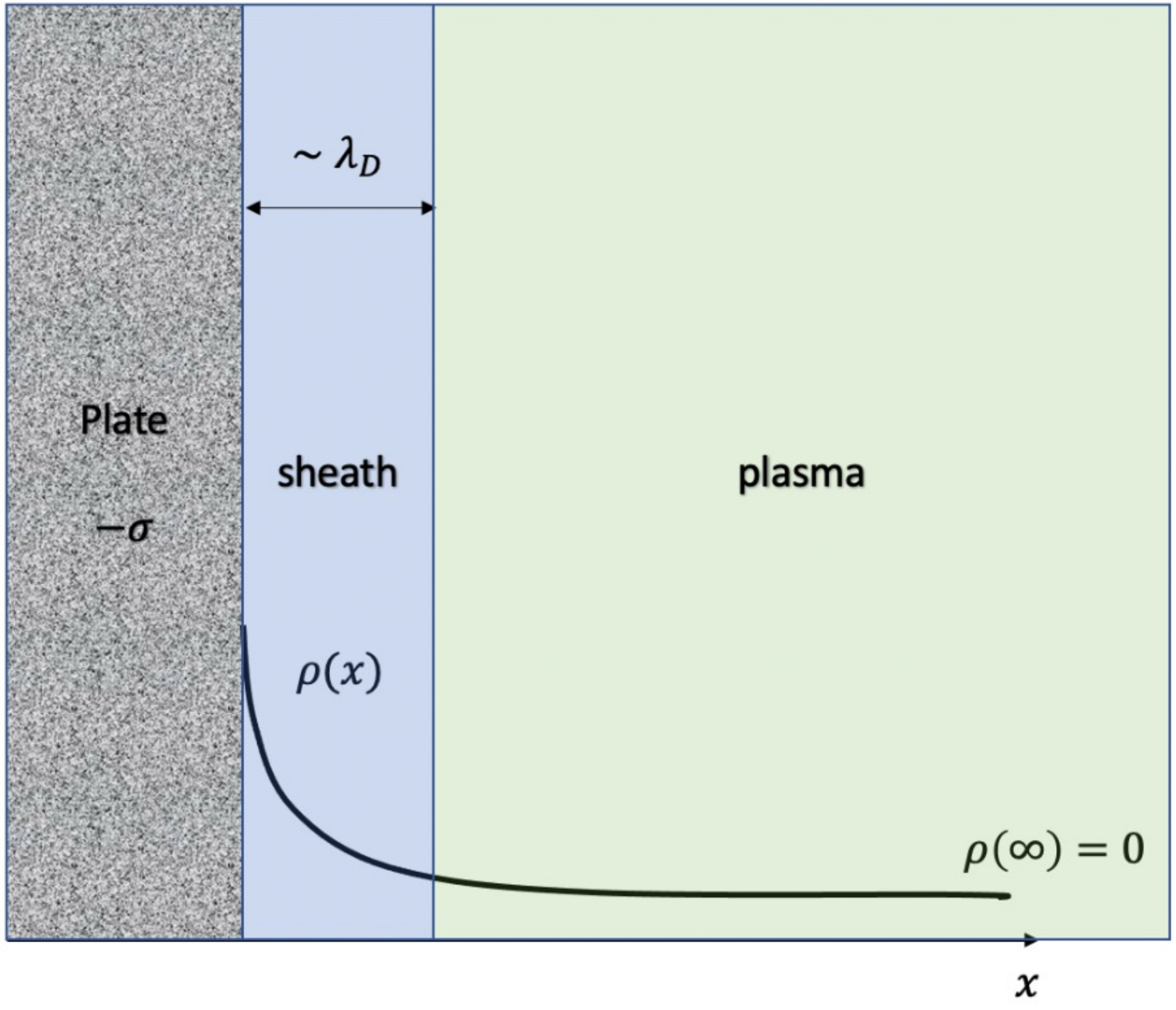
- In a charged gas, new parameters q and ϵ_0 comes into play (only the ratio q^2/ϵ_0 can enter in the equations). New scales appear

$\Rightarrow$ Length scales $\lambda_D = \sqrt{\epsilon_0 kT/nq^2}$ and $\lambda_L = q^2/\epsilon_0 kT$ (actually, $\lambda_D^2 \lambda_L = \ell^3$)

$\Rightarrow$ Timescale $\omega_p = \sqrt{nq^2/m\epsilon_0} = c/\lambda_D$

- In the following, we investigate the physical significance of these scales

Steady state limit: The Debye screening



Poisson equation

$$\Delta\varphi(r) = -\frac{2en_\infty}{\varepsilon_0}\sinh\left(\frac{e\varphi(r)}{kT}\right).$$

Potential as a function of z

$$\varphi = \varphi_0 e^{-z/\lambda_D}, \qquad \lambda_D^2 = \frac{\varepsilon_0 kT}{2n_\infty e^2}$$

Space-charged sheath

$$\rho(z) = e(n_i - n_e) = \frac{-2e^2 n_\infty}{kT}\varphi(z) = -\frac{\varepsilon_0\varphi(z)}{\lambda_D^2}$$

The plasma parameter

- The calculation made above (and quasi-neutrality) assumed that $\Gamma = \frac{1}{n\lambda_D^3} \ll 1$
- Γ is called the plasma parameter. The previous condition is easily fulfilled in all (even very sparse) astrophysical ionized media.
- The plasma parameter orders the plasma scales $\Gamma = \ell^3/\lambda_D^3$, and $\Gamma^2 = \lambda_L^3/\ell^3$
- As a consquence,

$$\lambda_L \ll \ell \ll \lambda_D$$

The Panekoek-Rossland atmosphere

- Consider the case of an ionized atmosphere, ions of mass m_i and charge +e, electrons of mass m_e, both at temperature T.

- Density profiles for the species : $n_j(z) = n_{0,j}\exp(-\frac{z}{H_j})$, with $H_e \gg H_i$

- Neutrality problem: an electric field arise.

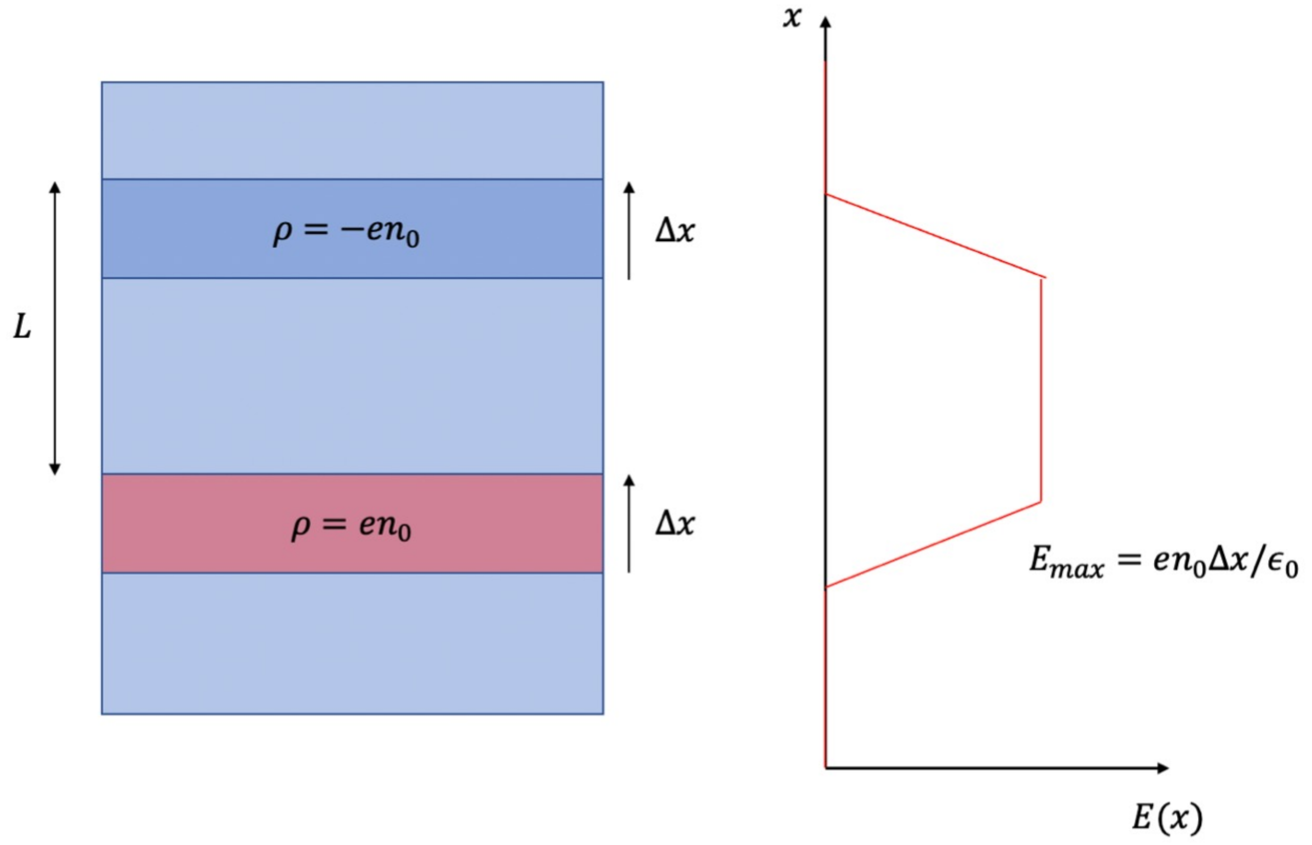
- Taking into a steady-state electric field E_{PR} in the force balance, while imposing everywhere quasi-neutrality (assumption $\frac{\lambda_D}{H} \ll 1$), we obtain

$$-2kT\frac{dn}{dz} - n(m_e + m_i)g = 0 \Rightarrow n(z) = n_0 e^{-z/H}, \qquad H = \frac{2kT}{m_i g}$$

- And the Panekoek-Rossland electric field $E_{PR} = mg/2e$

- Stellar atmospheres, ionospheres…

Collective phenomena: time response



Equation de Poisson :

$$\frac{dE}{dx} = -\frac{e(n_0 - n_e(x))}{\varepsilon_0} \Rightarrow E(x) \sim en_0\Delta x/\epsilon_0$$

Dynamique :

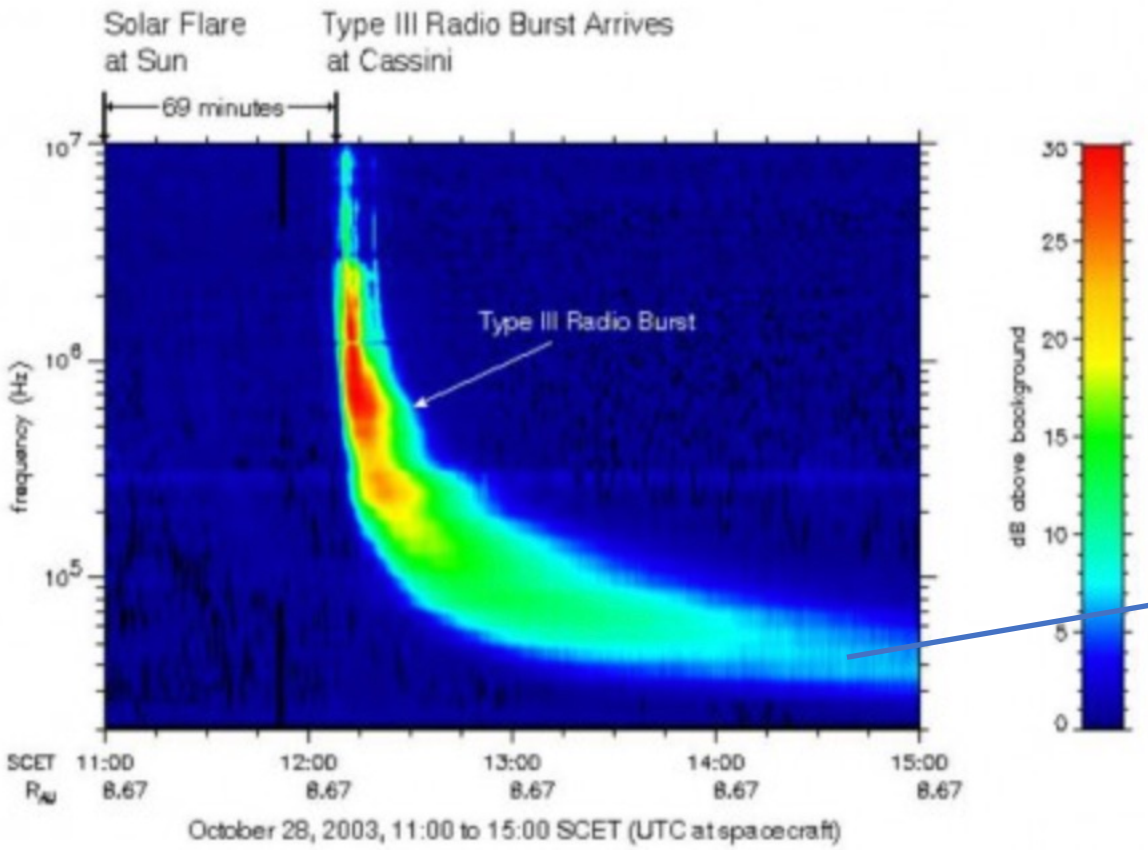
$$\frac{d^2\Delta x}{dt^2} = -\frac{eE}{m} = -\frac{e^2 n_0}{m\varepsilon_0}\Delta x,$$

Finalement :

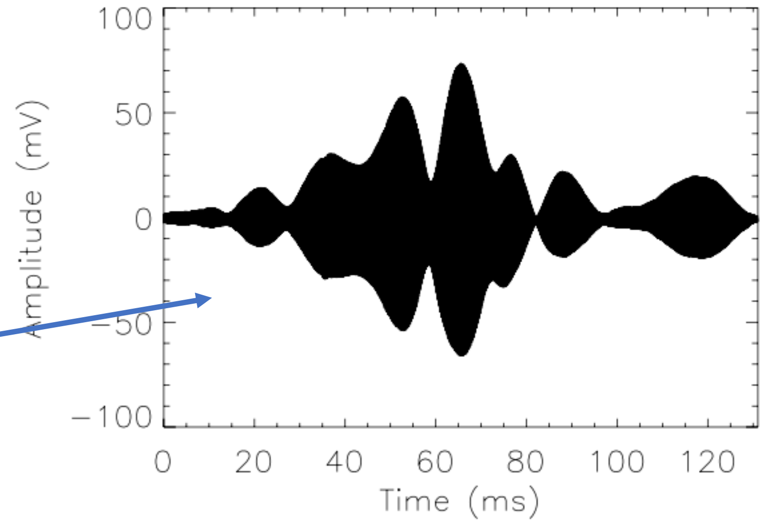
$$E(0 < x < L, t) \simeq \frac{en_0\Delta x_0}{\epsilon_0}\cos\omega_p t$$

The plasma oscillation : space observations, type III bursts

A type III radio burst



In-situ :



Propagation of a transverse EM wave in a plasma

- Consider the problem of the propagation of a transverse wave in a plasma. The wave equation is

$$\Delta \mathbf{E} - \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu_0 \frac{\partial \mathbf{j}}{\partial t},$$

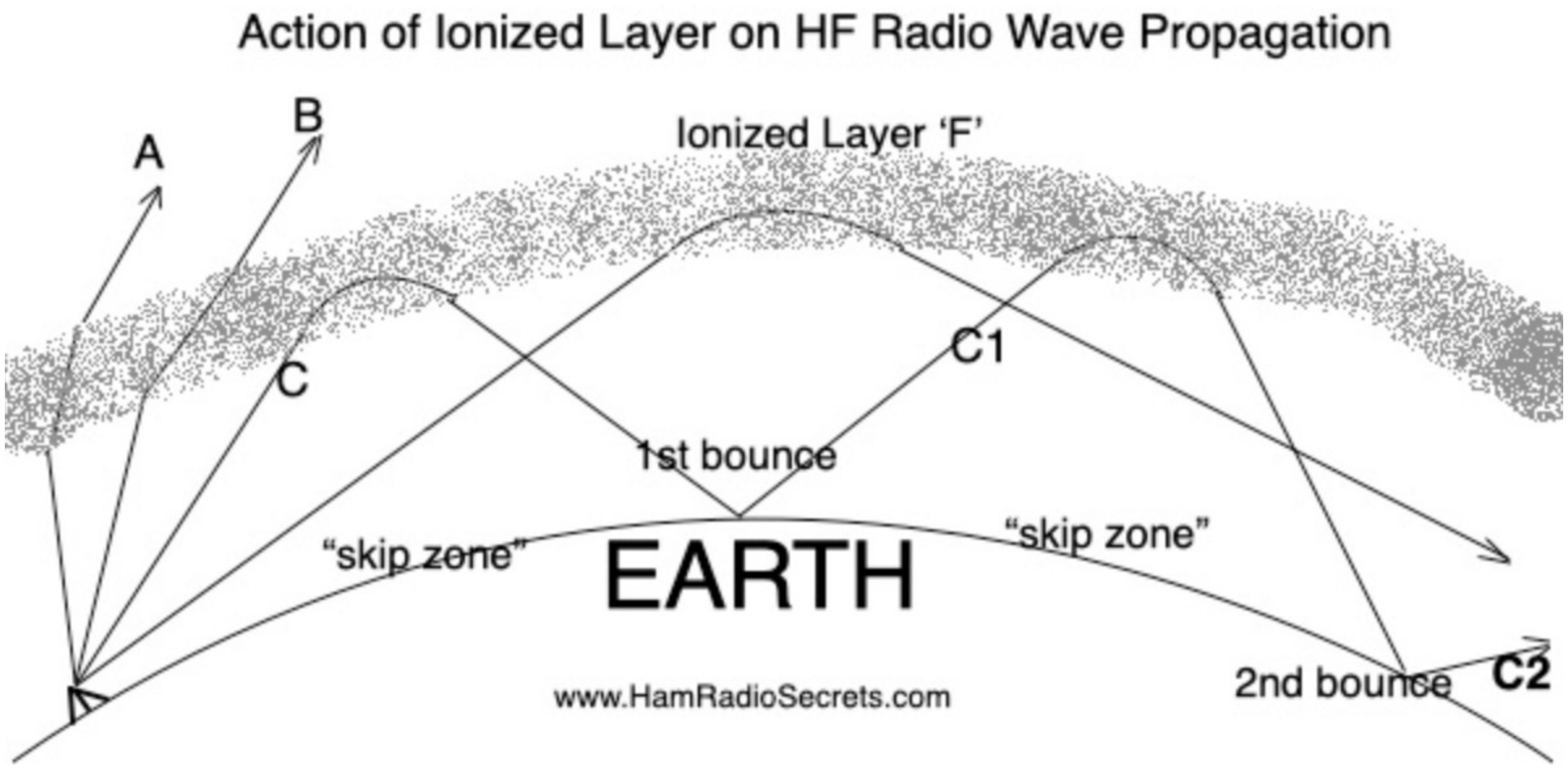
- And the linearized source term is $\mathbf{j} = n_0 e \mathbf{u}_e$ with $\dfrac{\partial \mathbf{u}_e}{\partial t} = -\dfrac{e}{m_e}\mathbf{E},$

- So that $\Delta \mathbf{E} - \dfrac{1}{c^2}\left(\dfrac{\partial^2}{\partial t^2} + \omega_p^2\right)\mathbf{E} = 0$

- The dispersion relation is $\omega^2 = \omega_p^2 + k^2 c^2$

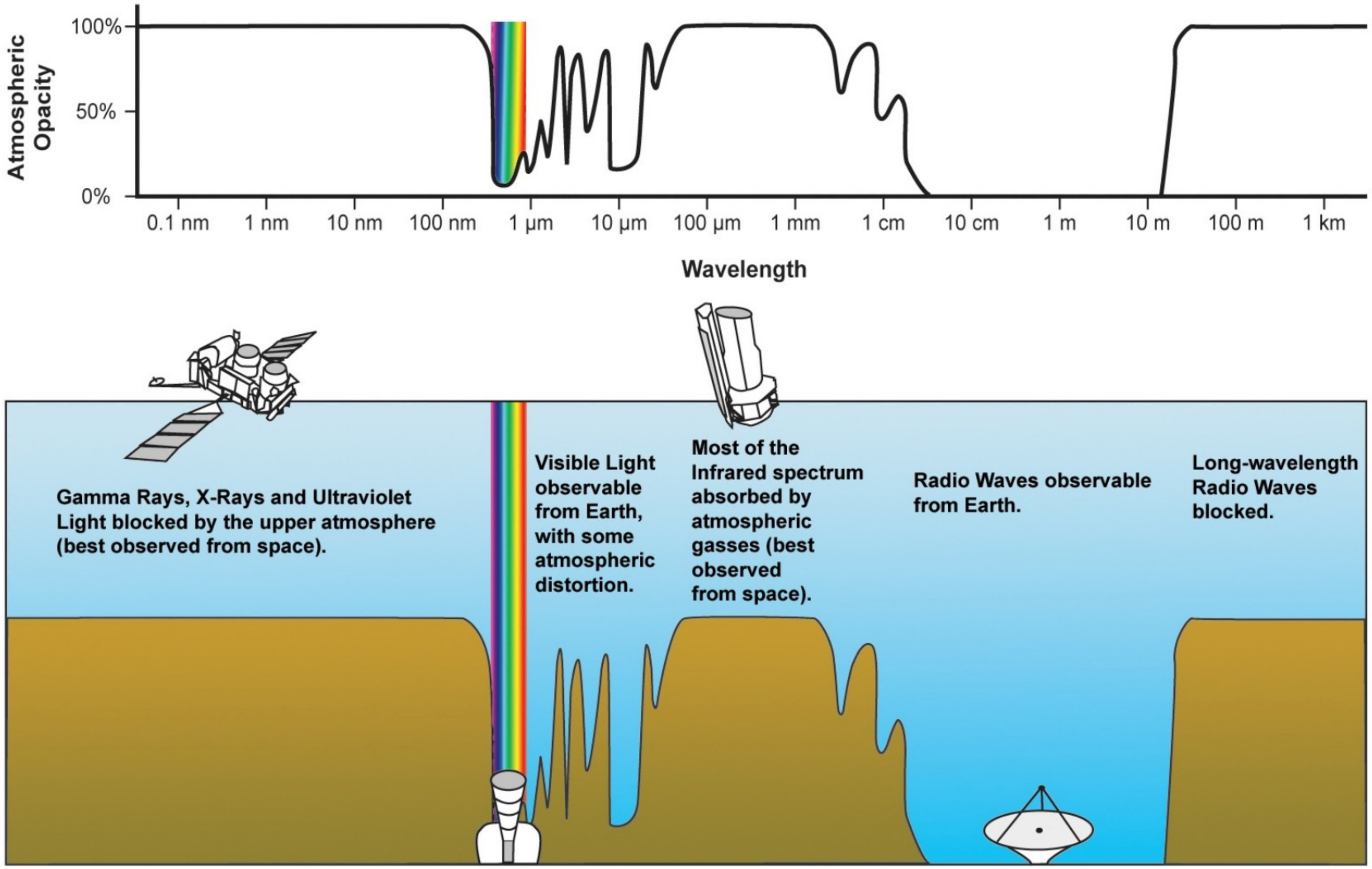
- And the refractive index is $n = \dfrac{kc}{\omega} = \sqrt{1 - \dfrac{\omega_p^2}{\omega^2}} < 1.$

Long distance radio communication

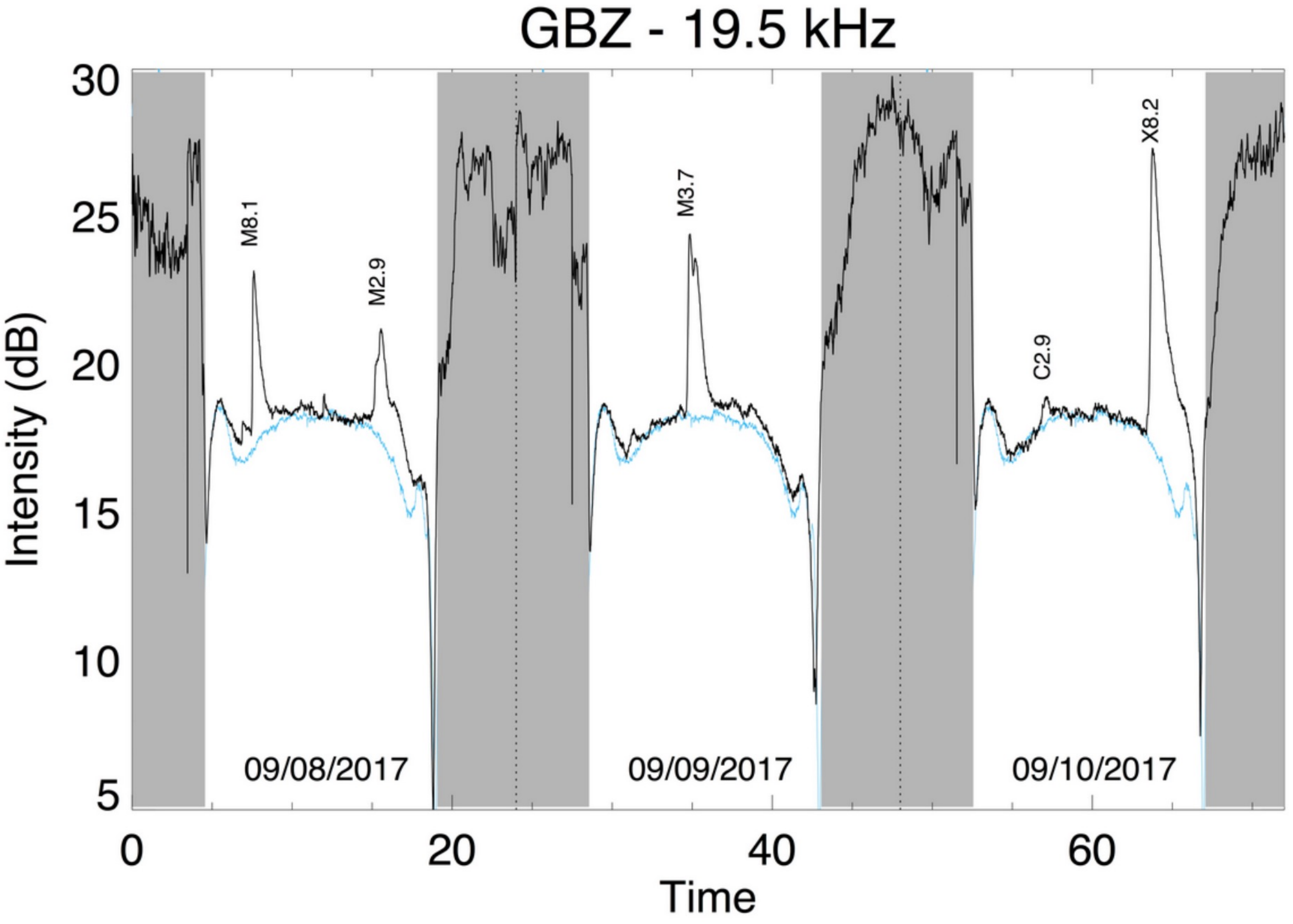


1901 : Marconi « crosses the Atlantic » with a radio transmission at 300 kHz

Atmospheric opacity



Ionospheric wave transmission



Monitoring the solar activity by observing VLF signals (the solar activity influences the ionospheric ionization degree)