Electrodynamics and Radiative Processes I

Lecture 13 – Plasma effects

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Additional Ref
The Physics of Fluids and Plasma by Arnab Raichoudhuri
https://www.plasma-universe.com/

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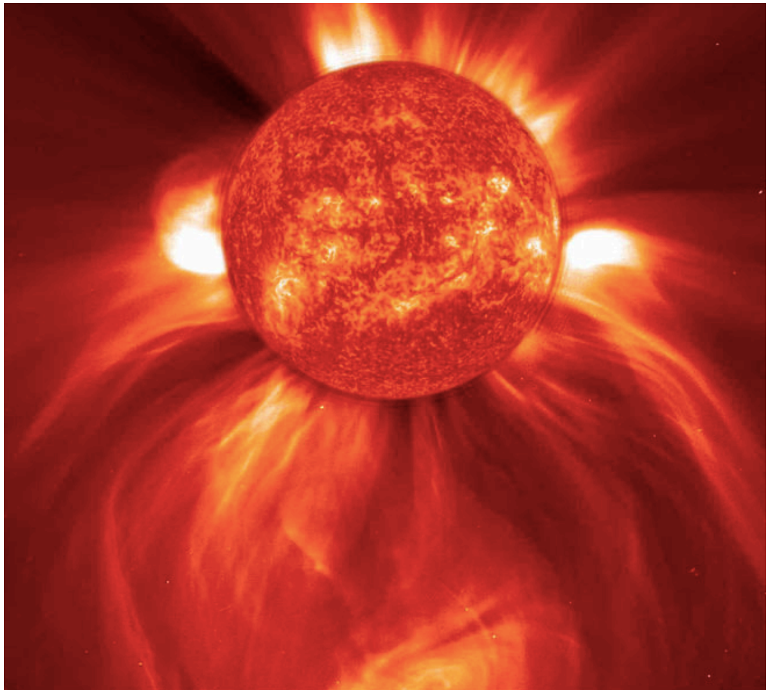
Plasma Effects

Most of the baryonic matter in the universe is plasma.

Magnetic fields play vital roles in astrophysical processes: star formation, thermal conduction, accretion, turbulence, particle acceleration, dynamos, etc.

Plasma astrophysics allows the study of phenomena at extreme regions of parameter space that are inaccessible in the laboratory.

Visible Universe is 99.999% plasma.
The Sun is about 100% plasma, as are all stars.
Plasma makes up nearly 100% of the interplanetary, interstellar and intergalactic medium. The Earth's ionosphere is plasma.

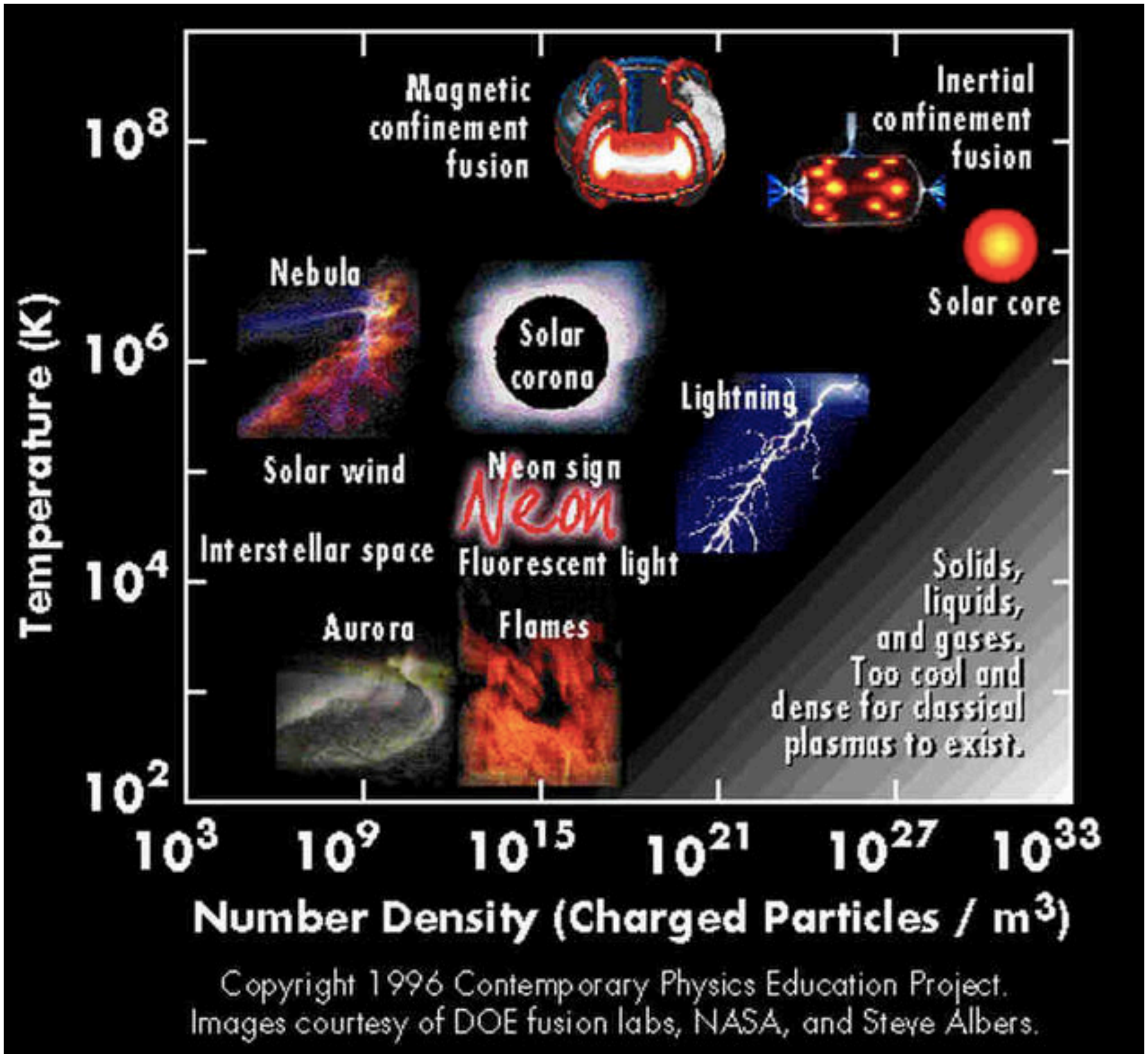


Standard definition of Plasma

- ✓ "Plasma" named by Irving Langmuir in 1920's
- ✓ The standard definition of a plasma is as the 4th state of matter (solid, liquid, gas, plasma), where the material has become so hot that (at least some) electrons are no longer bound to individual nuclei. Thus a plasma is <u>electrically conducting, and can exhibit collective dynamics.</u>
  A plasma is an ionized gas, or a partially-ionized gas (quasi-neutral).
- ✓ Even though the interaction between any pair of particles is typically weak, the collective interactions between many particles is strong. 2 examples: Debye Shielding & Plasma Oscillations.

Refer: https://www.plasma-universe.com/

Types of Plasma



The Plasma Universe is a term coined by Nobel Laureate Hannes Alfvén to highlight the importance of plasma throughout the Universe.

Plasma Effects

So far we have assumed that our propagation medium to be vacuum.

But radiation propagate through plasma.

A plasma is a gas in which an important fraction of the atoms is ionized, so that the electrons and ions are separately free.

Globally neutral, ionized gas is called plasma.

Plasma Effects

- Because some or all particles are electrically charged and capable of creating and interacting with electromagnetic fields, many phenomena not present in ordinary fluids and solids can be found in plasmas.

- A plasma is a conductor of electricity, but a volume with dimensions greater than the so-called Debye length exhibits electrically neutral behavior.

- At a microscopic level, corresponding to distances shorter than the Debye length, the particles of a plasma do not exhibit collective behavior but instead react individually to a disturbance, for example, an electric field.

Plasma Astrophysics

Most of the observable matter in the Universe has been in the plasma state. In this state, normal atoms have had some or all of their electrons ripped away because of intense heating or collisions.

On the largest scales, matter is dominated by gravity, but on smaller scales, those charged ions interact with each other and with electric and magnetic fields to help create structure and channel momentum and energy.

<u>Plasma astrophysics aims to study and help understand how plasmas behave in order to understand the detailed birth, evolution, and death of the wide variety of structures we can see in the universe: from stars and planetary systems, to galaxies and clusters of galaxies.</u>

Reference :http://www.bu.edu/csp/files/2014/08/Zweibel_BU_2014-v2.pdf

Dispersion in cold isotropic plasma

Relation between ω and k are called dispersion relation

Consider plasma of electrons with density n

For a medium with dielectric constant ε → $c^2k^2 = \epsilon\omega^2$ → Dispersion relation

Dielectric constant ε → $\epsilon = 1 - \left(\frac{\omega_p}{\omega}\right)^2$

Plasma frequency → $\omega_p^2 = \frac{4\pi n e^2}{m}$

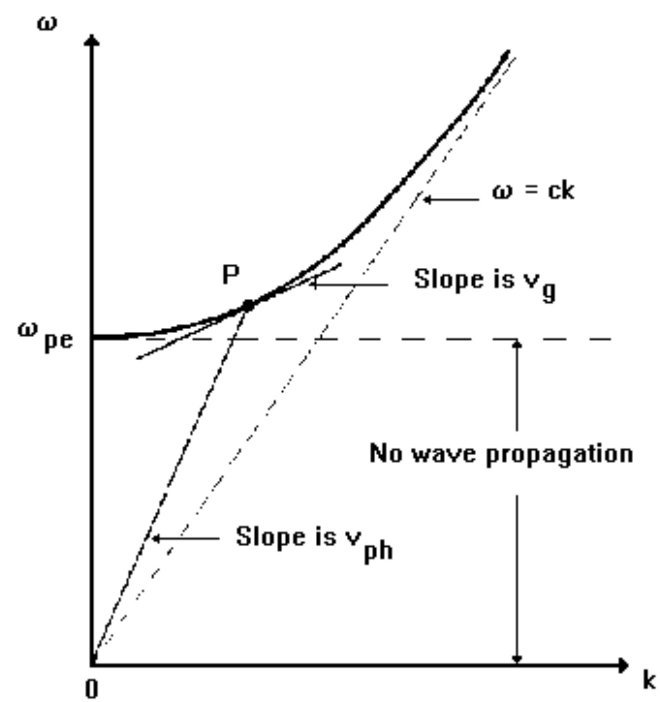
$\omega_p = 5.63 \times 10^4 n^{1/2}\ s^{-1}$, Plasma frequency for electron

Dispersion relation

All the information about the propagation of a given plasma wave mode is contained in the appropriate dispersion relation, which relates the angular frequency w to the wave number k (magnitude of the propagation vector k).

Some of the important parameters readily seen from the dispersion equation are:

(i) Phase velocity : v(ph)=w/k
(ii) Group velocity : v(g)=dw/dk
(iii) Propagation region frequency range where the wave is able to propagate
(iv) Reflection points: frequency at which the propagation region is limited by infinite phase velocity
(iv) Resonance points:
frequency at which energy can be transferred to plasma particles (zero phase velocity, and infinite group velocity)
(v) Wave growth or damping



Dispersion in cold isotropic plasma

Dispersion relation connecting k and ω can be written as

$$k = c^{-1}\sqrt{\omega^2 - \omega_p^2} \qquad \omega_p^2 = \frac{4\pi n e^2}{m}$$

$$\omega^2 = \omega_p^2 + k^2 c^2.$$

When $\omega<\omega_p$ the wave number is imaginary

ω_p : plasma cut off frequency below which no electromagnetic propagation.

Example : Earth's ionosphere prevents radiation < 1 MHz from being observed from Earth's surface (corresponding to $n\sim10^4$ cm^{-3})

plasma frequency

Plasma frequency cutoff helps to probe ionosphere.

$$\omega_p^2 = \frac{4\pi n e^2}{m}$$

↓

Electron density can be determined as a function of height.

A pulse of radiation in a narrow range about ω be directed straight upward from Earth

When there is a layer where n is large enough to make $\omega_p > \omega$, the pulse will be totally reflected from layer.

Get information of height from time delay of pulse

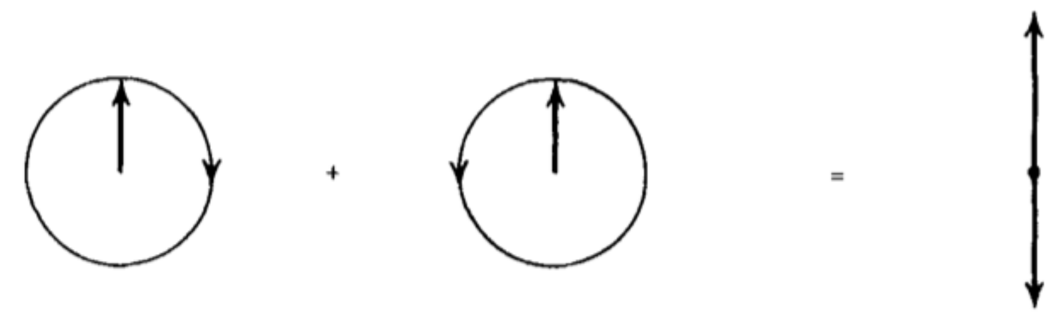
Repeating these measurements at many different frequencies electron density as a function of height can be determined

Faraday Rotation

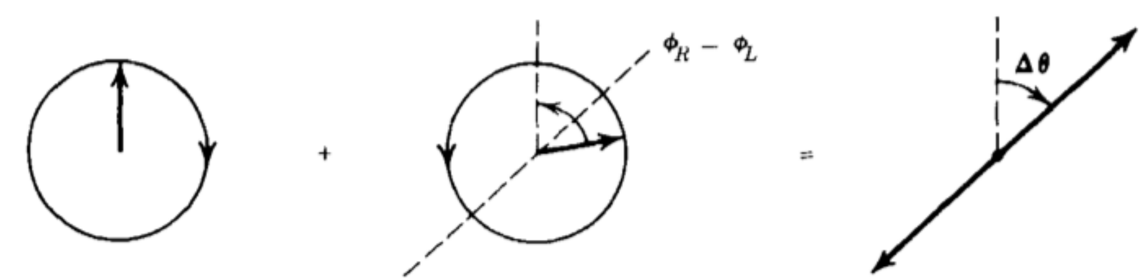
A plane polarized wave will not keep a constant plane of polarization, but its plane will rotate as it propagates.

$$\Delta\theta = \frac{2\pi e^3}{m^2 c^2 \omega^2} \int_0^d n B_{\|} \, ds$$

Decomposition of linear polarization into right and left circular polarization



Faraday rotation of the plane of polarization



Fundamental processes in plasma astrophysics

- ✓ Waves
- ✓ Shocks
- ✓ Instabilities
- ✓ Turbulence
- ✓ Particle acceleration
- ✓ Dynamo : Converts kinetic energy to magnetic energy
- ✓ Reconnection: Converts magnetic energy to kinetic/thermal energy and particle energization alters magnetic field connectivity

About Final Exam

25^{th} August(9 AM-12 PM)

Closed book/notes
Calculators allowed

Total :100 marks

Objective: 20

Theory: 20

Problem: 60

Request

Explain all the symbols you use.
Complete numerical calculations.
Write neatly.

Practice problems discussed in Lectures, Assignments, Rybicki and Lightman and more

Example questions Final Exam

25^{th} August(9 AM-12 PM)

Objective question (each for 2 marks, total 20)

1) The Electric field of a moving charge "q" is composed of two terms. What are they and how do they depend on the distance to the charge?

2) Write down expression for Lorentz transformed space-time four vector and charge-current four vector. How will the length four vectors vary between inertial frames.

Example questions Final Exam

25^{th} August(9 AM-12 PM)

Theory question (each for 6 marks, total 20)

When a charge is accelerated by the Coulomb force, its emission is called Bremsstrahlung. Draw the spectrum (specific intensity as a function of frequency), assuming that there is a frequency ν_a below which the medium is optically thick and that $h\nu_a << kT$ (T is the temperature of the medium). What will happen at $h\nu \sim kT$. Draw Bremsstrahlung spectra for two different temperature T_1 and T_2 with same number density. For what particular situation does the Bremsstrahlung spectrum become a Black Body spectrum? Mention two astrophysical situations where free-free emission is observed. Comment on the polarisation state of the overall emission in Bremsstrahlung process.

Example questions Final Exam

25th August(9 AM-12 PM)

Problems(each for 15 marks, total 60)

Similar to the problems from your assignments

End of Lectures

Thank you

Send your feedbacks to
bhaswati@ncra.tifr.res.in
Mention,
a) Components you liked
b) Components you want to change