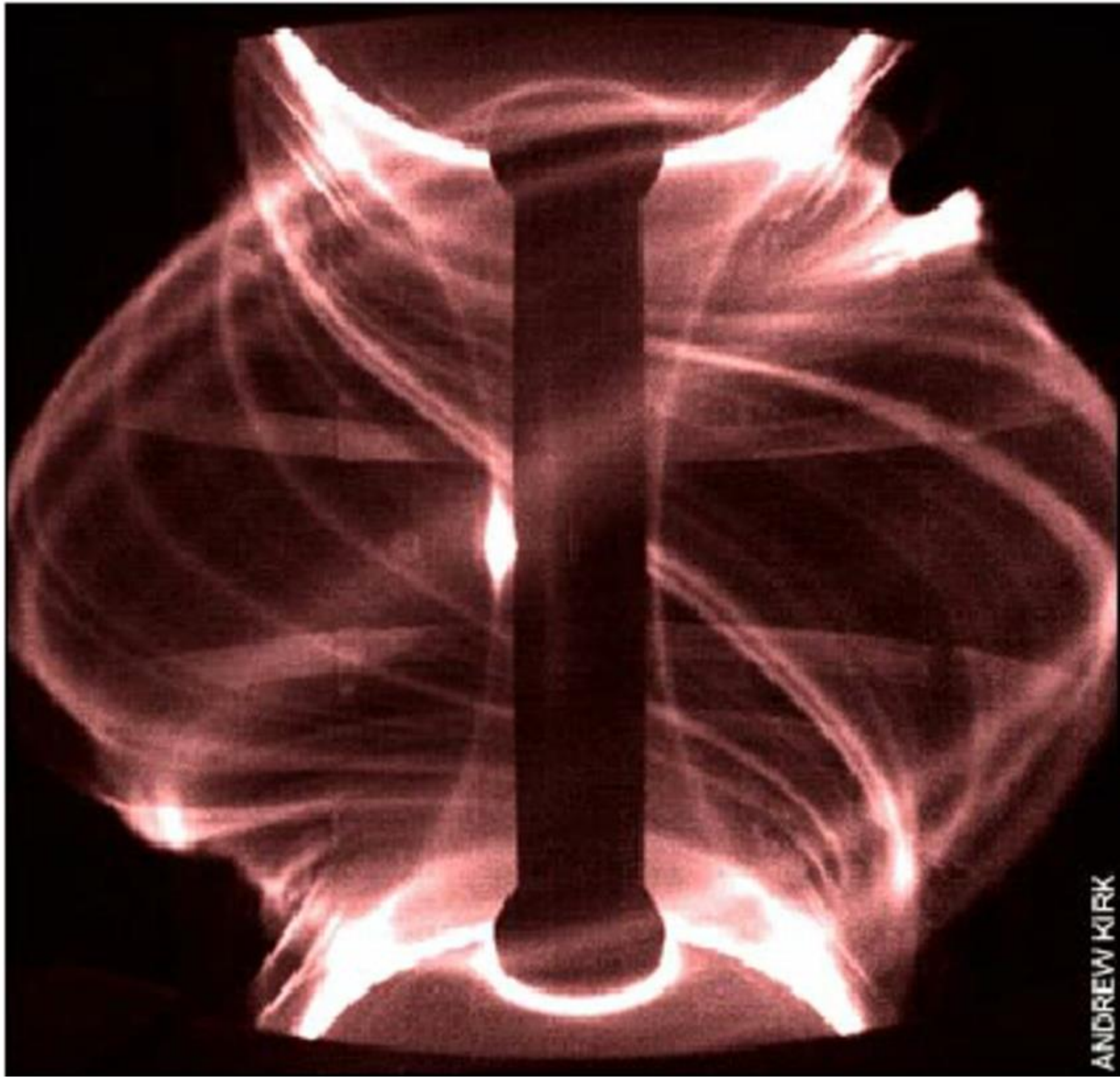
IMPERIAL

Introduction to Plasma Physics

Yasmin Andrew



ICTP-IAEA Fusion Energy School, ICTP, Trieste, Italy, 11 – 22 May 2026

ICTP and plasma physics

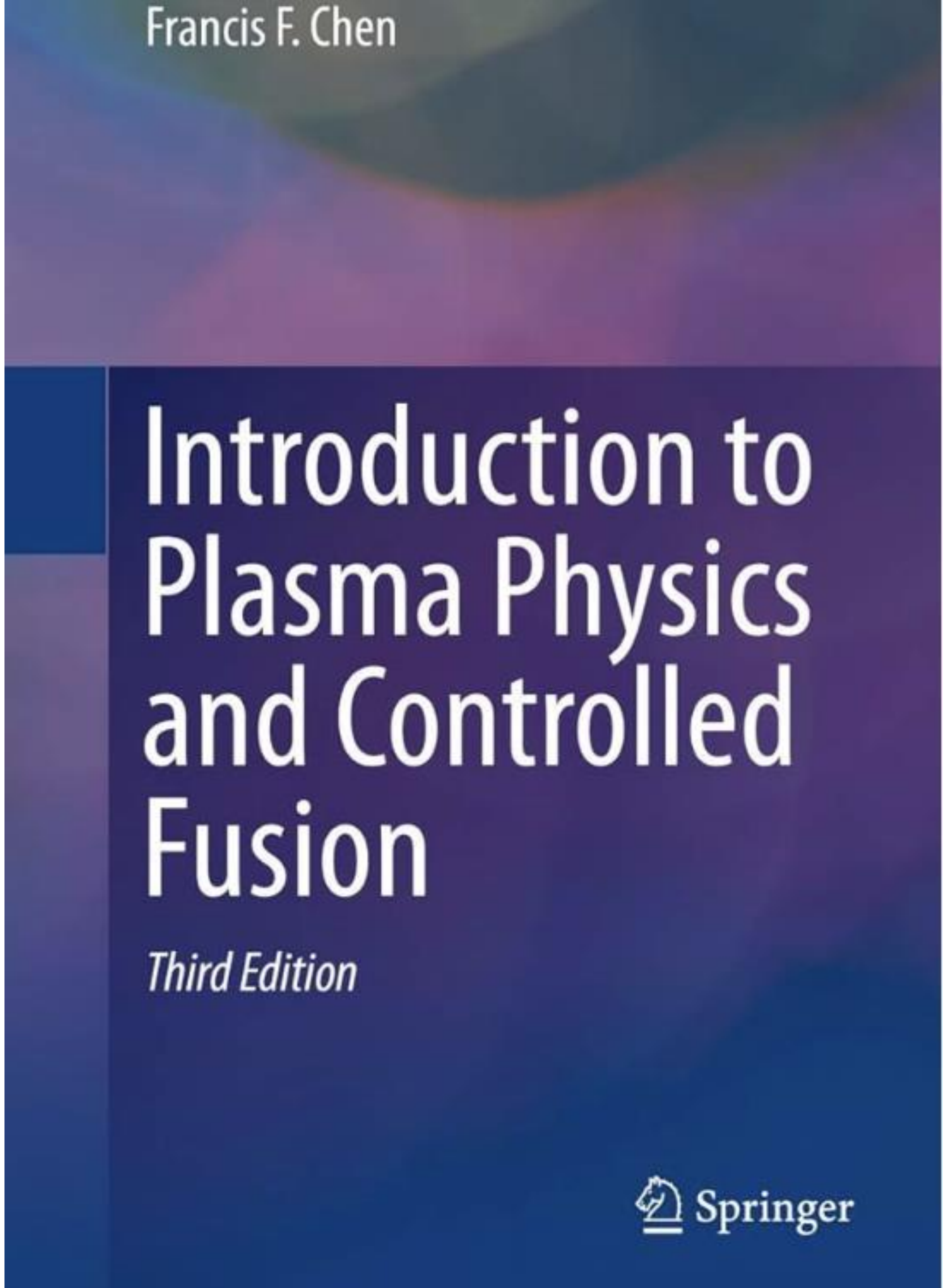
- The International Centre for Theoretical Physics (ICTP) first ran an international conference on plasma physics in 1964 with the International Atomic Energy Agency (IAEA)
- This event was also the inauguration of the ICTP
- A notable contribution from ICTP to global plasma physics; closely tied to the development of fusion plasma physics over the next decades
- The ICTP has continued to support research and training in plasma physics and fusion through the ICTP-IAEA school on Plasma Physics

Reading list

- Introduction to Plasma Physics and Controlled Fusion, Francis Chen 3rd edition, Cham, Switzerland, Springer [2018]

- Plasma Physics: an introductory course, Richard Denedy, Cambridge, Cambridge University Press [1999]

- The Physics of Plasmas, T.J.M. Boyd, J.J. Sanderson, Cambridge, Cambridge University Press [2003]



Learning Objectives:

- Develop an understanding of what plasmas are
- Explore different applications of plasmas

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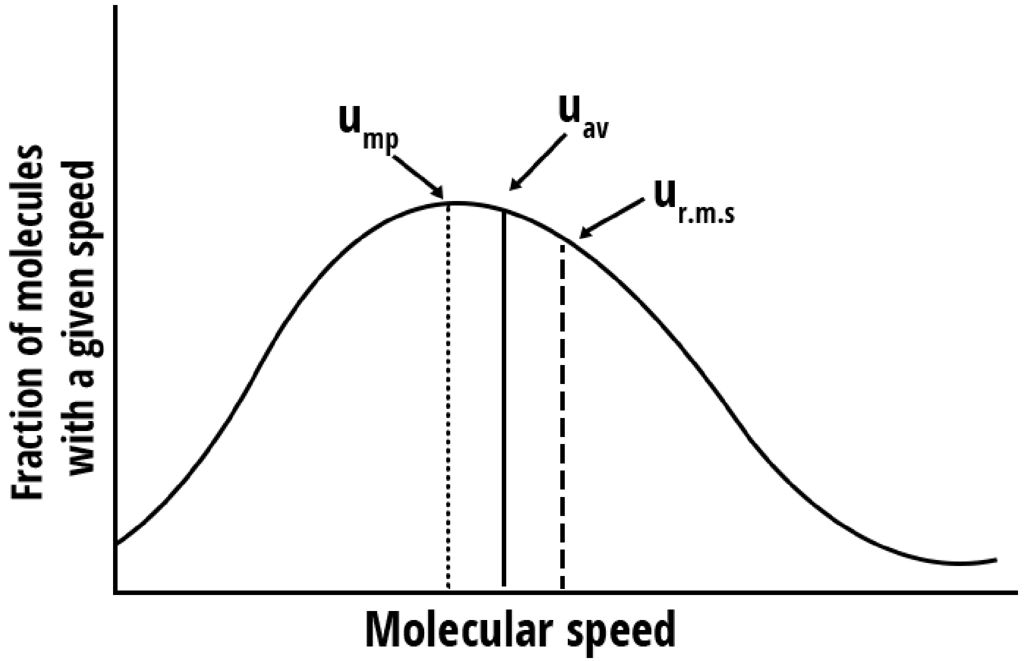
Temperature

- Temperatures conventionally measured in K
- Typically, plasma temperature measured in eV
- 1 eV = 1.6 $\times 10^{19}$ J



Maxwellian velocity distribution

- Maxwell-Boltzman distribution of particle velocities in an idealised gas
- The width of the distribution is characterised by T
- Average kinetic energy of the particles,

$$E_{av} = {}^{3}/_{2}\, KT,$$

where, K = 1.38 $\times 10^{-23}$ J K^{-1} and T is in K, for three degrees of freedom

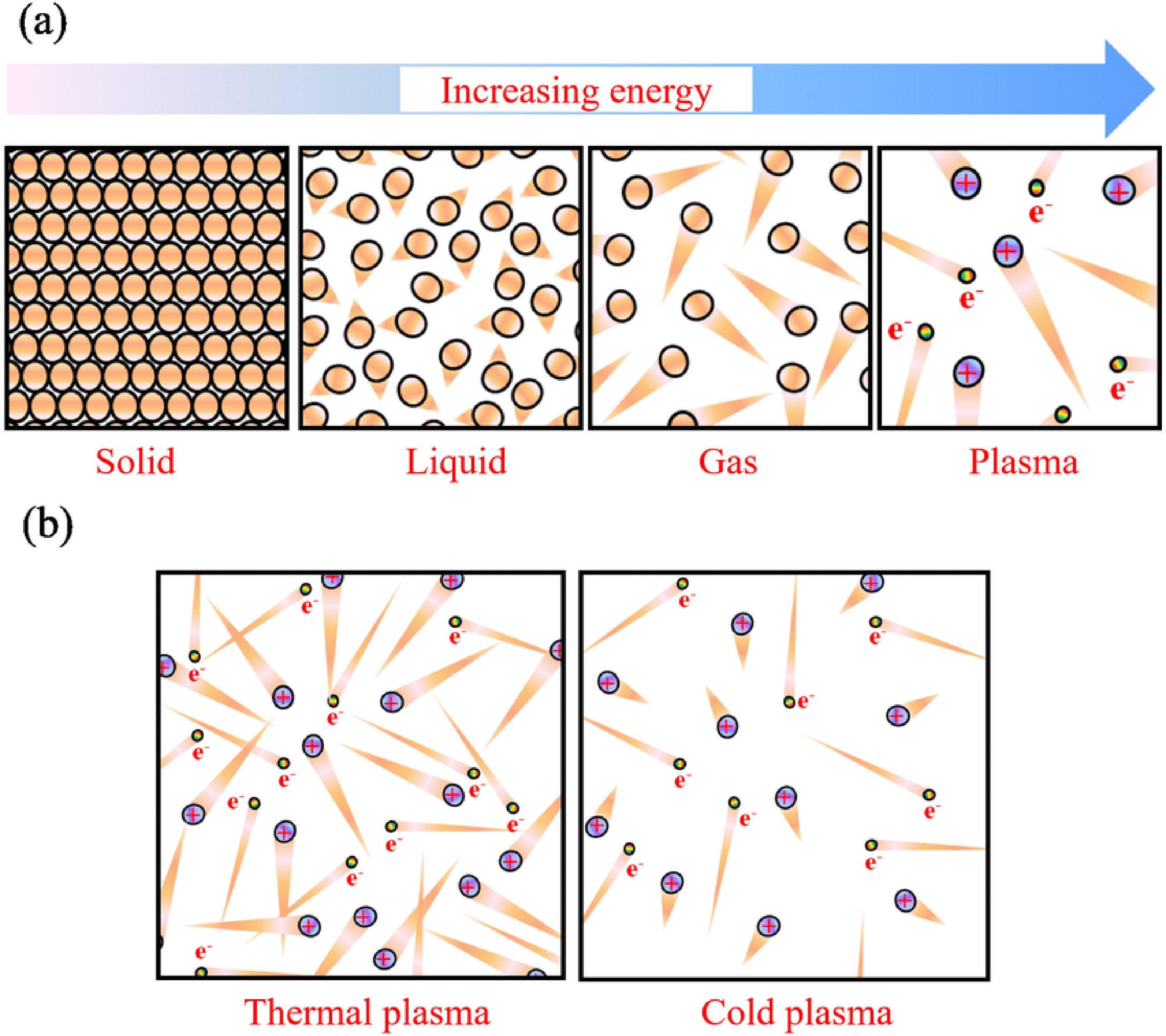
$$E = KT$$

$$\mathrm{T} = {}^{E}/_{K}$$

$$\mathrm{T} = \frac{1.6 \times 10^{19}}{1.38 \times 10^{-23}}$$

$$1\ eV = 11\,600\ K$$

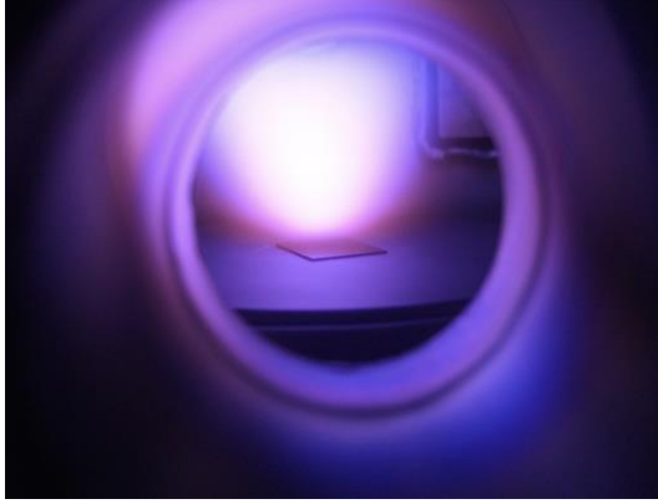
Plasma

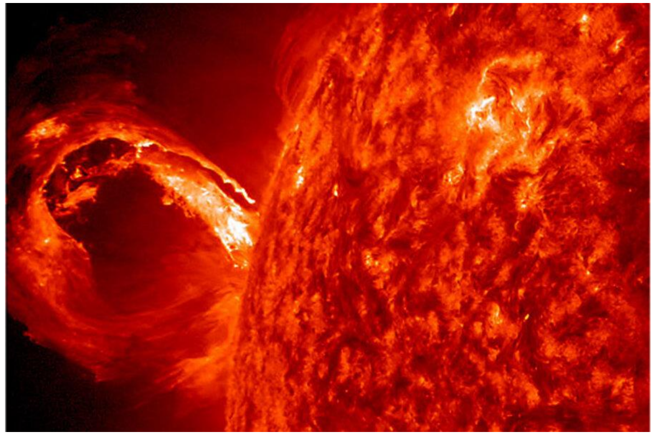


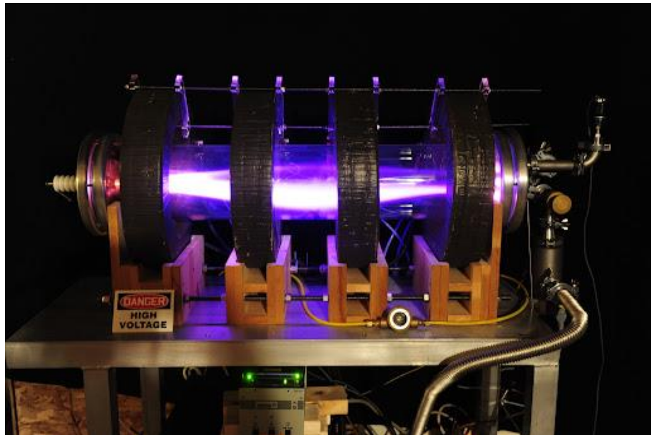
Yan, Dayun, Sherman, Jonathan, Keidar, Michael PY , Oncotarget (2016), *Cold Atmospheric Plasma, A Novel Promising Anti-cancer treatment modality,* **8** DOI:10.18632

Plasma

- To create a plasma, gas needs to be ionised
- For example, E = 13.65 eV is needed to ionise a hydrogen atom
- However, an ionised gas is not necessarily a plasma







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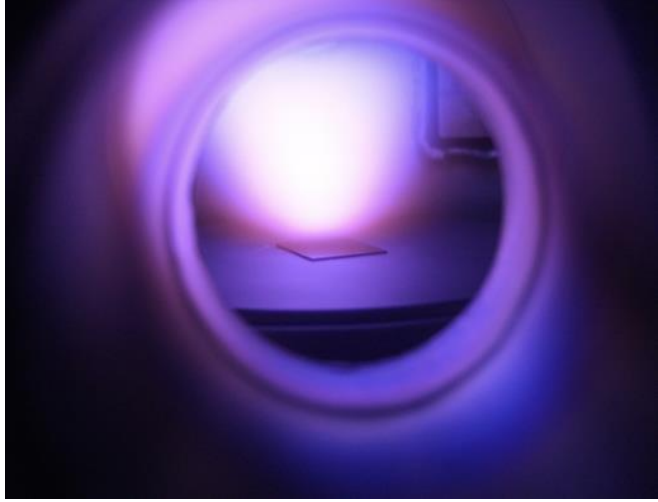
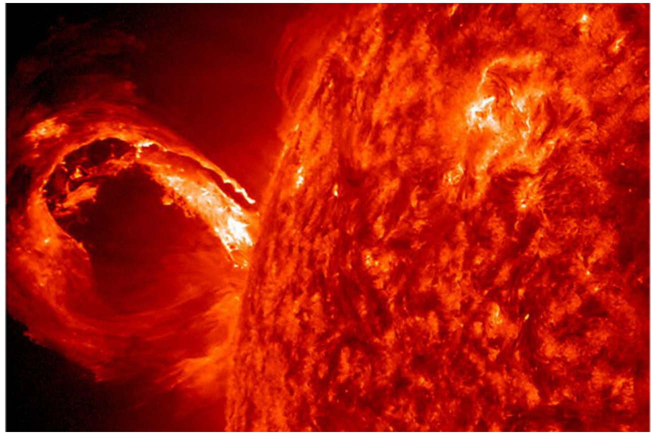
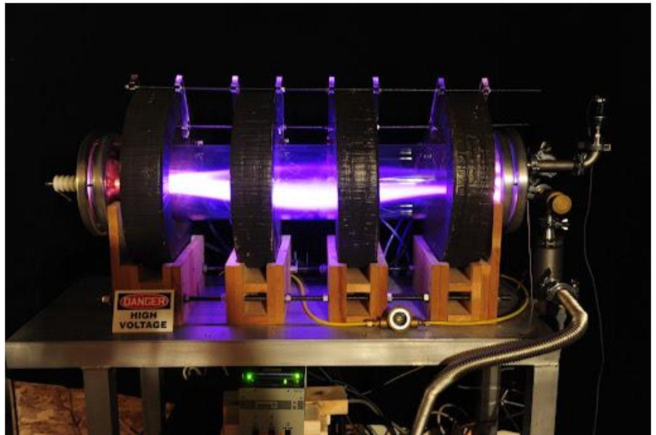
A plasma is a quasineutral gas of charged and neutral particles that shows collective behaviour.







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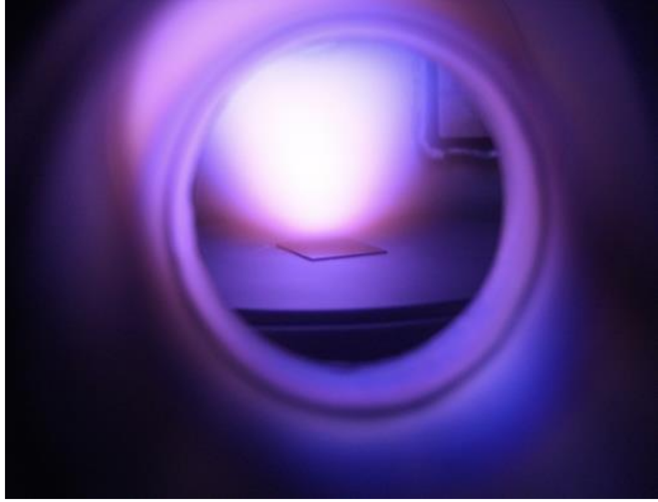
A plasma is a quasineutral gas of charged and neutral particles that shows collective behaviour.

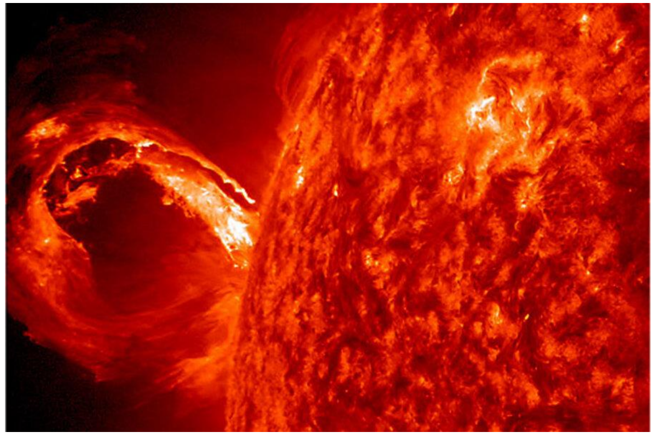
Quasineutrality

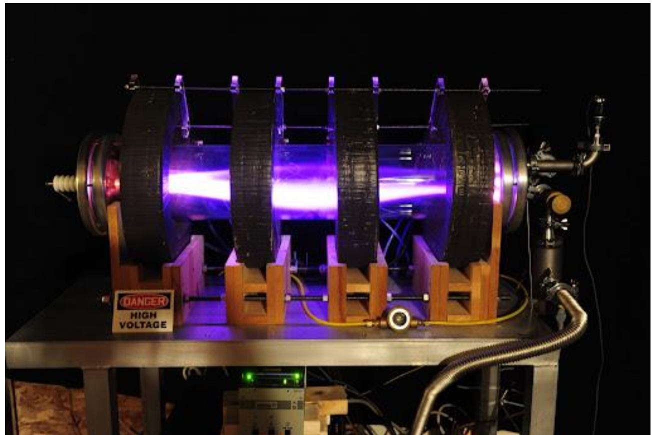
- There needs to be approximately equal numbers of positive and negative charges on a time scale much longer compared with collective interaction time scale for a plasma to be **quasineutral**.

$$Q = -en_e + Zen_i$$
$$Q = 0\ C$$

Q is the total charge (C),
e = 1.6×10^{19} C
Z: ion charge (C)
n_e: plasma electron (number) density (m^{-3})
n_i: plasma ion number density (m^{-3})







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A plasma is a quasineutral gas of charged and neutral particles that shows collective behaviour.

Quasineutrality

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$$Q = -en_e + Zen_i$$
$$Q = 0\,C$$

Q is the total charge (C), e = $1.6\text{x}10^{19}$ C, Z: ion charge (C)

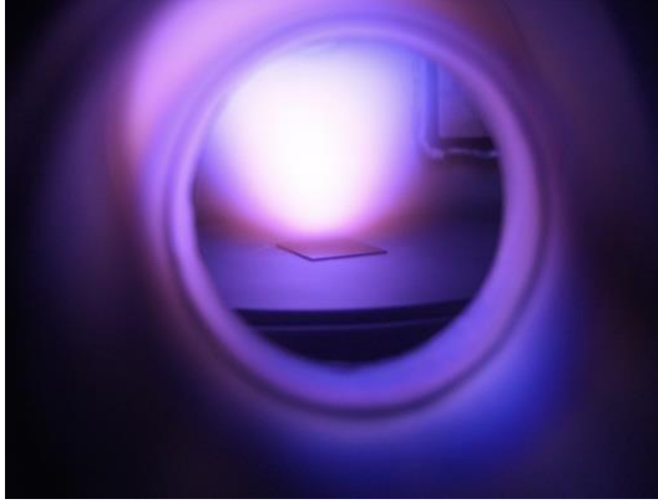
n_e: plasma electron (number) density (m^{-3}), n_i: plasma ion number density (m^{-3})

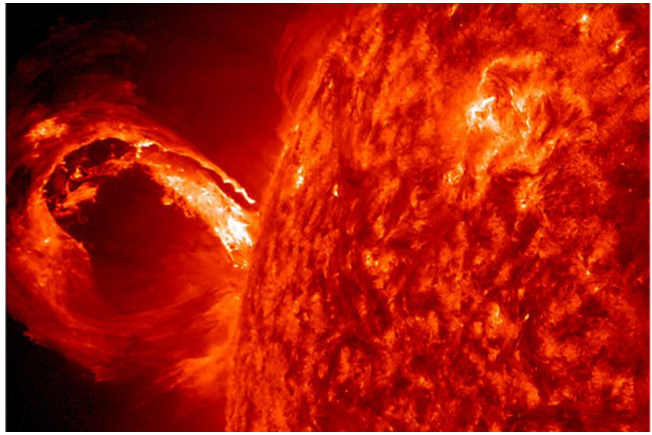
- Due to differences in ion and electron motion, transport and plasma fluctuations local differences arise in n_e and n_i

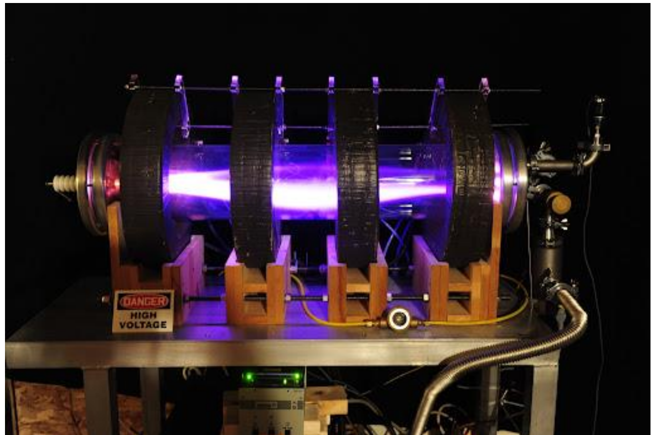
- This can lead to localized electric fields in the plasma, so that:

$$Q \neq 0\,C$$

- Therefore, the plasma is referred to as **quasineutral o**n a macroscopic level.

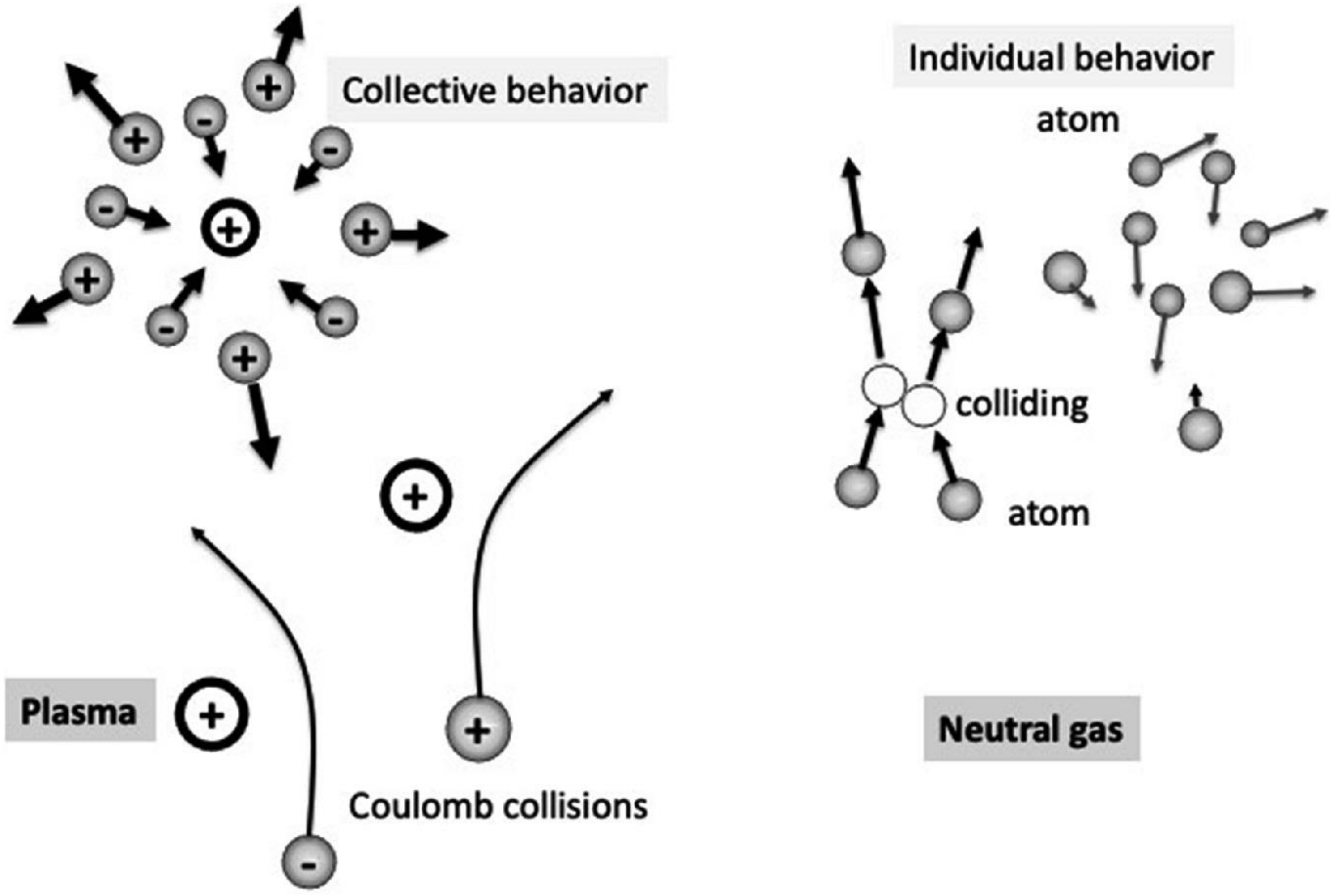






Collective behaviour

- The charged particles in a plasma can generate localised concentrations of charges which give rise to electric fields
- Motion of charge particles also generates currents and hence magnetic fields
- These electric and magnetic fields affect charged particles at a distance
- Long range Coulomb forces between charge particles can lead to a range of particle motions encountered in plasma physics
- Collective behaviour refers to both plasma particle motion on a short, local scales and in remote regions.



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Collective behaviour

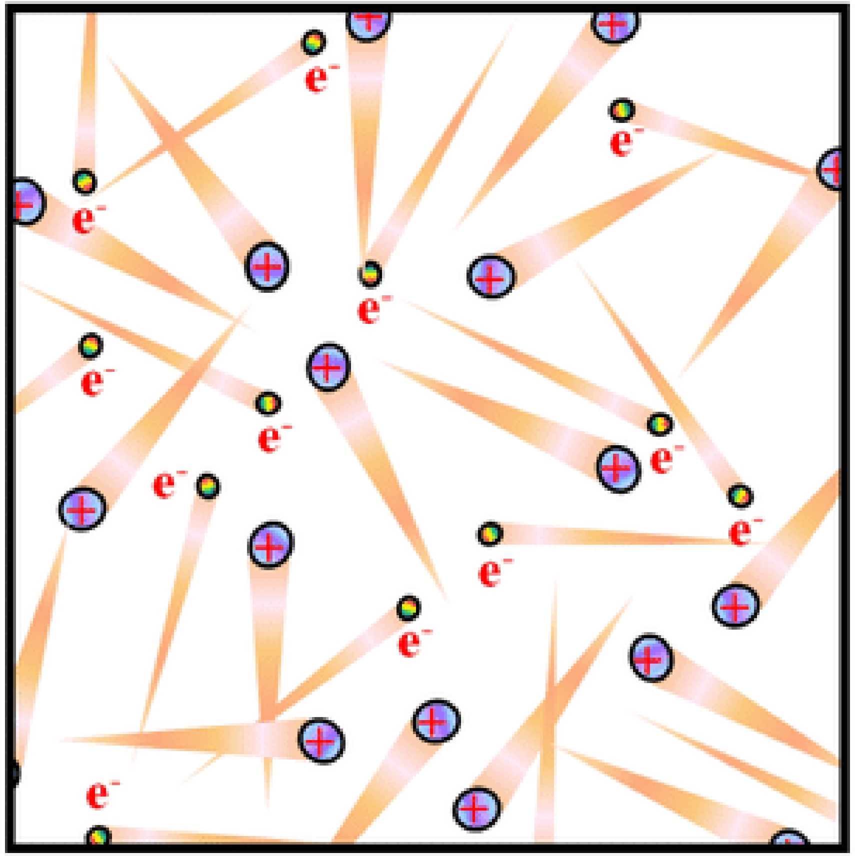
- Approximately equal numbers of positive and negative charges exist on a time scale much longer than the collective interaction time scale, for a plasma to be quasineutral.

- A charged particle would move through a plasma medium and interact simultaneously with many other charged particles.

- Each particle interaction is more than 2-body

- Each particle has a a collective interaction

- There is a maximum limit to the scale length of the collective interaction in a plasma defined by the **Debye shielding**



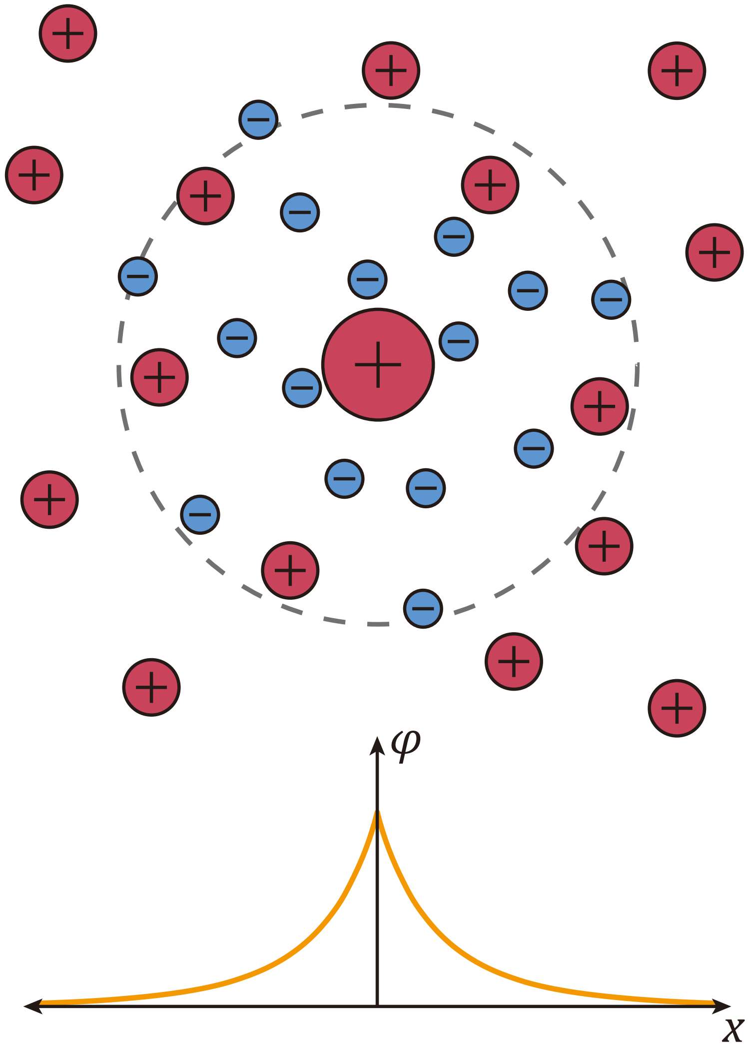
Debye Shielding

- Consider a neutral plasma, Q = 0 C, with T = 0 eV
- If a positively charged object is introduced
- Since, $m_e << m_i$, the electrons are more mobile and will move towards the positively charge object
- The electrons act to screen the rest of the plasma by forming a cloud around the positive object, so within the dashed circle:

$$n_e = n_o \gg n_i$$

- In a plasma with T = 0 eV, the shielding effect is perfect, and the negatively charged plasma is infinitely thin.

- However, in plasmas with $T \neq 0\ eV$, this is never the case



Debye length

- In a thermal plasma with particles described by a Maxwell-Boltzman velocity distribution, n_e is given by:

$$n_e = n_0 e^{-E/KT} \text{ ....(1)}$$

$$n_e = n_0 e^{e\phi/KT_e} \text{......................(2)}$$

where, E is energy in J, ϕ is the potential in V and T_e is the electron temperature in K

- Consider Poisson's equation:

$$\nabla^2\phi = -\frac{\rho}{\varepsilon_0} \text{..........................(3)}$$

$$\nabla^2\phi = -\frac{(n_i Zq - n_e q)}{\varepsilon_0} \text{.............(4)}$$

where, ρ is the volume charge density (C m^{-3}) and vacuum permittivity, ε_0 = 8.854 x10^{-12} C^2 $N^{-1}m^{-2}$

- Assume $n_i Z = n_0$ and substitute (2) into (4):

$$\nabla^2\phi = -\frac{en_0}{\varepsilon_0}\left(1 - e^{\frac{e\phi}{KT_e}}\right) \text{......(5)}$$

Debye length

- If we assume spherical symmetry, equation (5) can be re-written as:

$$\frac{1}{r^2}\frac{d}{dr}\left(\frac{r^2 d\phi}{dr}\right) \quad = -\frac{en_0}{\varepsilon_0}\left(1 - e^{\frac{e\phi}{KT_e}}\right) \text{......(5)}$$

- At a point far away from the positive charge $\phi \ \text{--}\!\!\rightarrow 0$, so $e\phi \ll KT_e$:

$$e^{\frac{e\phi}{KT_e}} = 1 + \frac{e\phi}{KT_e}$$

- Equation 5 can be re-written as:

$$\frac{1}{r^2}\frac{d}{dr}\left(\frac{r^2 d\phi}{dr}\right) = -\frac{en_0}{\mathcal{E}_0}\left(1 - 1 - \frac{e\phi}{KT_e}\right)$$

$$\frac{1}{r^2}\frac{d}{dr}\left(\frac{r^2 d\phi}{dr}\right) = -\frac{en_0}{\mathcal{E}_0}\left(-\frac{e\phi}{KT_e}\right) \text{.............(6)}$$

$$\frac{1}{r^2}\frac{d}{dr}\left(\frac{r^2 d\phi}{dr}\right) = \frac{e^2 n_0}{KT_e \mathcal{E}_0}\phi \text{ ....(7)}$$

Boundary conditions

- Far away from the positively charged object:

$$\phi \to 0 \text{ ......(7)}$$

- Close to the positively charged object:

$$\phi \to \frac{q}{\varepsilon_0 4\pi r} \text{ ......(8)}$$

- Simplify equation (6) :

$$\frac{1}{r^2}\frac{d}{dr}\left(\frac{r^2 d\phi}{dr}\right) = \alpha^2 \phi, \quad \text{........(9)}$$

where, $\alpha^2 = \frac{n_0 e^2}{\varepsilon_0 K T_e}$

- Rearrange equation (9) :

$$\frac{d^2}{dr^2}(r\phi) = \alpha^2 r\phi, \quad \text{........(10)}$$

- Let $\varphi = r\phi$ so that the solution is of the form $Ae^{-\alpha r}$ and using the boundary condition (7) and (8):

$$\varphi = \frac{q}{4\pi\varepsilon_0 r} e^{-\frac{r}{\lambda}}, \quad \text{........(11)}$$

where, $\alpha = {}^{1}/_{\lambda}$

Coulomb potential | Screening effect

- Then:

$$\frac{d^2\varphi}{dr^2} = \frac{1}{\lambda^2}\frac{q}{4\pi\varepsilon_0 r}e^{-\frac{r}{\lambda}} \text{......(12)}$$

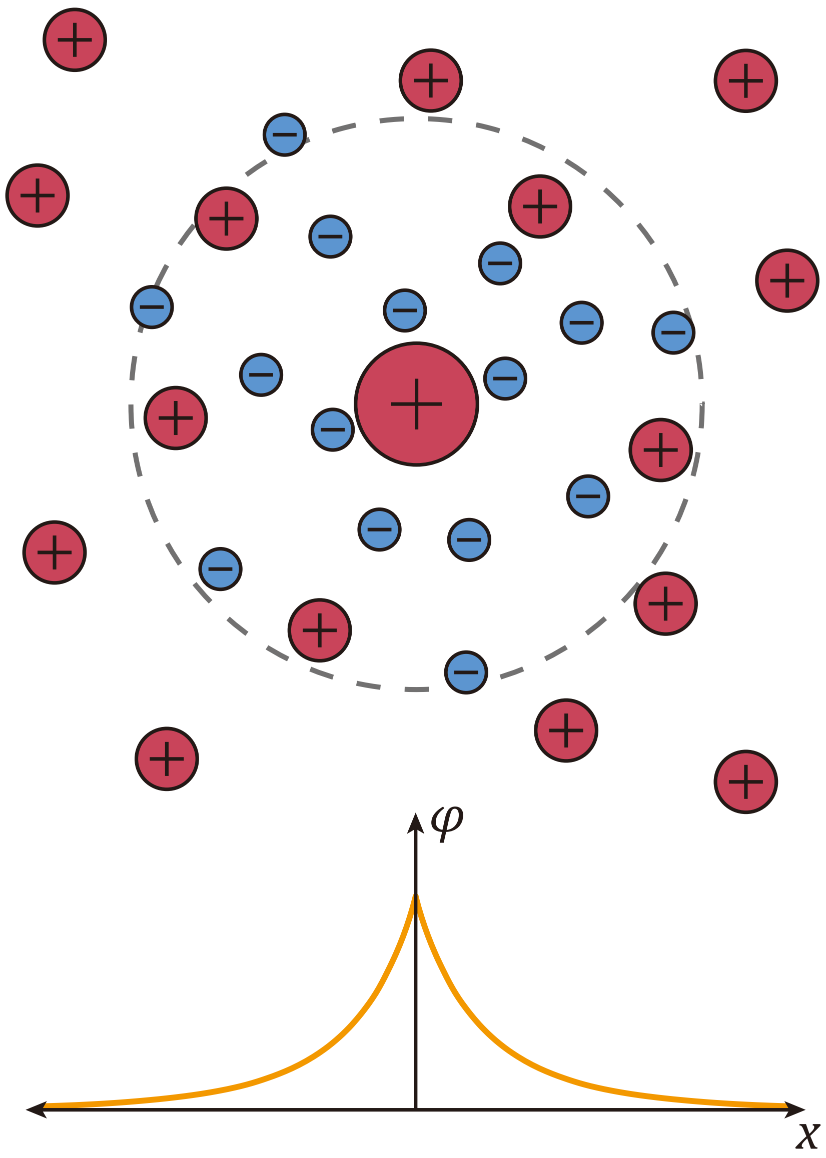
$$\frac{d^2\varphi}{dr^2} = \frac{n_0 e^2}{\varepsilon_0 KT}\frac{q}{4\pi\varepsilon_0 r}e^{-\frac{r}{\lambda}} \text{......(13)}$$

or:

$$\frac{1}{\lambda^2} = \frac{n_0 e^2}{\varepsilon_0 KT_e} \text{......(14)}$$

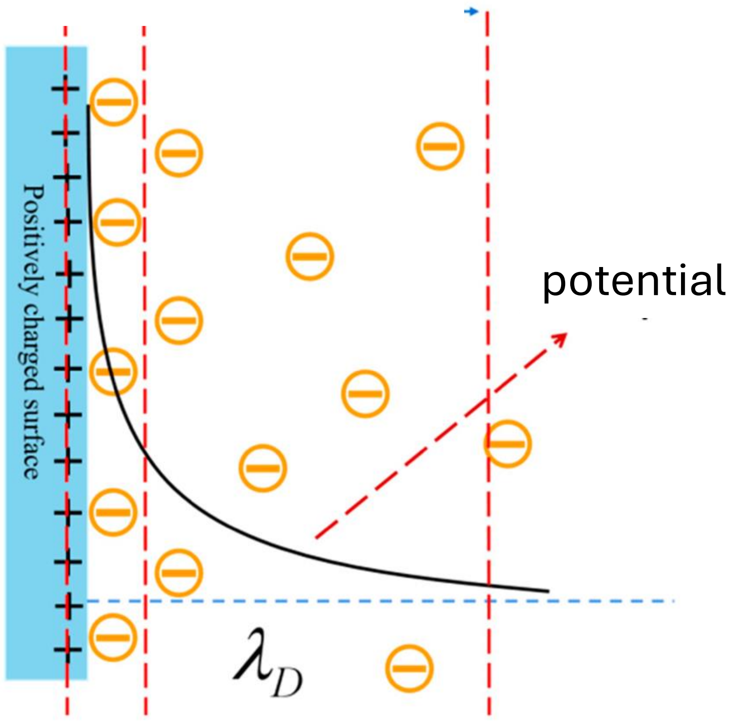
- Equation (14) yields the **Debye length** :

$$\lambda_D = \left(\frac{\varepsilon_0 KT_e}{n_0 e^2}\right)^{1/2}$$



Debye Shielding

- A point charge, q, is shielded by a cloud of charged particles with radius, λ_D, and a total charge of –q
- At distances shorter than λ_D individual particles are visible to the point charge
- At distances greater than λ_D the plasma exhibits **collective behaviour**, individual particles are invisible to the point charge
- As a result, the plasma is described as quasineutral for $L \gg \lambda_D$ for the system
- There needs to be enough particles inside the Debye Sphere, N_D, to shield the bulk plasma from the positive charge



Number of particles in a Debye Sphere, N_D

- Assume a sphere of volume:

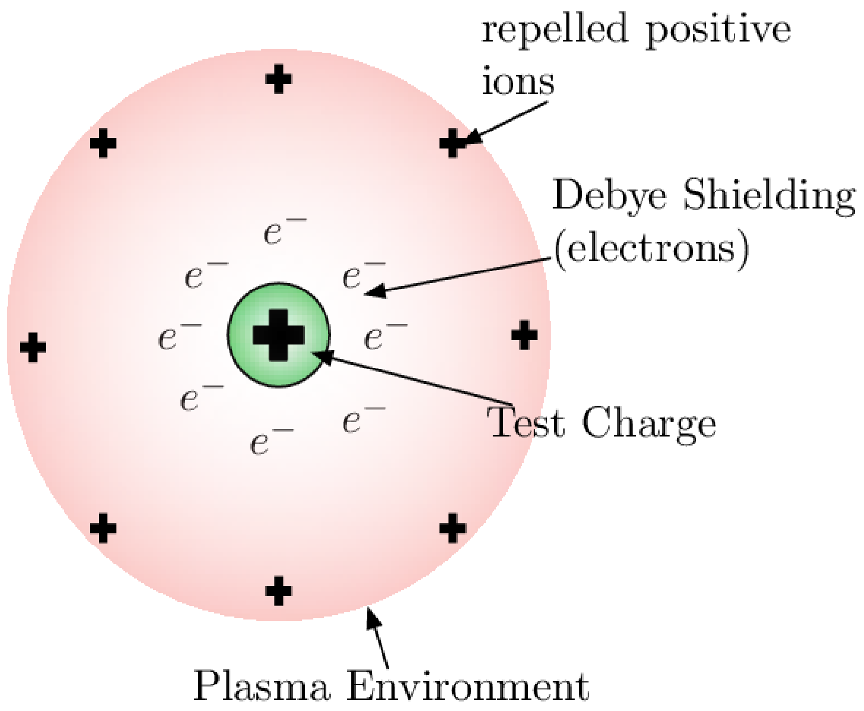
$$V = \frac{4}{3}\pi r^3$$

- If we use the plasma density, n_e then:

$$N_D = n_e V$$

$$N_D = \frac{4}{3}\pi \lambda_D^3 n_e$$

$$N_D = \frac{4}{3}\pi \left(\frac{\varepsilon_0 K T_e}{n_0 e^2}\right)^{3/2} n_e$$



Plasma frequency

- What happens if electrons in a plasma are displaced by a small amount?
- If an electron moves away from its original position, an electric field is created due to localised charge imbalance and the electron will be pulled back towards its original location
- Inertia can cause the electron to go slightly past its starting location and a restoring force means the electron starts to oscillate with a frequency
- This is the plasma frequency:

$$\omega_p = \left(\frac{n_e e^2}{m\varepsilon_0}\right)^{\frac{1}{2}}$$

The plasma frequency provides a characteristic timescale over which the plasma responds and is linked to the plasma collective behaviour

Debye Length and plasma frequency

- The values of λ_D and ω_p provide information on spatial and temporal scale lengths over which plasma quasineutrality is valid:

Charge imbalance can exist in a plasma

$$L < \lambda_D < L$$

$$t < {}^{1}/_{\omega_p} < t$$

Quasineutrality is a valid description

- The values of λ_D and ω_p are related through the plasma electron thermal velocity:

$$v_{th} = \lambda_D \omega_p$$

$$v_{th} = \left(\frac{\varepsilon_0 K T_e}{n_0 e^2}\right)^{1/2} \left(\frac{n_0 e^2}{m \varepsilon_0}\right)^{1/2}$$

$$v_{th} = \left(\frac{K T_e}{m}\right)^{1/2}$$

The value of λ_D is the distance an average plasma electron moves over a plasma time period.

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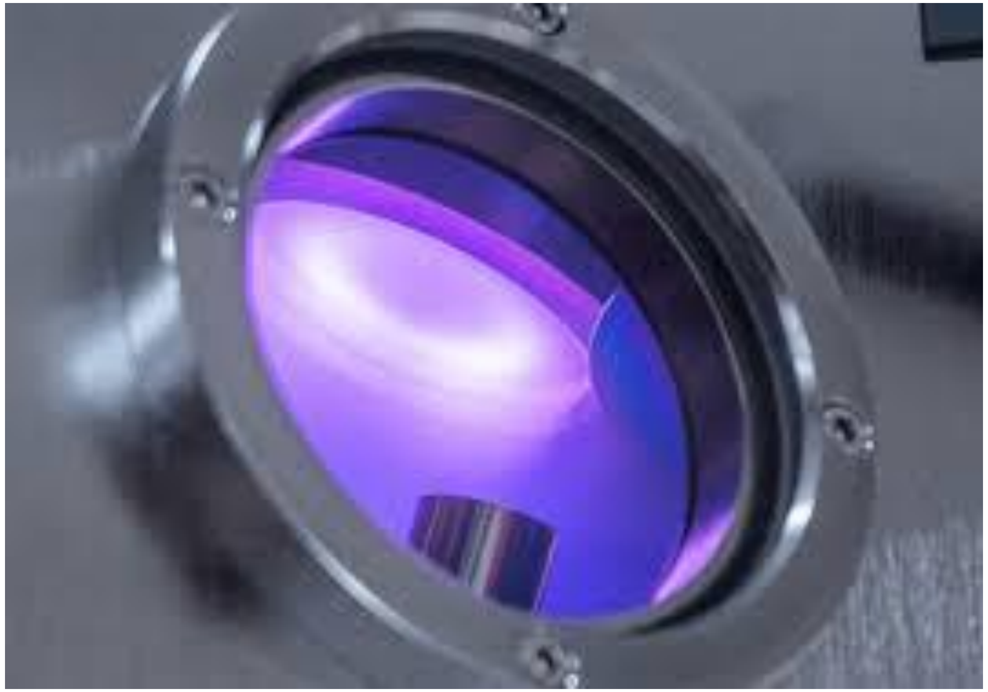
Applications of plasmas

- Plasmas include a very wide range of n and KT:

$$10^6 < n_e < 10^{34}$$

$$10^{-1} < T_e < 10^6$$

- This large range in parameters mean that plasmas have a very wide range of applications



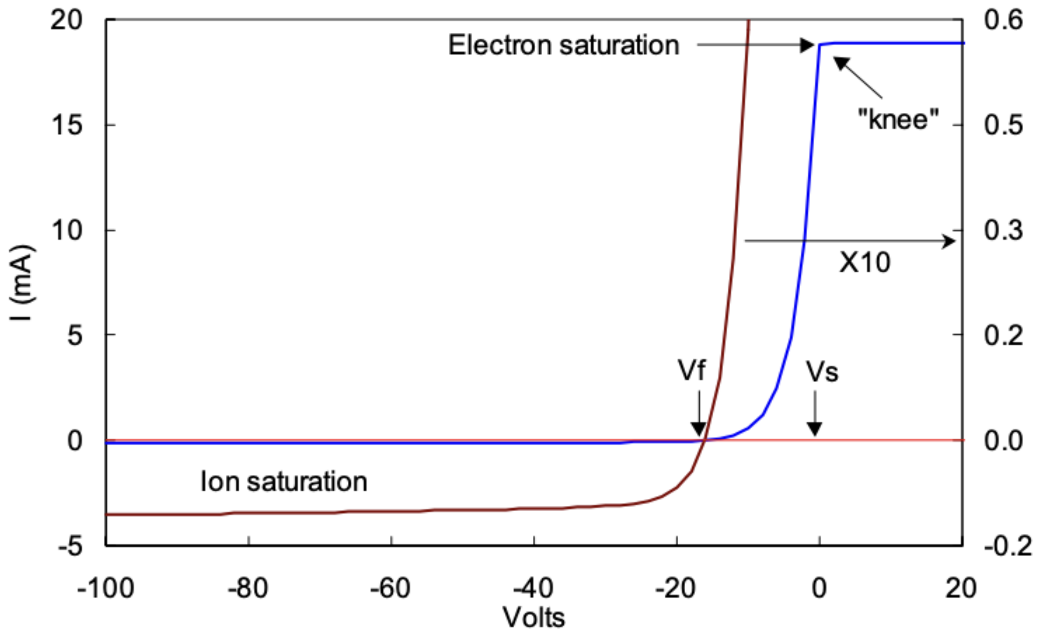
Low temperature plasmas

- Low temperature have typical n and KT values of:

$$10^{14} < n_e < 10^{18} \text{ m}^{-3}$$

$$T_e \approx 2\ eV$$

- These plasmas were some of the earliest, Langmuir, Tonks and collaborators worked on these weakly ionized glow discharges in the 1920s
- The Debye shielding was directly observed as the dark plasma sheath in front of the DC electrode
- Direct applications of this work are lighting e.g. mercury lamps, fluorescent and neon lighting
- A wider commercial application is the semiconductor industry, etching and metal deposition for circuits in chips
- Is an important and wide academic area of research due to its commercial value

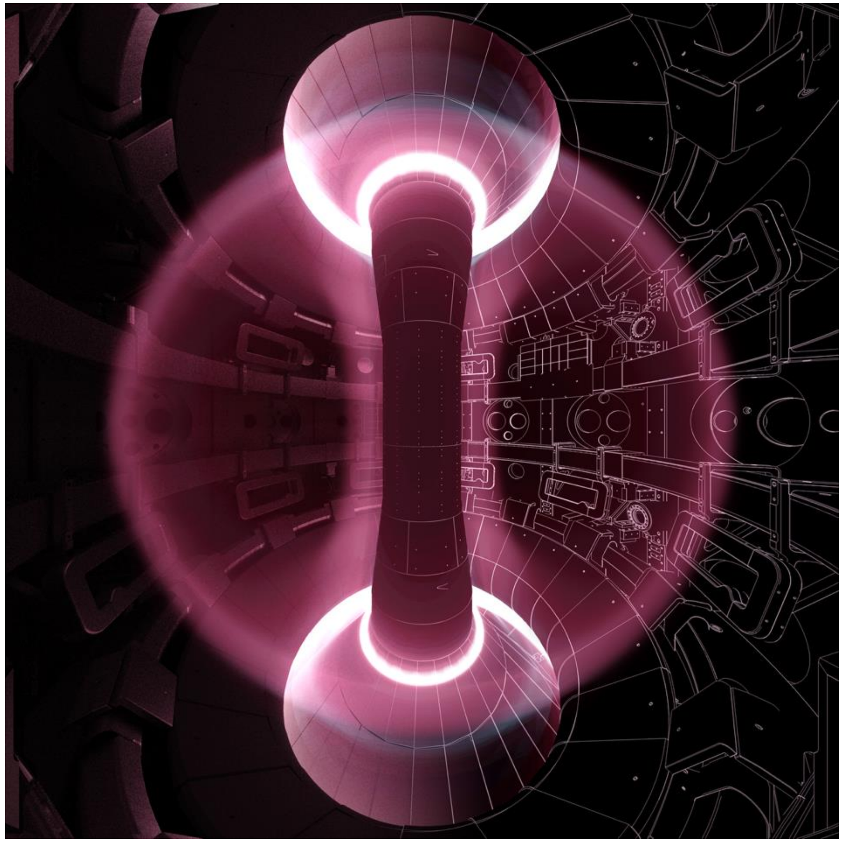


Controlled Nuclear Fusion

- Fusion plasmas have typical n and KT values of:

$$10^{18} < n_e < 10^{31}\ m^{-3}$$

$$T_e \approx 30\ keV$$



Space Plasma Physics

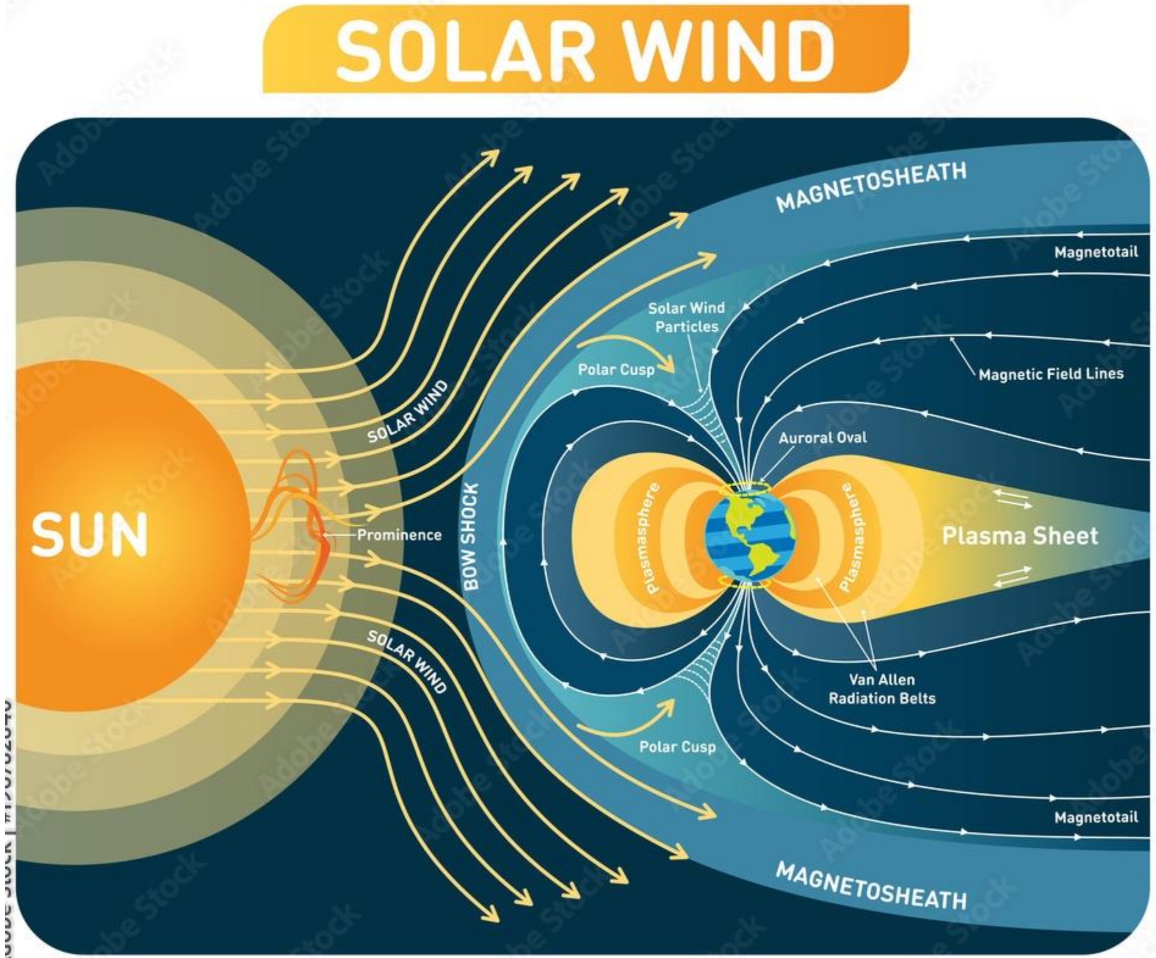
- An example of space plasma physics is the study of Earth's environment in space
- A continuous stream of plasma flows towards Earth from the Sun
- The magnetosphere protects Earth by trapping the charge particles

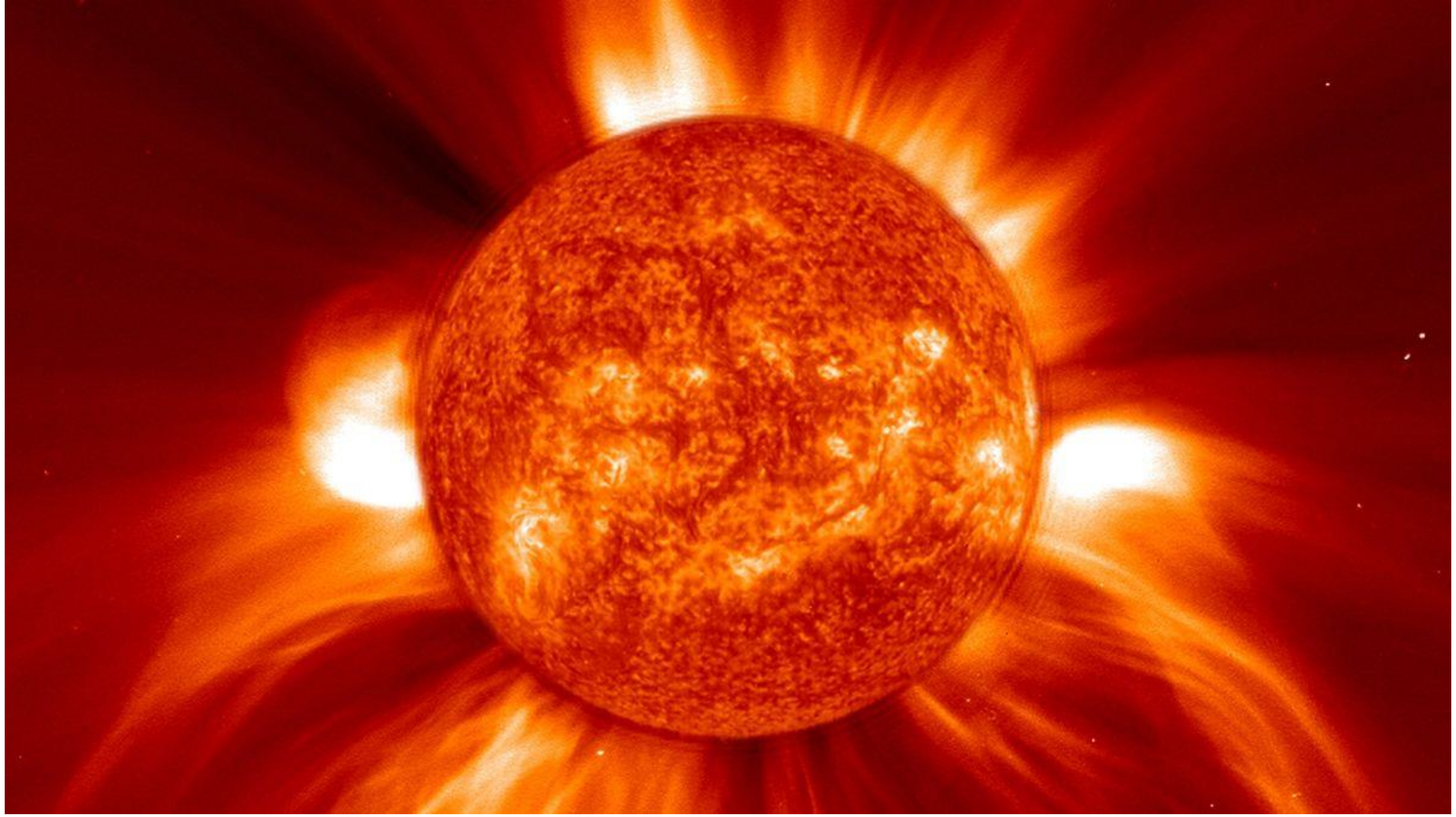
$$n_e \approx 10^7 - 10^{11}\, m^{-3}$$
$$T_e \approx 10\ eV$$
$$\mathrm{B} \approx 10\ nT$$
$$v_{drift} \approx 450\ km\ s^{-1}$$

- The ionosphere exists 50 km from the Earth's surface
- Plasma values vary with altitude, typical values:

$$n_e \approx 10^{12}\ m^{-3}$$
$$T_e \approx 0.1\ eV$$

- Other planets such as, Jupiter and Saturn, also have plasmas in their environments





Astrophysics

- The interiors and environment of stars are hot enough to be plasmas
- For example, in the core of the Sun temperature:

$$T_e \approx 2\ keV$$

- Nuclear fusion reactions release energy radiated from stars
- Astrophysics requires an understanding of plasma physics

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