Διαστημικό Περιβάλλον

Space Envirounment

Space Environment
Lecture 4

Sun, Solar Wind, Plasma

Why study the Sun?

- As a star, it's only one of many, and not so uniquely interesting.
- But as a plasma-physics laboratory, it is relatively nearby and has many interesting features: it is uniquely resolvable via many "messengers".

"If it weren't for its magnetic field, the Sun would be as boring as people think it is" – Robert Leighton (Caltech)

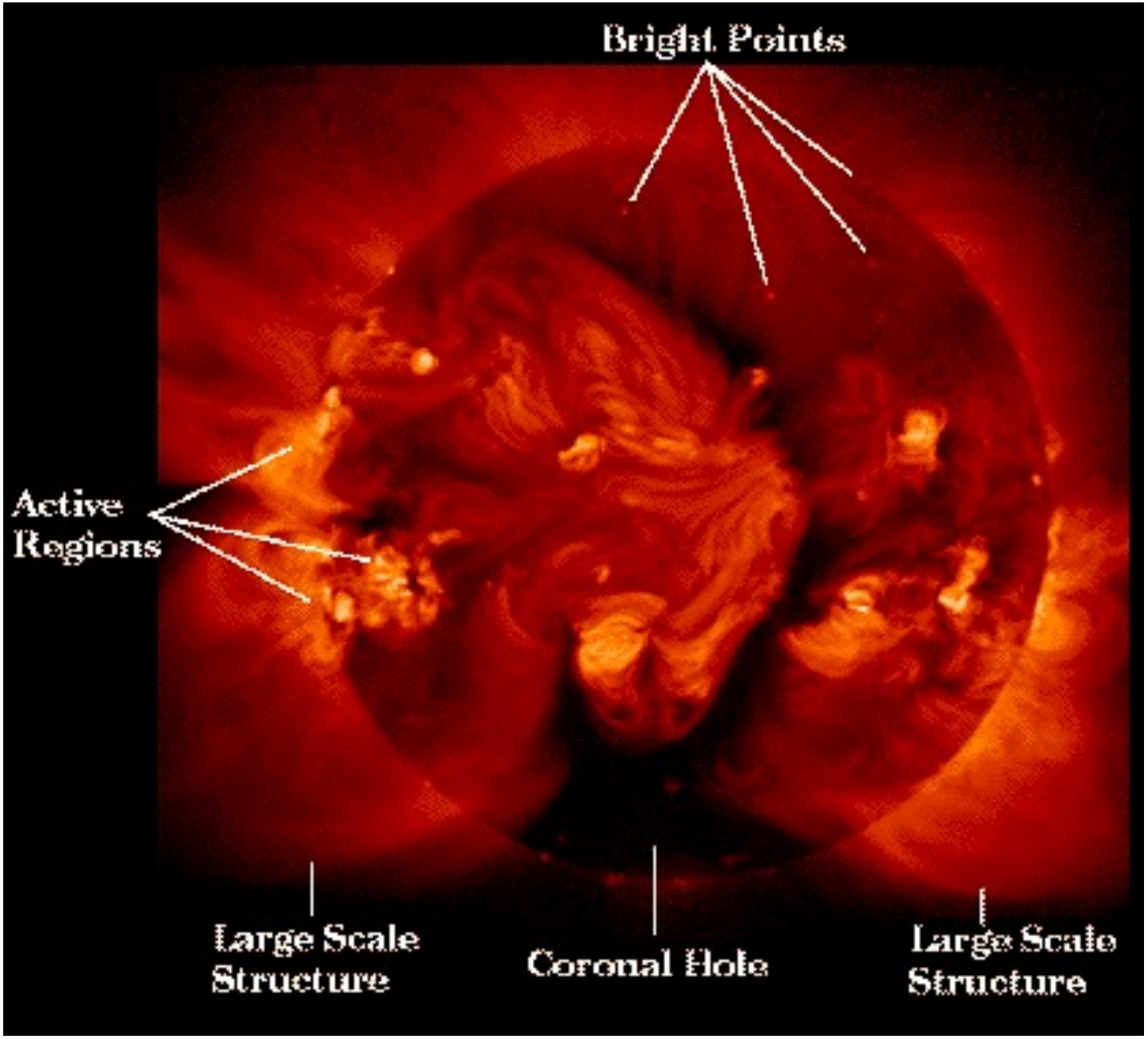
"Magnetism is to astrophysics as sex is to psychoanalysis, it explains everything that we don't understand" – Hendrik van de Hulst (Leiden)

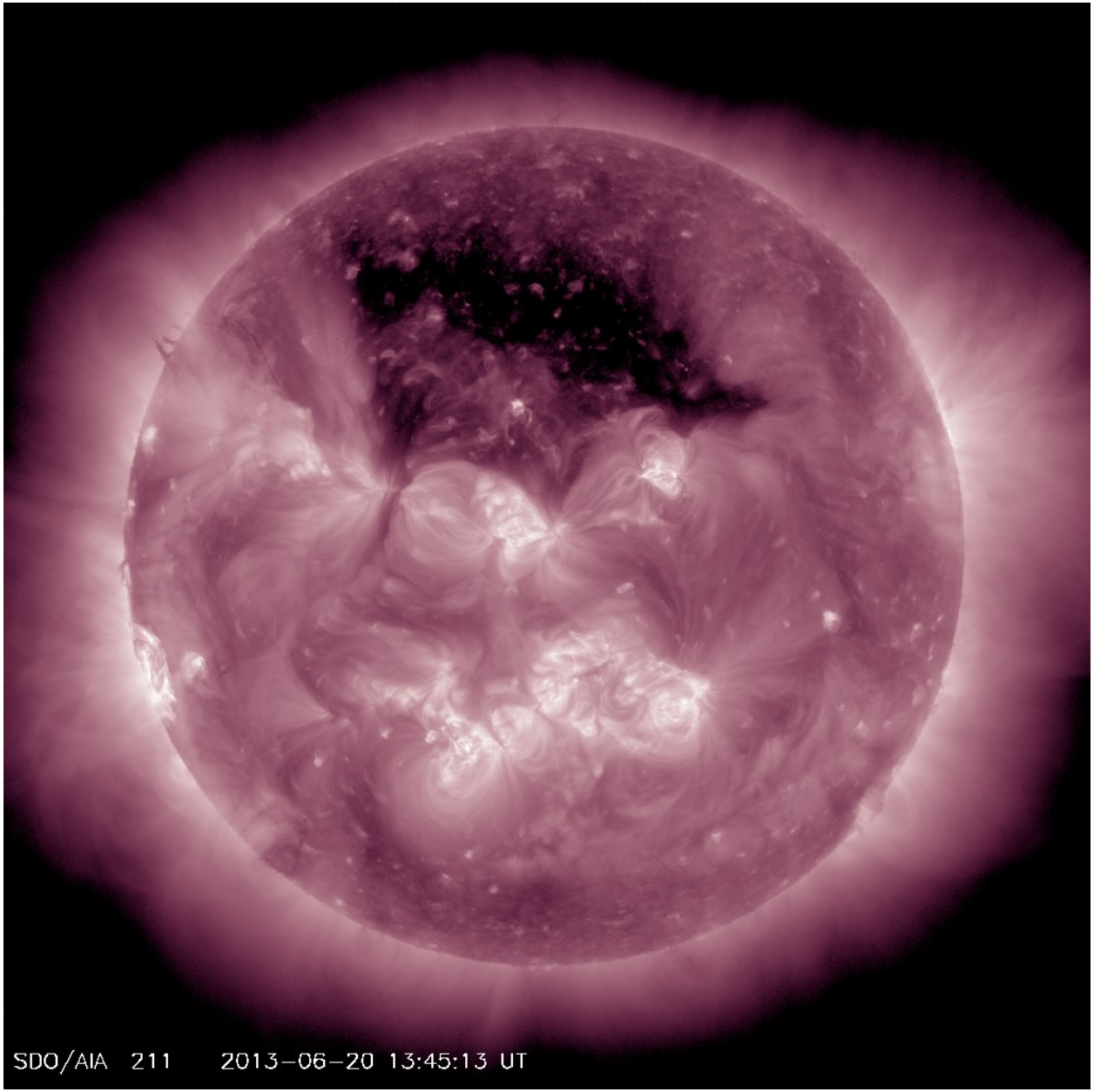
Περιορισμοί που σχετίζονται με την τηλεμετρία

- Telemetry is a crucial constraint for solar satellite observations, **limiting the cadence** of imaging instruments and/or the **spatial resolution**, and **reducing the quantity of spectral information** produced
- Initially, EIT on SOHO was allocated 1 kilobit/s (kbs) telemetry rate, corresponding to only 6 full-disk images/day!
- SOHO has a standard science telemetry rate of 40 kbs (=PSTN dialup …)

Solar-A Yohkoh 1991-2005(5 arcsec)

A dynamic magnetic world





SDO
2010-…
(0.6 arcsec)

Περιορισμοί που σχετίζονται με την τηλεμετρία

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- SOHO has a standard science telemetry rate of 40 kbs (**=PSTN dialup …**)

Περιορισμοί που σχετίζονται με την τηλεμετρία

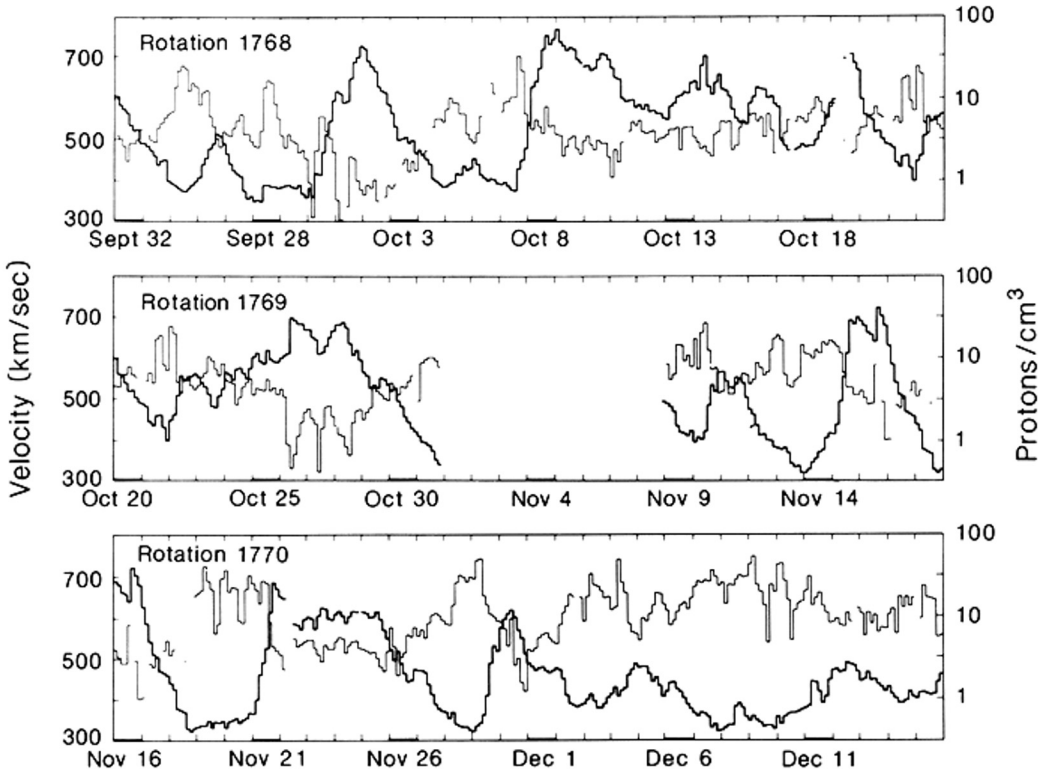
- Initially, EIT on SOHO was allocated 1 kilobit/s (kbs) telemetry rate, corresponding to only 6 full-disk images/day!
- SOHO has a standard science telemetry rate of 40 kbs (**=PSTN dialup …**)
- SDO: 150 Mbs (=4000x higher)

Η ατμόσφαιρα του Ήλιου είναι ασταθής και εξαχνώνεται με τη μορφή ενός αδιάκοπου ανέμου προς όλα τα σημεία του ηλιακού συστήματος.

Θεωρητική πρόβλεψη: K. Birkeland, 1908 / A. Eddington, 1910 / **L. Bierman, 1951 / E. Parker, 1958**

Πειραματική επιβεβαίωση: Luna 1, 1959 / **Mariner 2, 1962**

Apollo 11 Solar Wind Composition Experiment



Mariner 2, 1962

Η δραματική διαφορά θερμοκρασίας από τη φωτόσφαιρα στο στέμμα είναι αυτή που οδηγεί στη γέννηση του ηλιακού ανέμου

Η ενέργεια που εκλύεται από τον Ήλιο
μεταδίδεται/μεταφέρεται
από το πλάσμα
και το διαπλανητικό μαγνητικό πεδίο

Είδη ενέργειας:

- Θερμική της άτακτης θερμικής κίνησης των σωματιδίων (Τ)
- Κινητική της συντεταγμένης κίνησης του ρευστού (Κ)
- Δυναμική του μαγνητικού πεδίου(Β)

Ενεργειακή πυκνότητα:

η ενέργεια που εμπεριέχεται

στη μονάδα του όγκου

και είναι διαθέσιμη

για την παραγωγή έργου

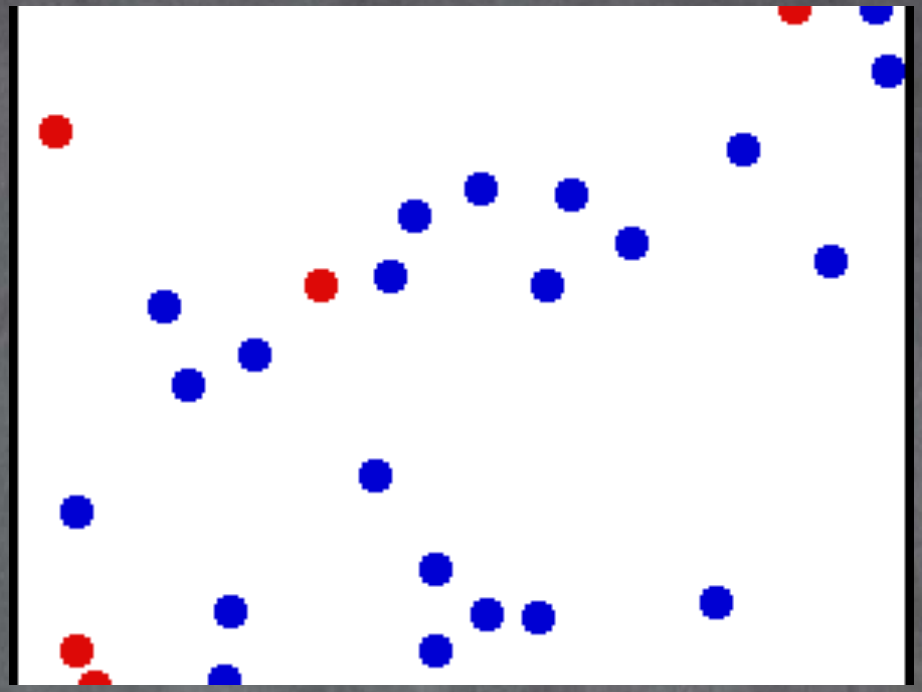
ενεργειακή πυκνότητα
(ενέργεια / όγκο)

$\cong$

πίεση
(δύναμη / επιφάνεια)

Είδη πίεσης

1. Θερμική



Θερμοκρασία = Κινητική ενέργεια

Είδη πίεσης

1. Θερμική: $n\, k_B\, T$

n = πλήθος σωματιδίων / V
k_B = σταθερά Boltzmann
$(1.38 \times 10^{-23}\ J/K)$
T = Θερμοκρασία

Είδη πίεσης

2. Δυναμική

Είδη πίεσης

2. Δυναμική: ρv^2

ρ = πυκνότητα (kg/m^3)

v = ταχύτητα ροής ηλιακού ανέμου (m/s)

Είδη πίεσης

3. Μαγνητική

Είδη πίεσης

3. Μαγνητική: $B^2 / 2\mu_0$

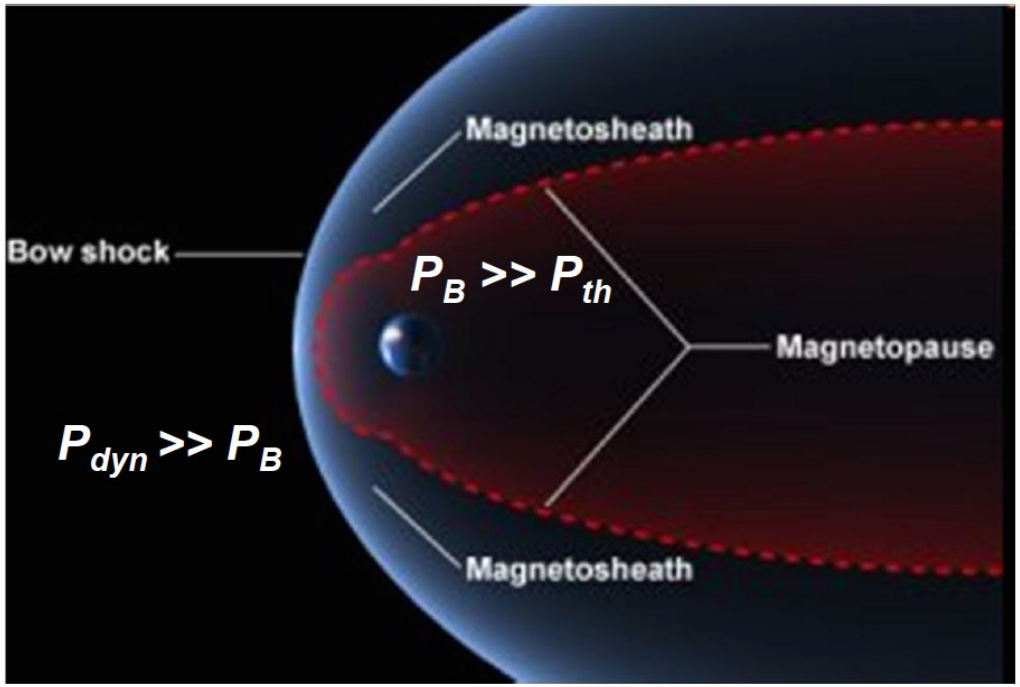
B = ισχύς μαγνητικού πεδίου (T)

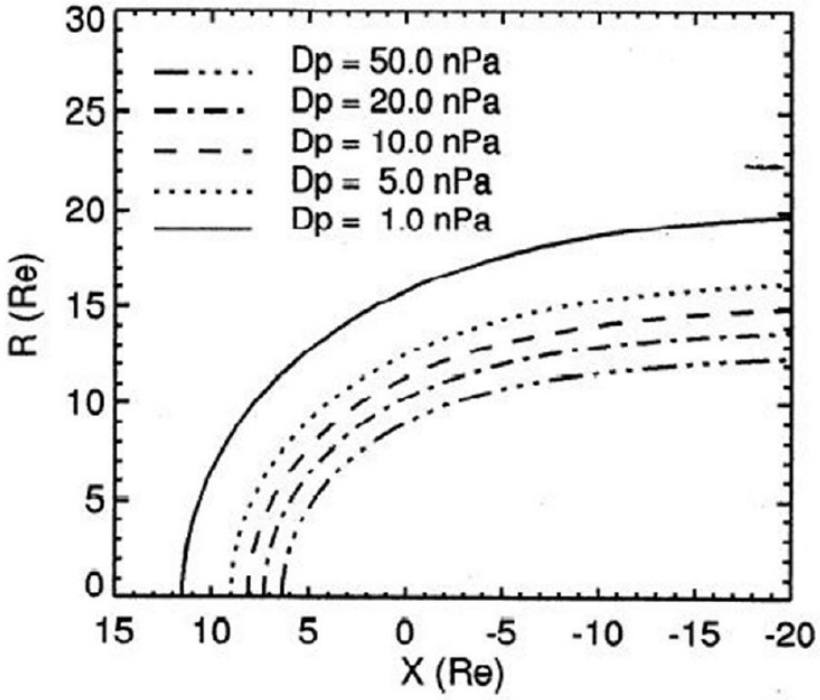
μ_0 = μαγνητική διαπερατότητα

$(1.26 \times 10^{-6}\ N/A^2)$

Magnetopause

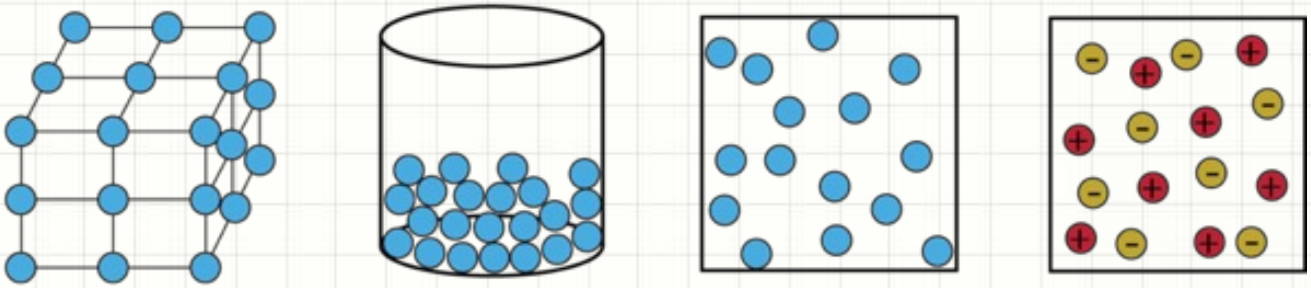
- 1930 Chapman and Ferraro
- 1960s: in-situ evidence (Explorer 10&12)
- nose at ~10 RE





States of Matter

= atom
= nucleus
= electron



Add Heat

Τί χαρακτηρίζουμε πλάσμα;

Την ιονισμένη ύλη

Τί χαρακτηρίζουμε πλάσμα;

Την ιονισμένη ύλη

Αέρια στα οποία

ιόντα και ηλεκτρόνια

ζουν **ελεύθερα** και **ανεξάρτητα**

A plasma is an

ionised gas

that is in a state of

electrical quasi-neutrality

(οιονεί ηλεκτρική ουδετερότητα)

the behaviour of which is governed by

collective effects

due to long-range electromagnetic interactions

between the charged particles

Πλάσμα

Ιονισμένο αέριο
που αποτελείται από

θετικά και αρνητικά φορτισμένα σωματίδια

με περίπου ίσες πυκνότητες φορτίου
δηλ. $n_i = n_e$

Πλάσμα

Μπορεί να δημιουργηθεί
από θέρμανση
ενός συνηθισμένου αερίου
έτσι ώστε η **κινητική ενέργεια** των ατόμων
να ξεπεράσει την **ενέργεια ιονισμού** τους.

Πλάσμα

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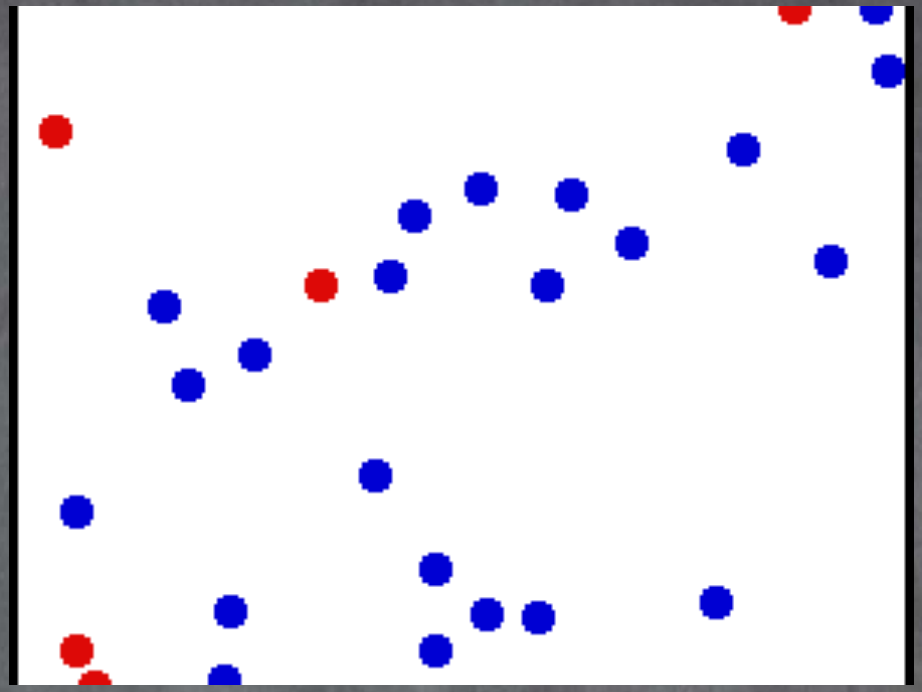
έτσι ώστε η **κινητική ενέργεια** των ατόμων
να ξεπεράσει την **ενέργεια ιονισμού** τους.
Τότε οι συγκρούσεις έχουν ως αποτέλεσμα την απελευθέρωση ηλεκτρονίων.
Αυτό αρχίζει να συμβαίνει σε θερμοκρασίες μερικών χιλιάδων Κ.



Θερμοκρασία = Κινητική ενέργεια

Πλάσμα

Ενέργεια ιονισμού

Πλάσμα

Ενέργεια ιονισμού:

$X + energy \rightarrow X^{+} + e^{-}$

$X^{+} + energy \rightarrow X^{2+} + e^{-}$

$X^{2+} + energy \rightarrow X^{3+} + e^{-}$

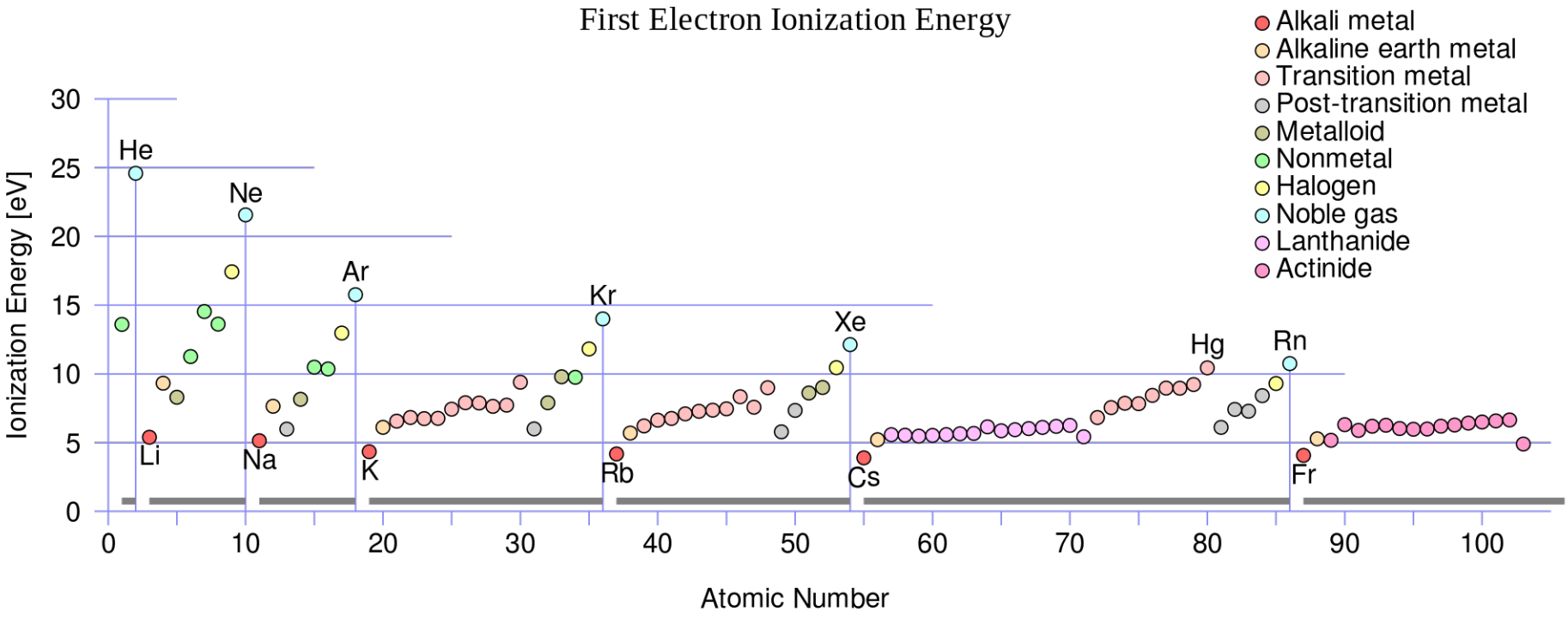
Για H: 13.59 eV

Για He: $1^{η}$ 24.58 eV, $2^{η}$ 54.42 eV

Πλάσμα

1 eV **αντιστοιχεί** σε 11,600 K,
διότι αυτή είναι η θερμοκρασία
που αν πολλαπλασιαστεί με τη σταθερά
Boltzmann $k_B = 1.38 \times 10^{-23}$ J/K
μάς δίνει 1.6×10^{-19} J –
που είναι η ενέργεια ενός eV:

1 eV = 1.6022×10^{-19} J


First Electron Ionization Energy
Alkali metal
Alkaline earth metal
Transition metal
Post-transition metal
Metalloid
Nonmetal
Halogen
Noble gas
Lanthanide
Actinide
Ionization Energy [eV]
Atomic Number
He
Ne
Ar
Kr
Xe
Hg
Rn
Li
Na
K
Rb
Cs
Fr
0
5
10
15
20
25
30
0
10
20
30
40
50
60
70
80
90
100

Τί χαρακτηρίζουμε πλάσμα;

Την ιονισμένη ύλη

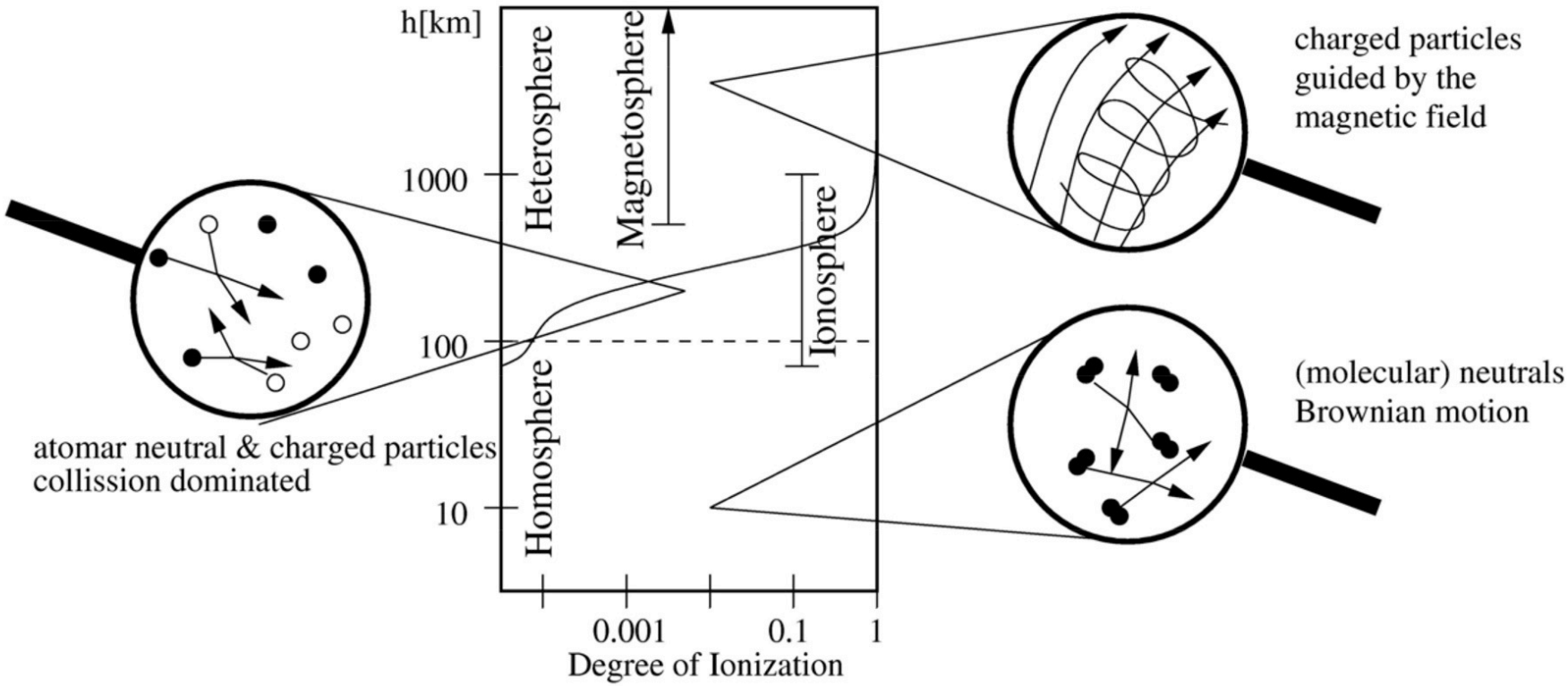
Πόσο ιονισμένη;

Πόσο ιονισμένη;

τόσο ιονισμένη (με τόσα ελεύθερα φορτία)
ώστε να έχει συλλογική συμπεριφορά
καθορισμένη από ΗΛΜ δυνάμεις

Πόσο ιονισμένη;

Since thermal decomposition **breaks interatomic bonds before ionizing**, most terrestrial plasmas begin as gases. In fact, a plasma is sometimes defined as a gas that is sufficiently ionized to exhibit plasma-like behaviour. Note that **plasma-like behaviour ensues after a remarkably small fraction of the gas has undergone ionization**. Thus, fractionally ionized gases exhibit most of the exotic phenomena characteristic of fully ionized gases.



Degree of ionization depends on

- intensity of the ionizing radiation,
- number of particles available for ionization, and
- recombination.

Εξίσωση Saha

temperature (eV)

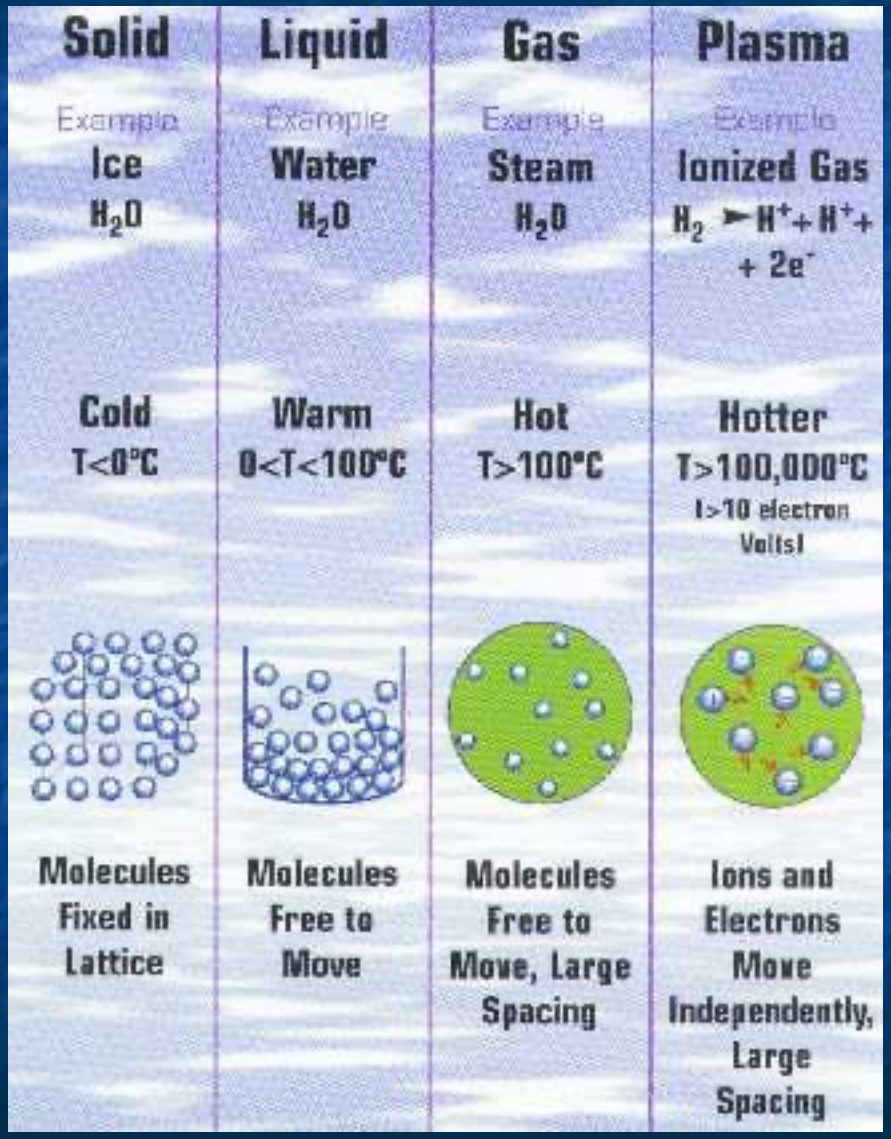
Degree of ionization from Saha's Eq.

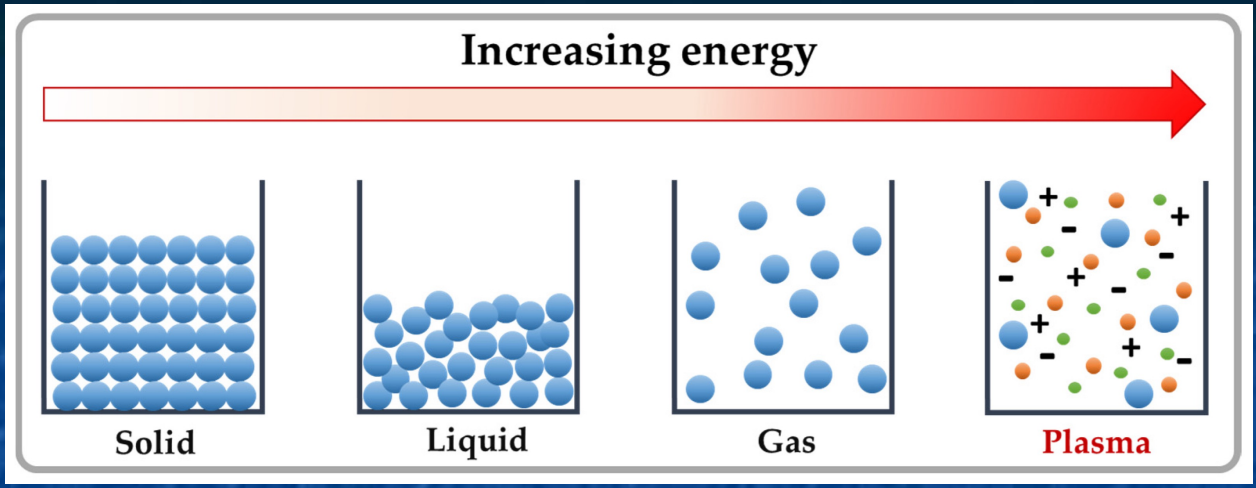
$$\frac{n_i}{n_n} = 3\times 10^{27}\,\frac{T^{3/2}}{n_i}\,e^{-U/T}$$

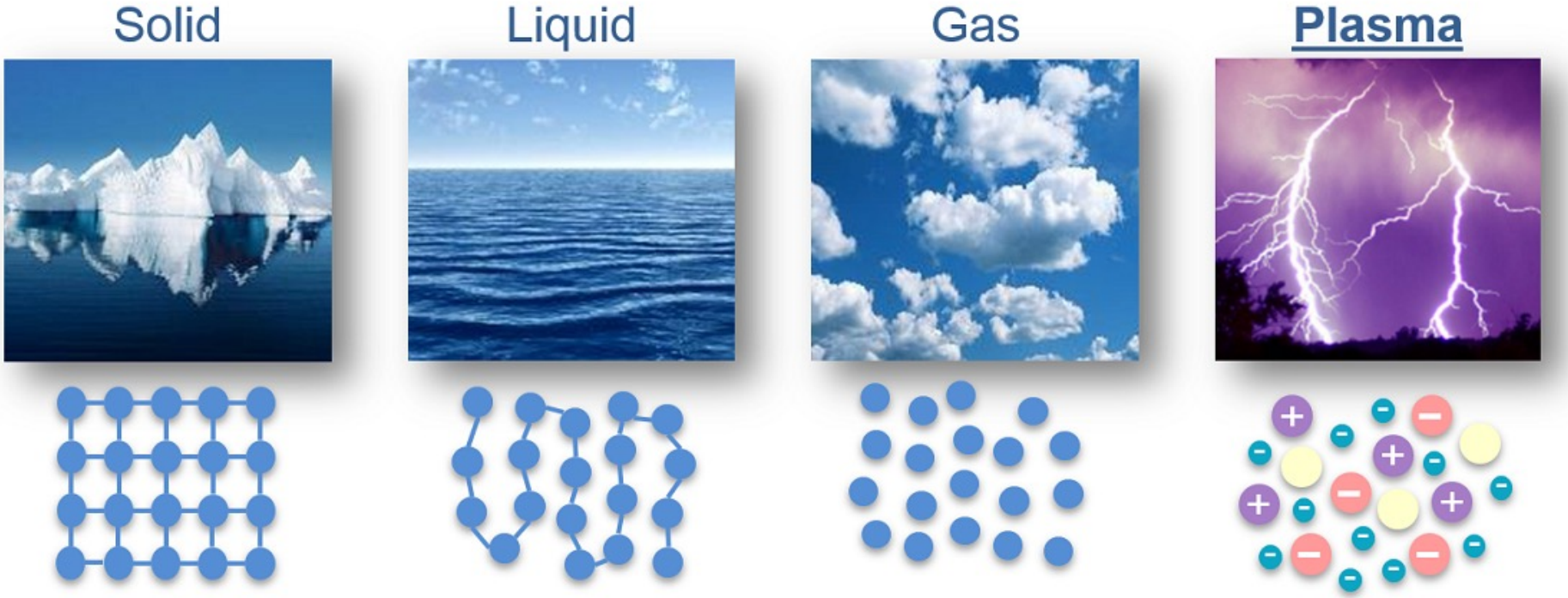
1 eV = 11,600 K

Ionization energy

Πλάσμα – η περίπτωση του νερού




Increasing energy
Solid
Liquid
Gas
Plasma


Solid
Liquid
Gas
Plasma


Δύο σε ένα

A plasma is an **ionised gas** that is in a state of electrical **quasi-neutrality**, the behaviour of which is governed by **collective effects** due to **long-range electromagnetic interactions** between the charged particles

Χαρακτηριστικές Παράμετροι Πλάσματος

Πυκνότητα ηλεκτρονίων $n_e = n_p$

Θερμοκρασία ηλεκτρονίων $T_e \neq T_p$

Βαθμός ιονισμού (από εξίσωση Saha)

Μήκος Debye λ_D

Παράμετρος Πλάσματος N_D

Συχνότητα πλάσματος ω_{pe}

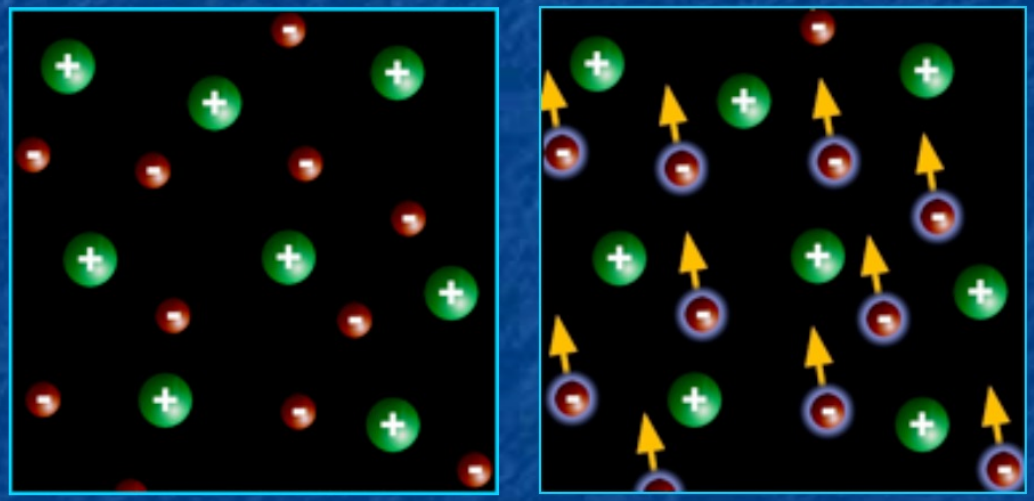
Definition

Plasma is loosely described as an electrically neutral medium of unbound positive and negative particles (i.e. the overall charge of a plasma is roughly zero). It is important to note that although they are unbound, these particles are not 'free' in the sense of not experiencing forces. When the charges move, they generate electric currents with magnetic fields, and as a result, they are affected by each other's fields. This governs their collective behavior with many degrees of freedom.[3][7] A definition can have three criteria:[*clarification needed*][8][9]

1. **The plasma approximation**: Charged particles must be close enough together that each particle influences many nearby charged particles, rather than just interacting with the closest particle (these collective effects are a distinguishing feature of a plasma). The plasma approximation is valid when the number of charge carriers within the sphere of influence (called the *Debye sphere* whose radius is the Debye screening length) of a particular particle is higher than unity to provide collective behavior of the charged particles. The average number of particles in the Debye sphere is given by the plasma parameter,[*ambiguous*] "Λ" (the Greek uppercase letter Lambda).
2. **Bulk interactions**: The Debye screening length (defined above) is short compared to the physical size of the plasma. This criterion means that interactions in the bulk of the plasma are more important than those at its edges, where boundary effects may take place. When this criterion is satisfied, the plasma is quasineutral.
3. **Plasma frequency**: The electron plasma frequency (measuring plasma oscillations of the electrons) is large compared to the electron-neutral collision frequency (measuring frequency of collisions between electrons and neutral particles). When this condition is valid, electrostatic interactions dominate over the processes of ordinary gas kinetics.

Some basic plasma properties

What defines plasma response? ⇒ *Start Qualitative*



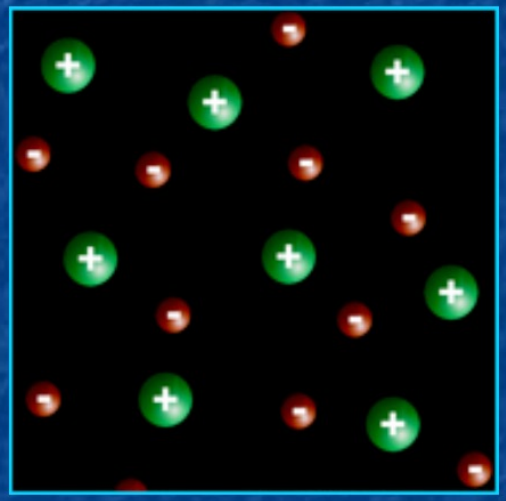
Q: What if we displace the electrons by a small amount in a fully ionized plasma?

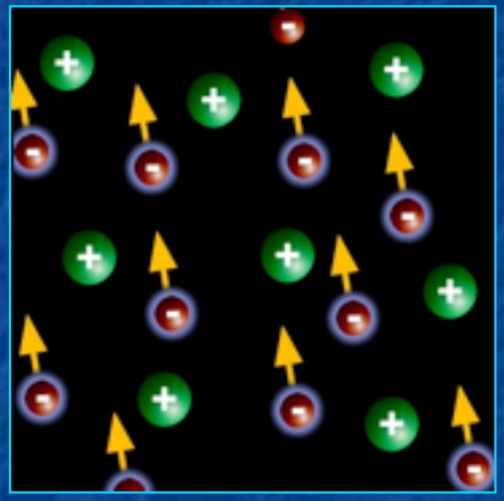
A: The electrons will feel a restoring force that pulls them back to the original ('equilibrium') position, analogous to the motion of a mass on a spring. The electrons will oscillate with a characteristic frequency related to the density of the plasma.

⇒ Known as the Electron Plasma Frequency

Some basic plasma properties

What defines plasma response? ⇒ *Now Quantitative*





Q: What if we displace the electrons by a small amount in a fully ionized plasma?

Spring Analogy

Spring Force $$\frac{\mathrm{d}^2 x}{\mathrm{d}t^2} = -\frac{k}{m}x$$

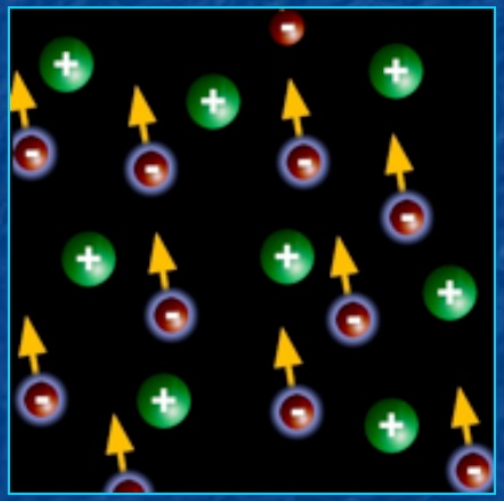
Spring Frequency $$\omega = \sqrt{\frac{k}{m}}$$

Plasma Frequency $$\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \varepsilon_\circ}}$$

⇒ Known as the Electron Plasma Frequency

Some basic plasma properties

What defines plasma response? ⇒ *Now Quantitative*



Plasma Frequency $\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \varepsilon_\circ}}$

Things to note:

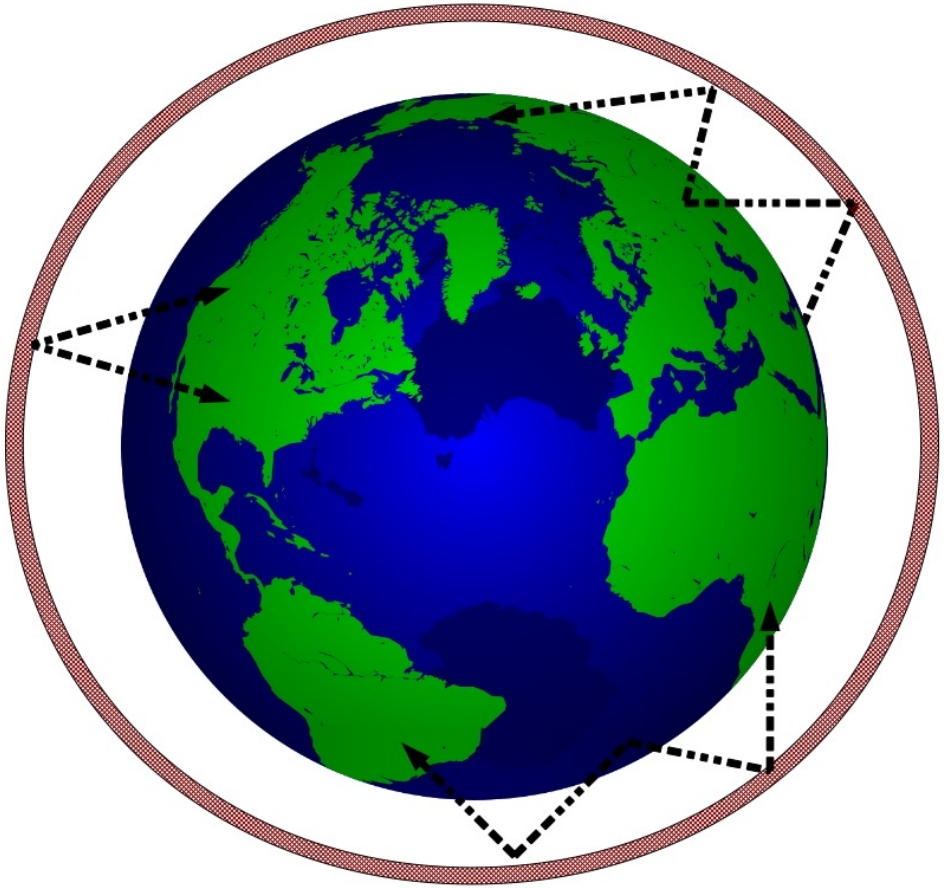
- m_e is << m_i , therefore the electrons are more mobile and characterize the response of the plasma as a whole to disruptions to quasineutrality
- In a partially ionized plasma (the ionosphere for example), the plasma frequency must be much higher than the collision frequency with neutrals in order to respond as a plasma to electric and magnetic perturbations.

Συχνότητα πλάσματος

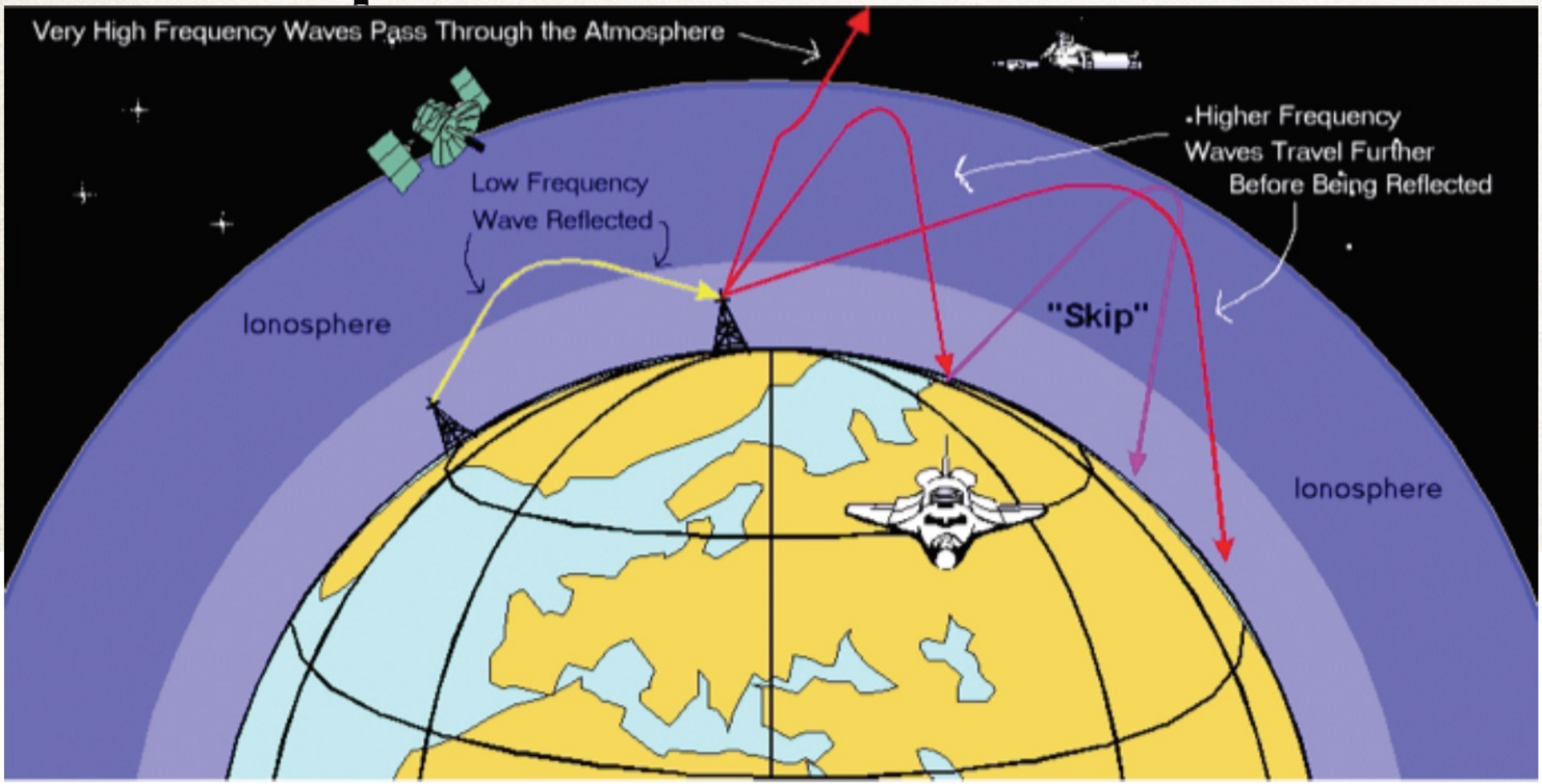
$$\omega_{\mathrm{pe}} = \sqrt{\frac{n_{\mathrm{e}} e^2}{m^* \varepsilon_0}}, [\mathrm{rad/s}] \text{ (SI units)}$$

$$f_{\mathrm{pe}} = \frac{\omega_{\mathrm{pe}}}{2\pi} \ [\mathrm{Hz}]$$

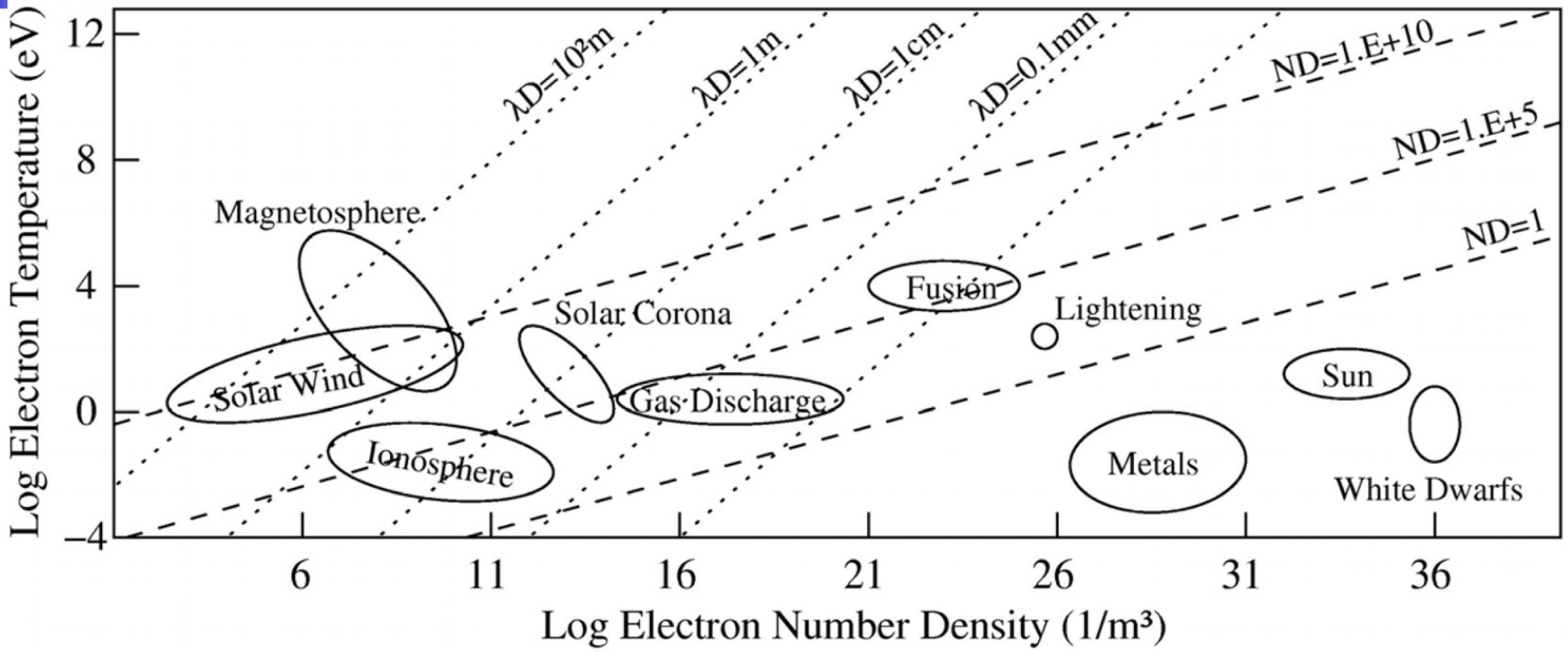
Κρίσιμη συχνότητα

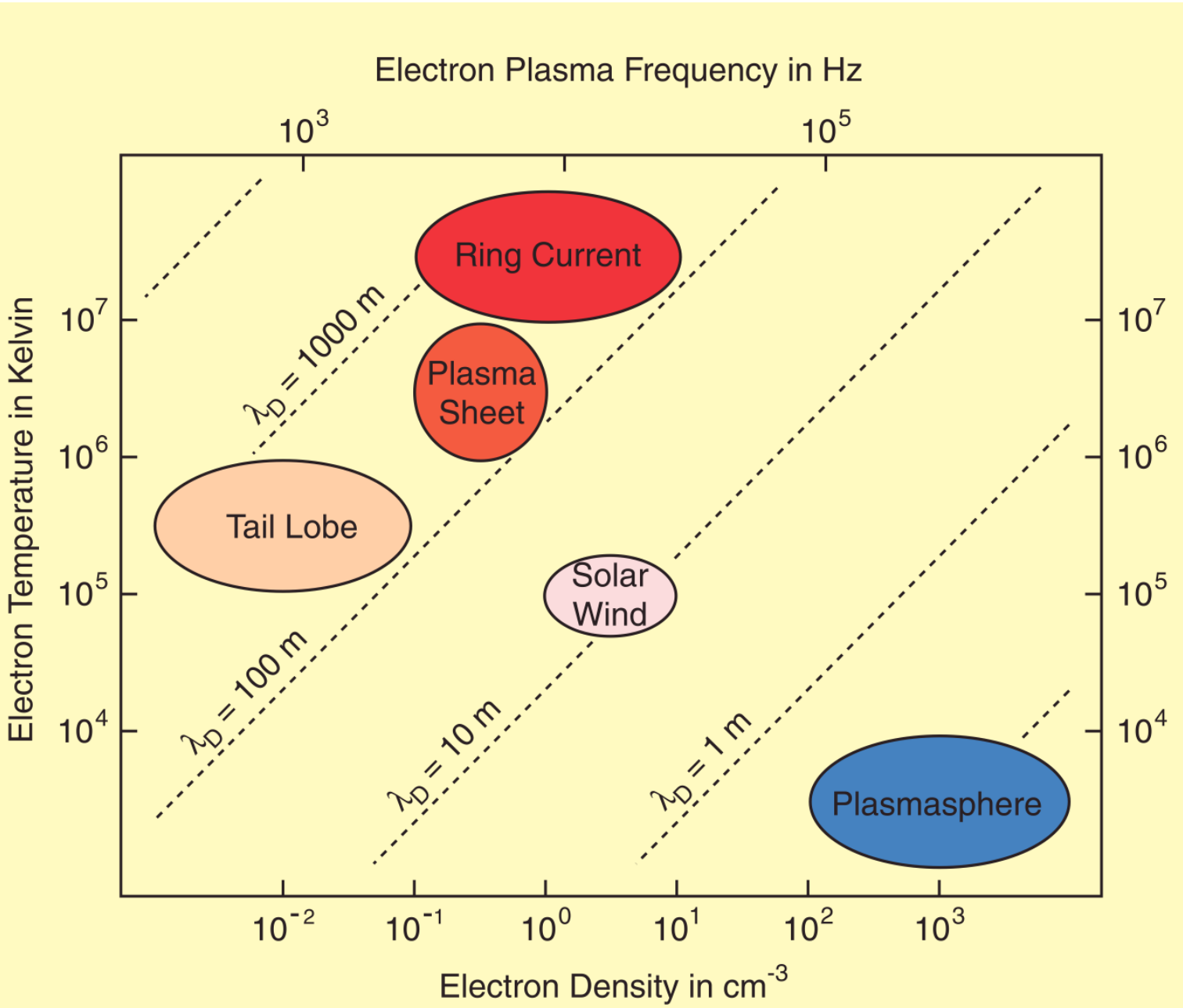


Ionospheric cutoff at ~10 MHz:



nT-Diagram


Log Electron Temperature (eV)
12
8
4
0
−4
6
11
16
21
26
31
36
Log Electron Number Density (1/m³)
λD=10²m
λD=1m
λD=1cm
λD=0.1mm
ND=1.E+10
ND=1.E+5
ND=1
Magnetosphere
Solar Wind
Ionosphere
Solar Corona
Gas Discharge
Fusion
Lightening
Metals
Sun
White Dwarfs


Electron Plasma Frequency in Hz
10^3
10^5
Ring Current
Plasma Sheet
Tail Lobe
Solar Wind
Plasmasphere
λ_D = 1000 m
λ_D = 100 m
λ_D = 10 m
λ_D = 1 m
Electron Temperature in Kelvin
10^7
10^6
10^5
10^4
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
Electron Density in cm^{-3}

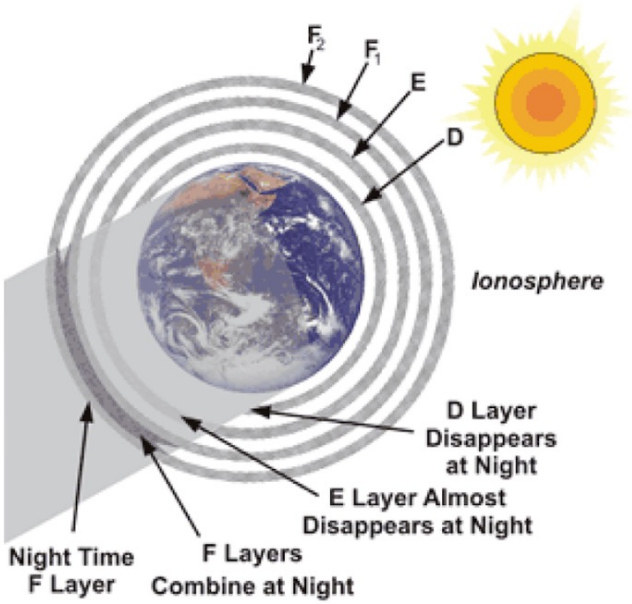
PLASMA ENVIRONMENTS

- Low Earth Orbit (LEO)
  - High Density (~10^5 cm^{-3} = 10^{11} m^{-3})
  - Low Temperature (~ 1,000 K)
  - Oxygen (O^+) and Electrons (e^-)
- Geosynchronous (GEO)
  - Low Density (~ 1 cm^{-3} = 10^6 m^{-3})
  - High Temperature (~1,000,000 K)
  - Protons (p^+) and Electrons (e^-)
- Auroral or Polar
  - Short Term Transitions Through High Energy Plasma When Crossing the Auroral Region (> 60^o Latitude)
    - The Worst of Both Worlds

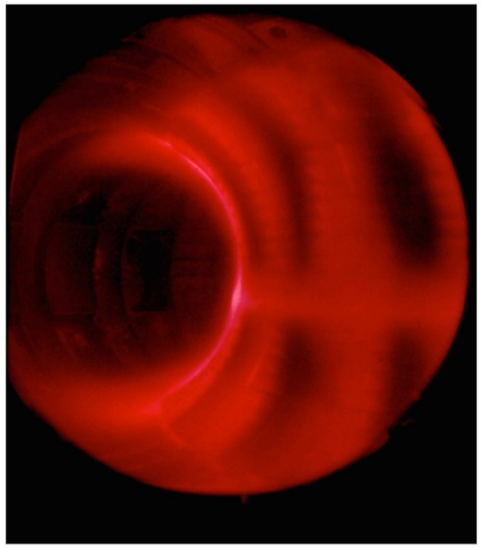
Πώς ιονίζονται τα άτομα της γήινης ατμόσφαιρας;

Plasma production:

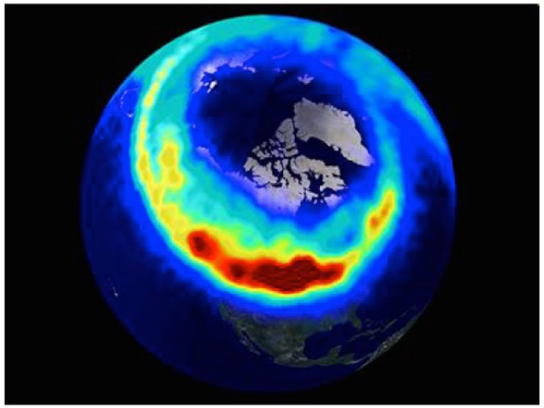
1) heating
2) ionizing radiation



Dayside ionosphere (solar UV)



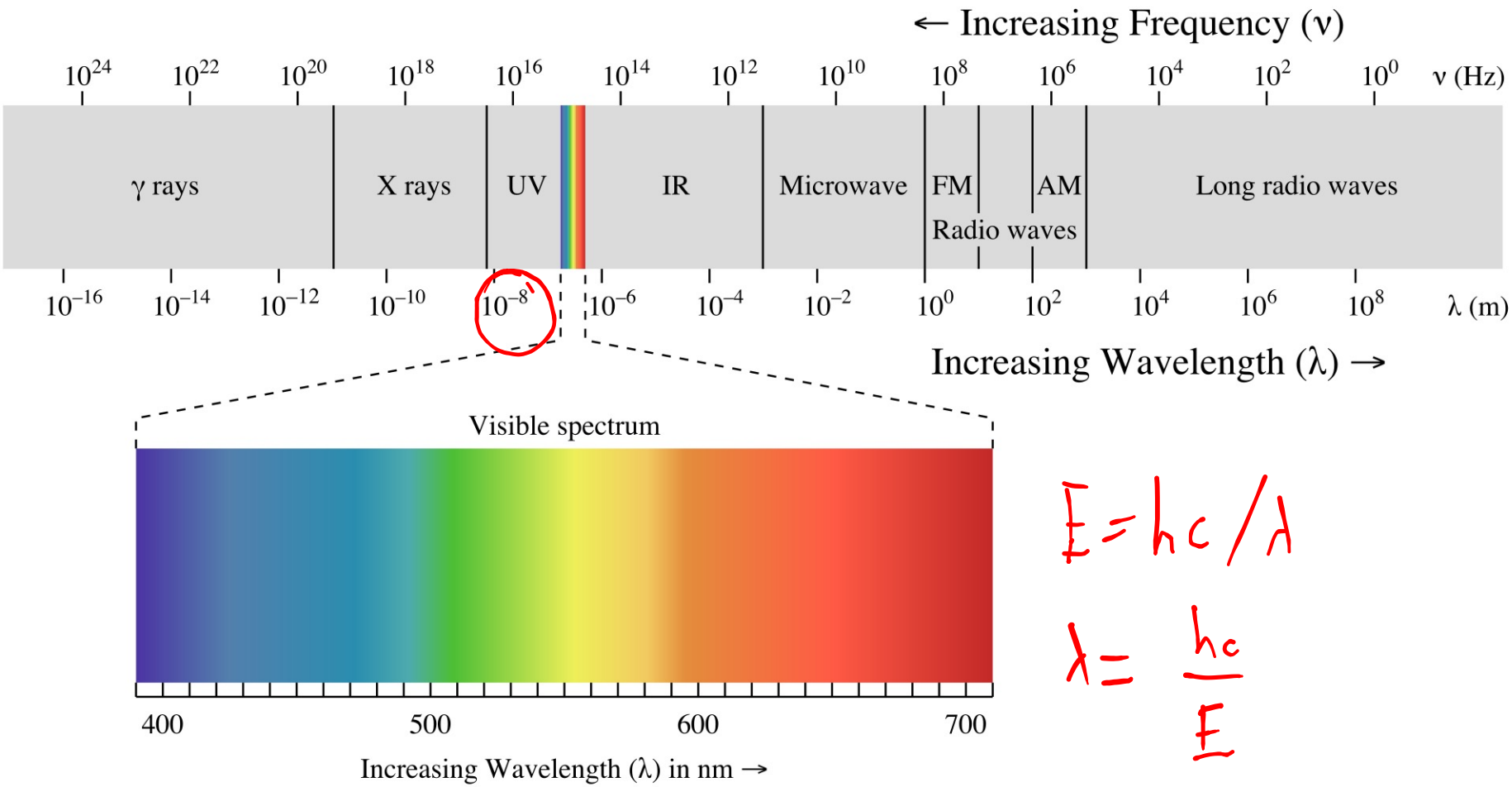
Glowing plasma inside a tokamak



Collisional ionization
auroral oval (precipitating ions and electrons)

Πώς ιονίζονται τα άτομα της γήινης ατμόσφαιρας;

Από το φως του Ήλιου



$$E = hc/\lambda$$

$$\lambda = \frac{hc}{E}$$

Πώς ιονίζονται τα άτομα της γήινης ατμόσφαιρας;

Από ποιο φως;