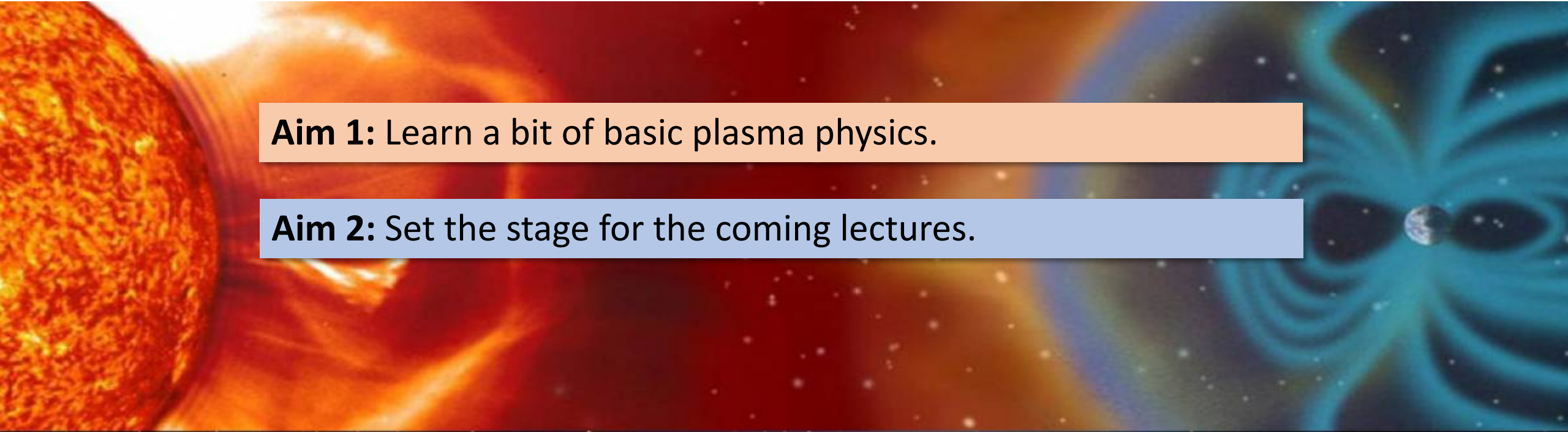


Introduction to Plasma Physics

Dr Imogen Gingell (i.l.gingell@soton.ac.uk)

Royal Society University Research Fellow, University of Southampton

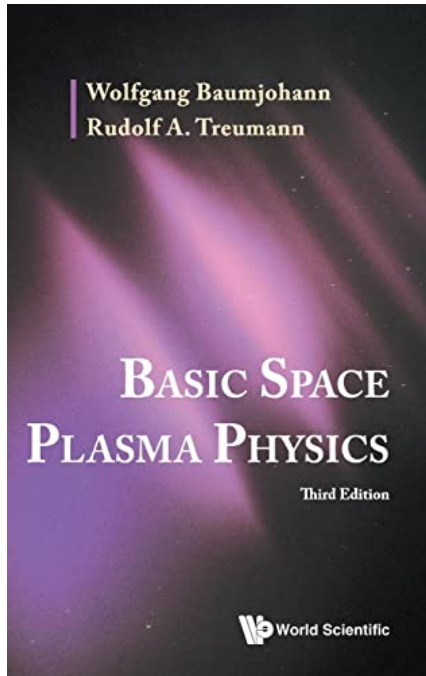
STFC Introductory Course in Solar & Solar-Terrestrial Physics 2026



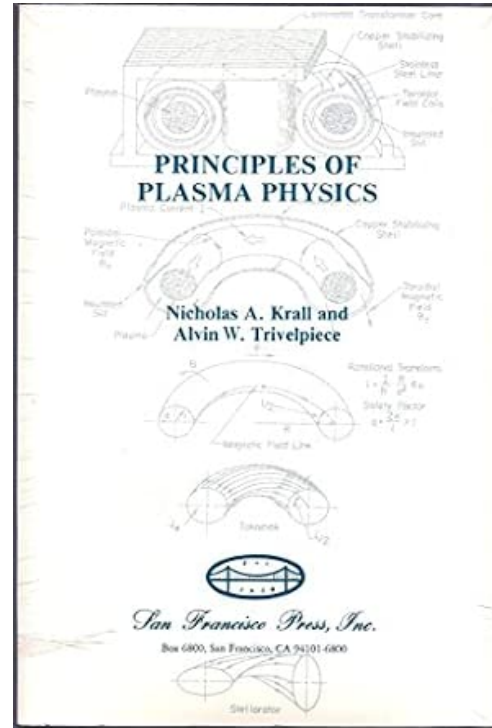
Aim 1: Learn a bit of basic plasma physics.

Aim 2: Set the stage for the coming lectures.

References

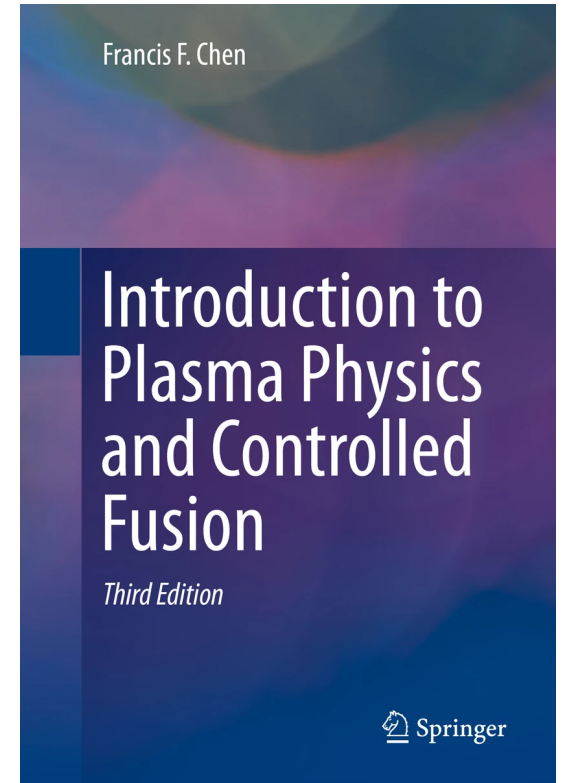


Basic Space Plasma Physics
Baumjohann & Treumann



Principles of Plasma Physics
Krall & Trivelpiece

**Introduction to
Plasma Physics &
Controlled Fusion**
Francis Chen



Fitzpatrick:

<https://farside.ph.utexas.edu/teaching/plasma/plasma.html>

Outline

What is a plasma?

Quasi-neutrality
Debye Shielding
Plasma Criteria

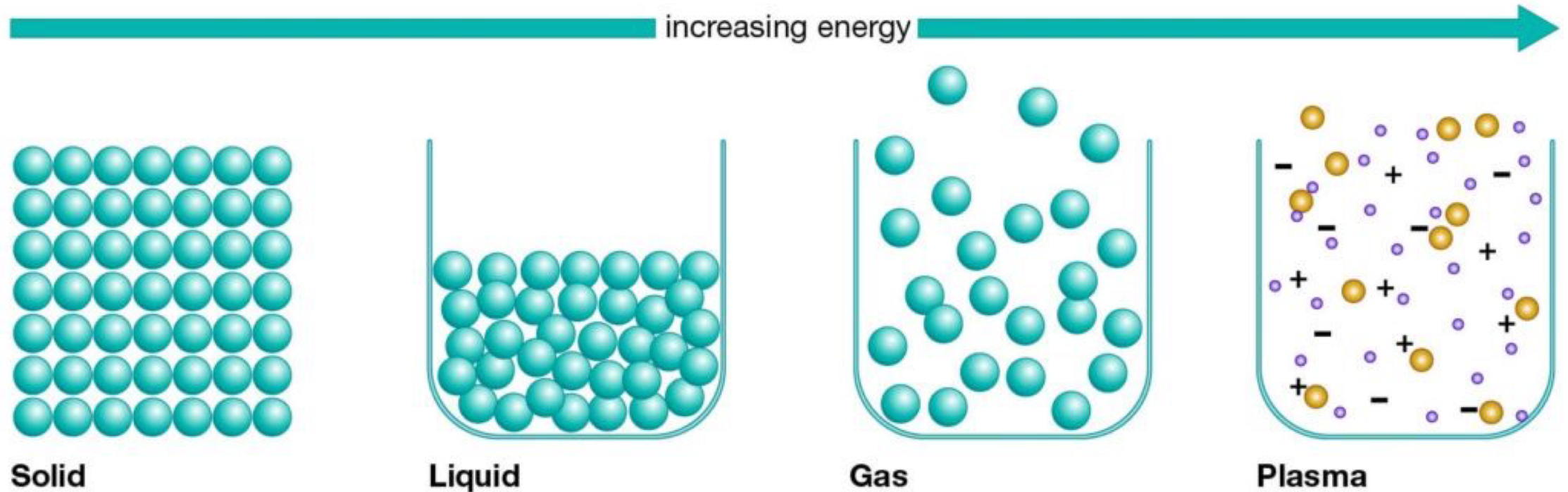
Single Particle Motion

Gyration
ExB drift, Gradient drift,
Curvature drift)
Adiabatic Invariants
Magnetic Mirroring

Plasma Physics Toolkits

Waves in Plasmas: Dielectric Tensor
Kinetic Theory: Vlasov Equation
Fluid Theory: Moments

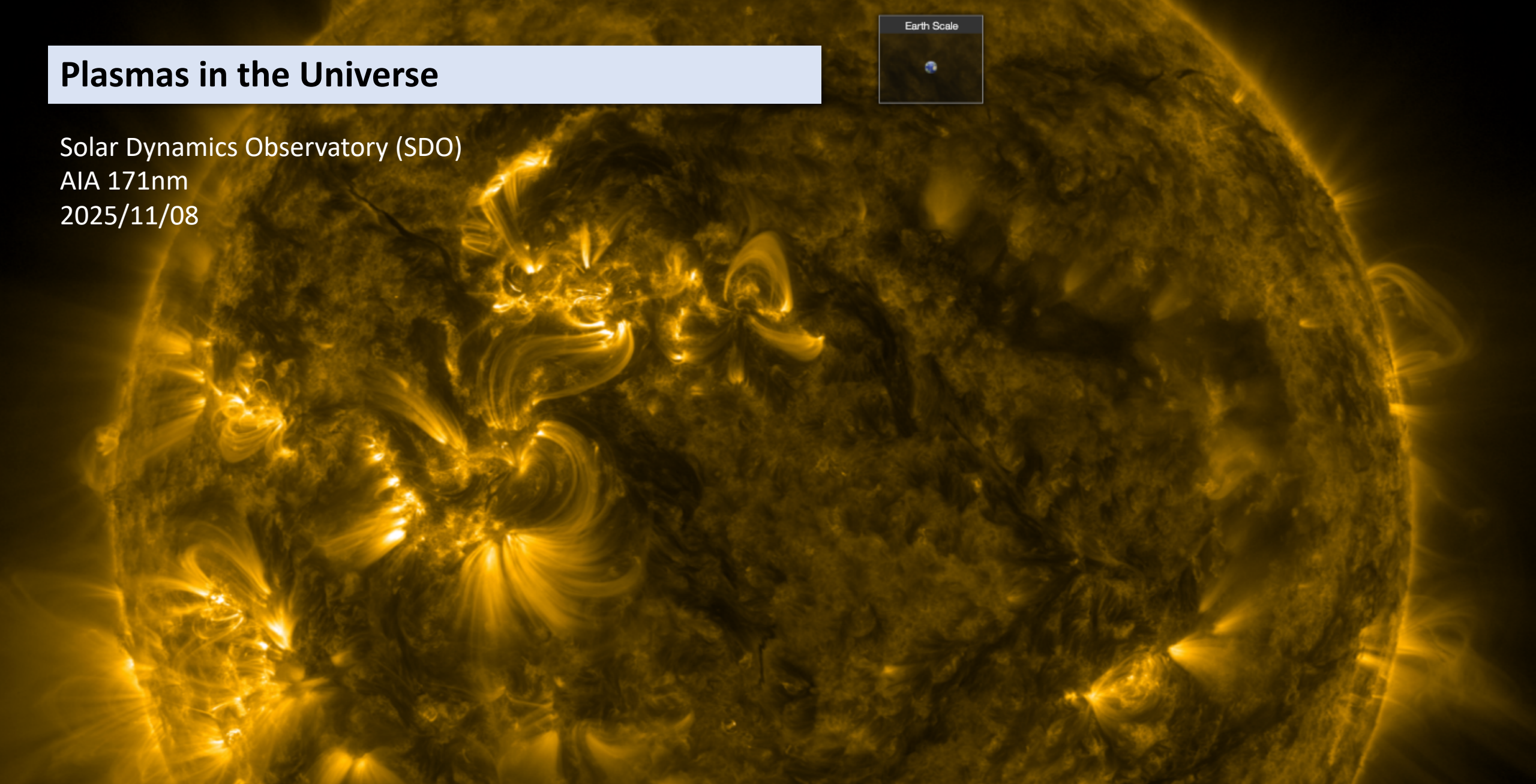
Part 1: What is a Plasma?



<https://studiouslyyours.com/fundamental-states-of-matter>

Plasmas in the Universe

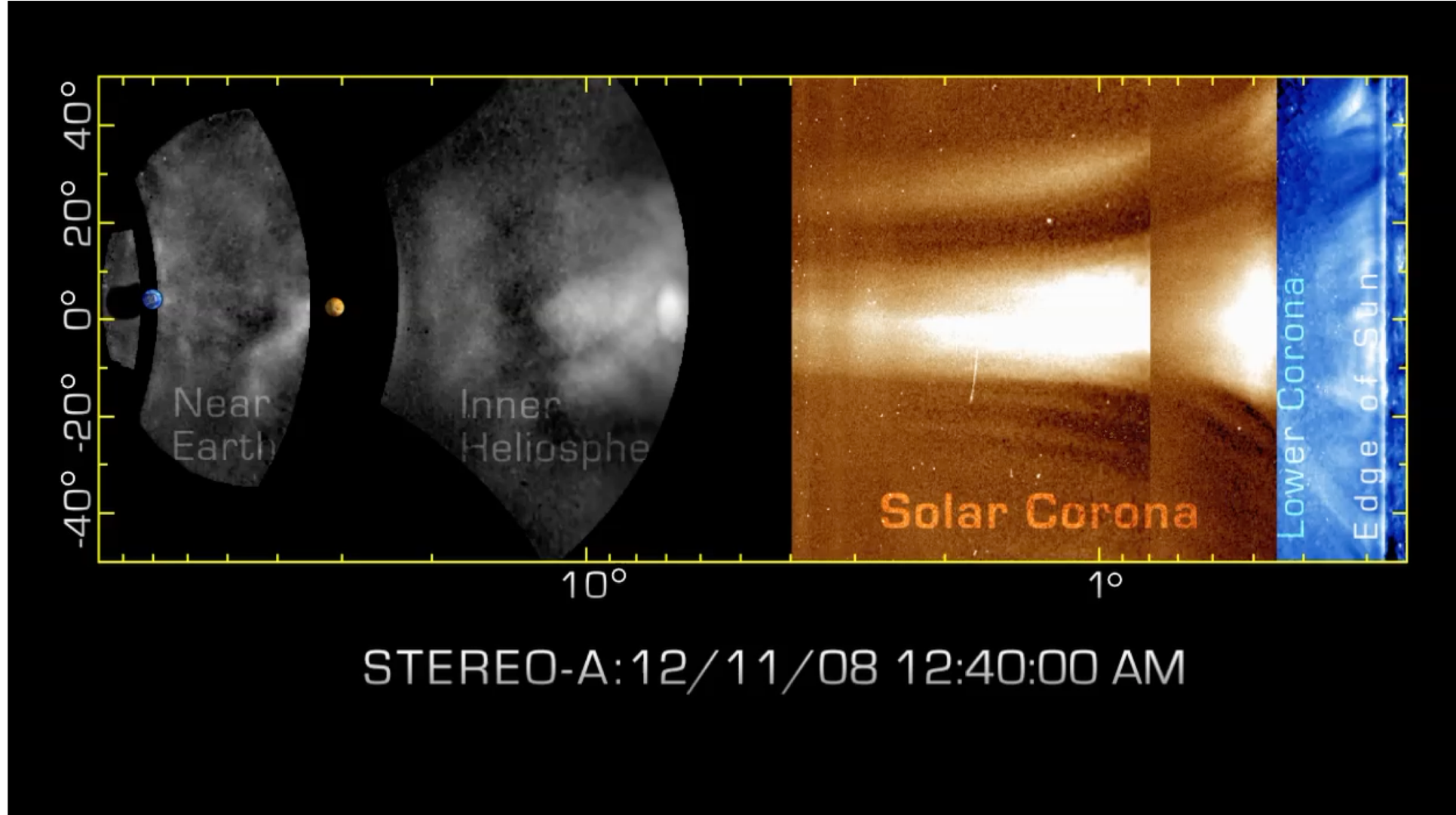
Solar Dynamics Observatory (SDO)
AIA 171nm
2025/11/08



Plasmas in the Universe

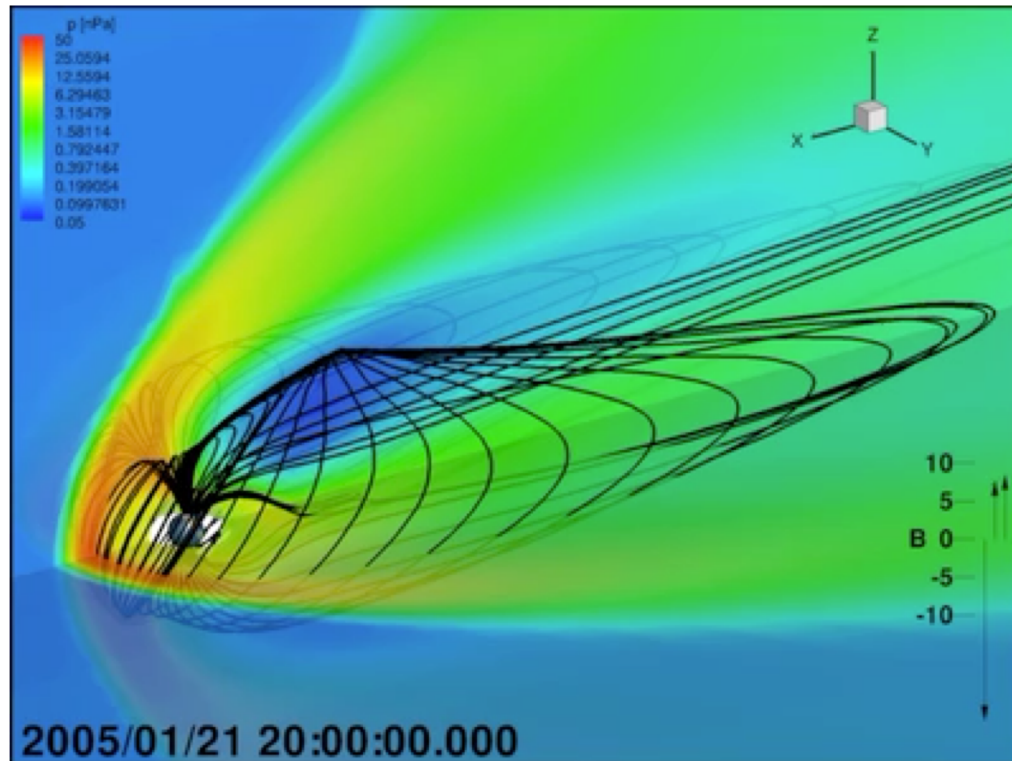
NASA's STEREO-A spacecraft allow scientists to trace the anatomy of the December 2008 CME and the solar wind as it evolves.

Credit: NASA/Goddard Space Flight Center/SwRI/STEREO

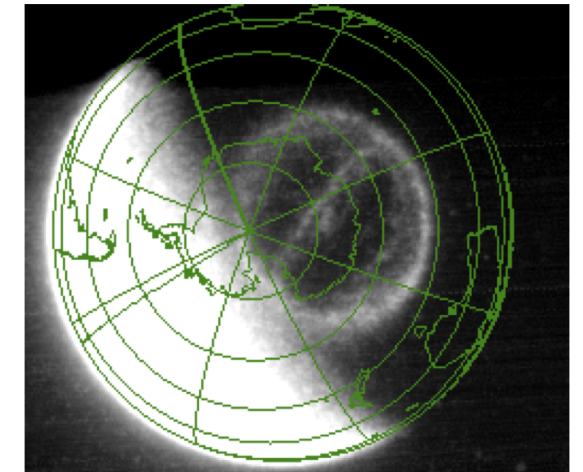
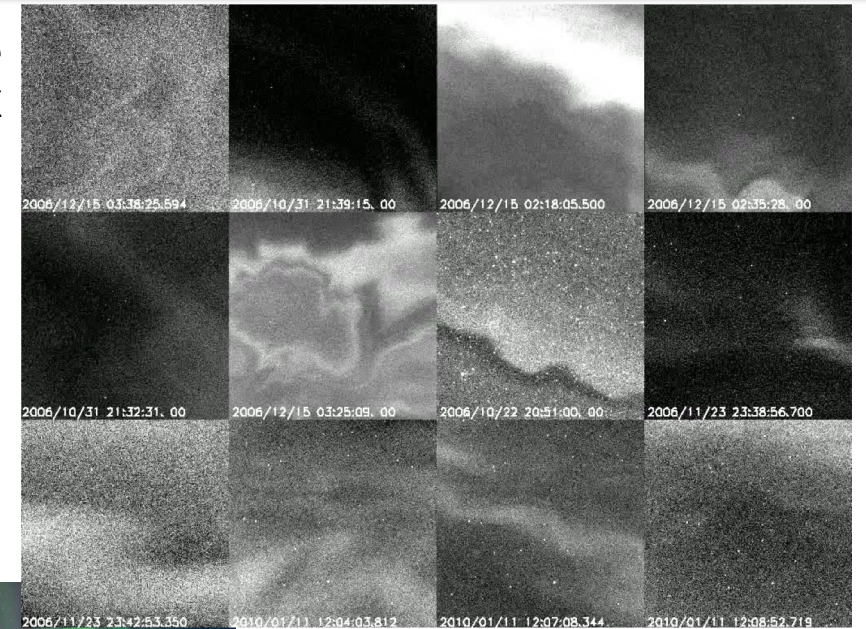


Plasmas in the Universe

Credit: Visualization by Darren DeZeeuw, Center for Space Environment Modeling, University of Michigan, USA



Aurora fine scale structure with ASK
Whiter et al.



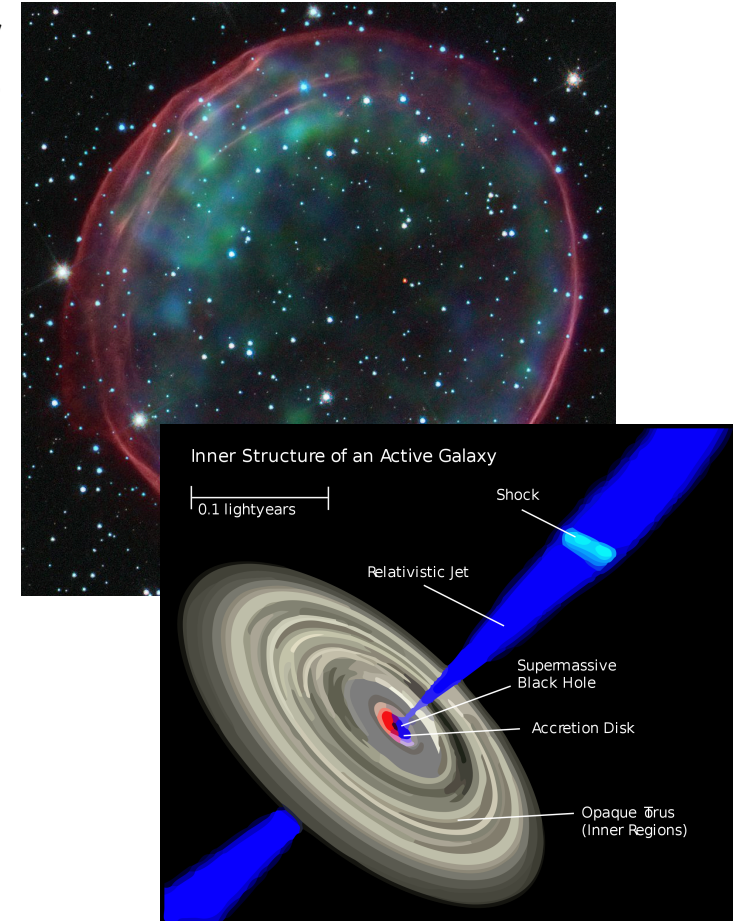
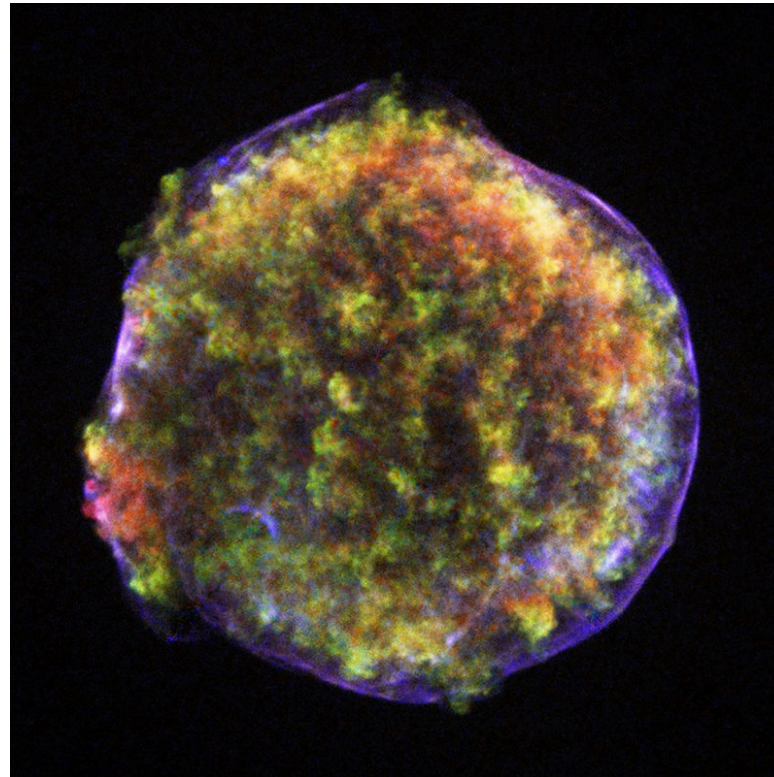
Plasmas in the Universe



Interstellar Bow Shock, LL Orionis,
Hubble Space Telescope.

SNR 0509-67 optical and x-ray
composite, Hubble

Supernova SN 1572 as seen in X-ray
light from the Chandra X-ray
Observatory, with shock wave in purple.



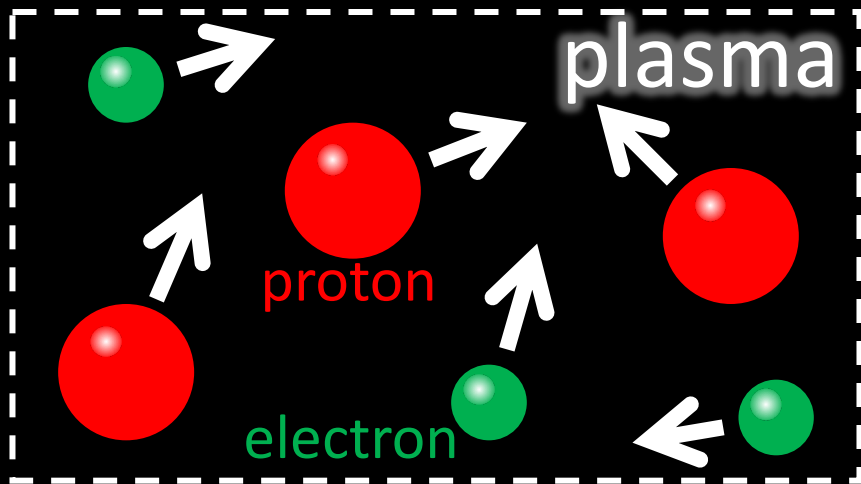
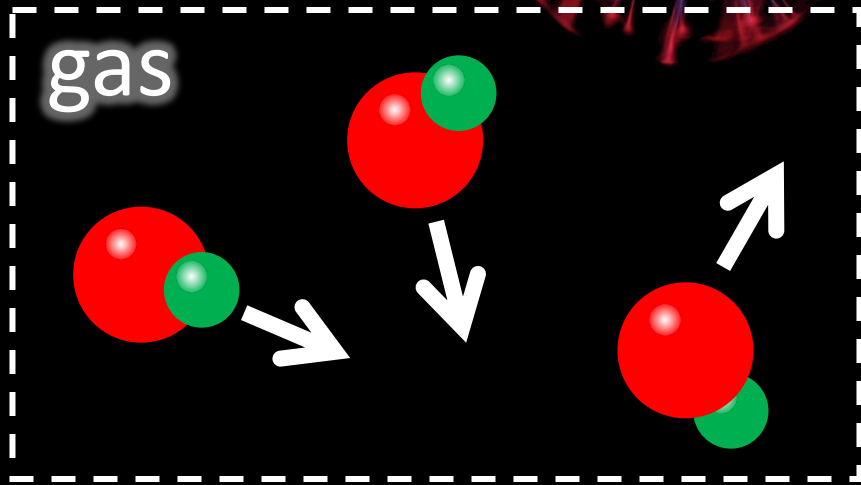
Shocks in AGN black hole jets

By Original: Unknown; Vectorization: Rothwild - Own work based on: Galaxies AGN Inner-Structure-of.jpg, CC BY-SA 3.0

Plasmas in the Universe



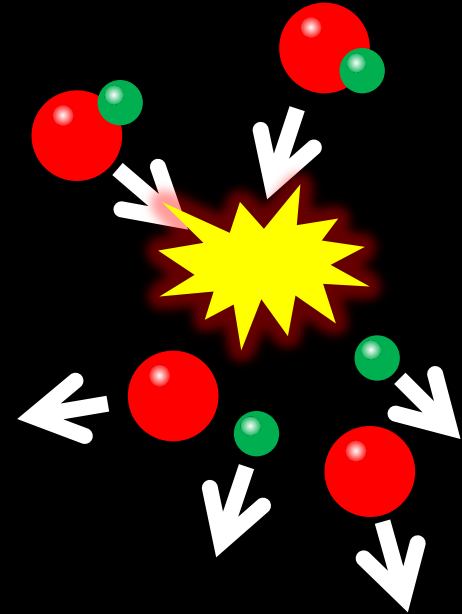
Plasma



How to
make a
plasma

- Heat: Starts to ionise if $\langle W \rangle = \frac{3}{2}k_B T \approx \text{ionisation potential } (I_0)$
- Photoionisation: Irradiate with photons with energy $>$ ionisation potential

Heat the gas
(solar corona)



Photoionisation
(ionosphere)



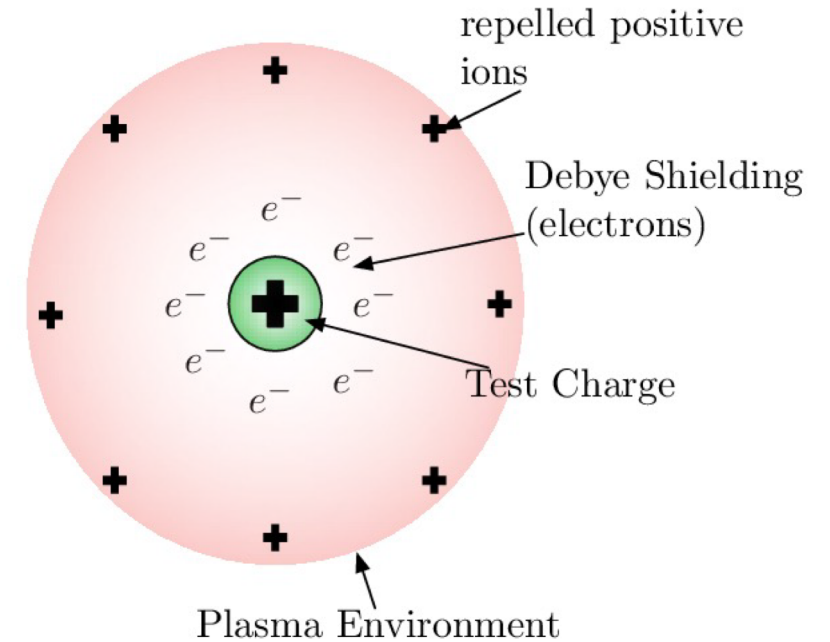
Part 1b: What is a Plasma?

(but rigorous this time)

Debye Shielding
Plasma Criteria
Collisions
Temperature

Quasi-Neutrality and Debye Shielding

- Plasmas are quasi-neutral, with equal concentrations of positive charges (ions) and negative charges (electrons)
- This is an approximation, which breaks in small volumes due to random thermal fluctuations
- **For quasi-neutrality to hold, we need a volume much bigger than the scale of the fluctuations**
- Above this length scale, electrons can effectively “shield” the electric fields in a process called **Debye Shielding**



Debye Shielding

- Consider ions and electrons in a quasi-neutral plasma with density and temperature n_0, T
- Electrons are in thermal equilibrium with Boltzmann distribution of energies, so

$$p(E) \sim e^{-E/kT}$$

- Introduce a test ion with charge q
- For electrons near the test ion:

Potential energy due to
ion charge $E = -q\phi$

$$n_e = Ae^{q\phi/kT}$$

ϕ is electrostatic potential
due to ion

Electron charge is $-q$
(using q as elementary charge)

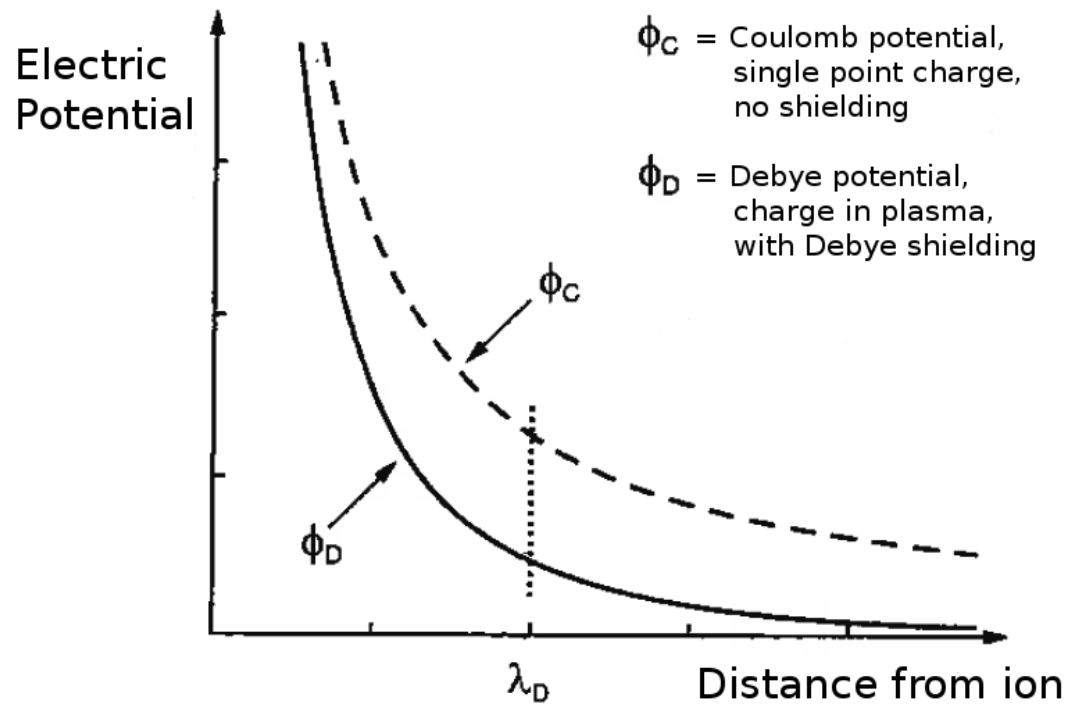
At ∞ , $\phi \rightarrow 0$ so $A = n_0$

$$\Rightarrow n_e = n_0 e^{q\phi/kT}$$

- Assume ions are heavy and don't move $\Rightarrow n_i = n_0$

Debye Shielding – Debye Length

$$\phi_D = \frac{qe^{-r/\lambda_D}}{4\pi\epsilon_0 r} \quad \lambda_D = \sqrt{\frac{\epsilon_0 kT}{n_0 q^2}}$$



Physical meaning of the shielding distance or Debye length λ_D :

- Distance over which Coulomb potential is reduced exponentially by polarisation of plasma
- Distance over which balance obtained between thermal particle energy and electrostatic potential

First Plasma Criterion

If $L < \lambda_D$, does not behave like a plasma
E.g. Low density particle beam in an accelerator

If $L \gg \lambda_D$, need to use plasma physics
Electric fields won't penetrate more than a few λ_D

Debye Shielding

For shielding effect, we need enough particles in a “Debye sphere” (radius λ_D)

$$\# \text{ particles in Debye sphere, } N_D = \frac{4}{3}\pi\lambda_D^3 n_e$$

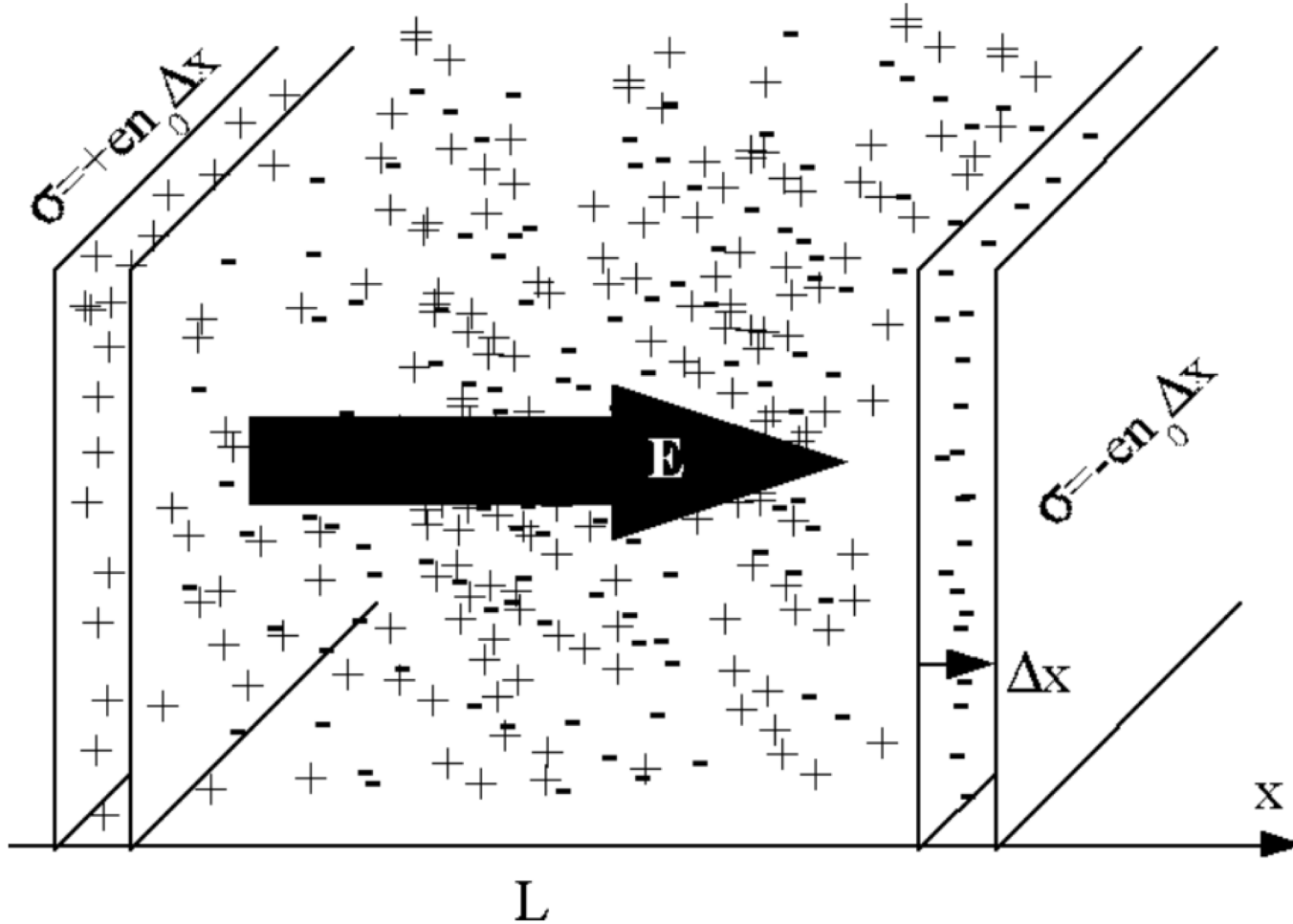
This allows us to quantify a criterion for ‘free particles’:

- Given that mean potential energy due to nearest neighbour is inversely proportional to mean inter-particle distance (and hence $\propto n_e^{1/3}$) ...
- ...the mean potential energy ($\propto n_e^{1/3}$) must be $\ll$ kinetic energy (kT)

Second Plasma Criterion

To behave as a plasma, we need $n_e\lambda_D^3 \gg 1$

Plasma Oscillations

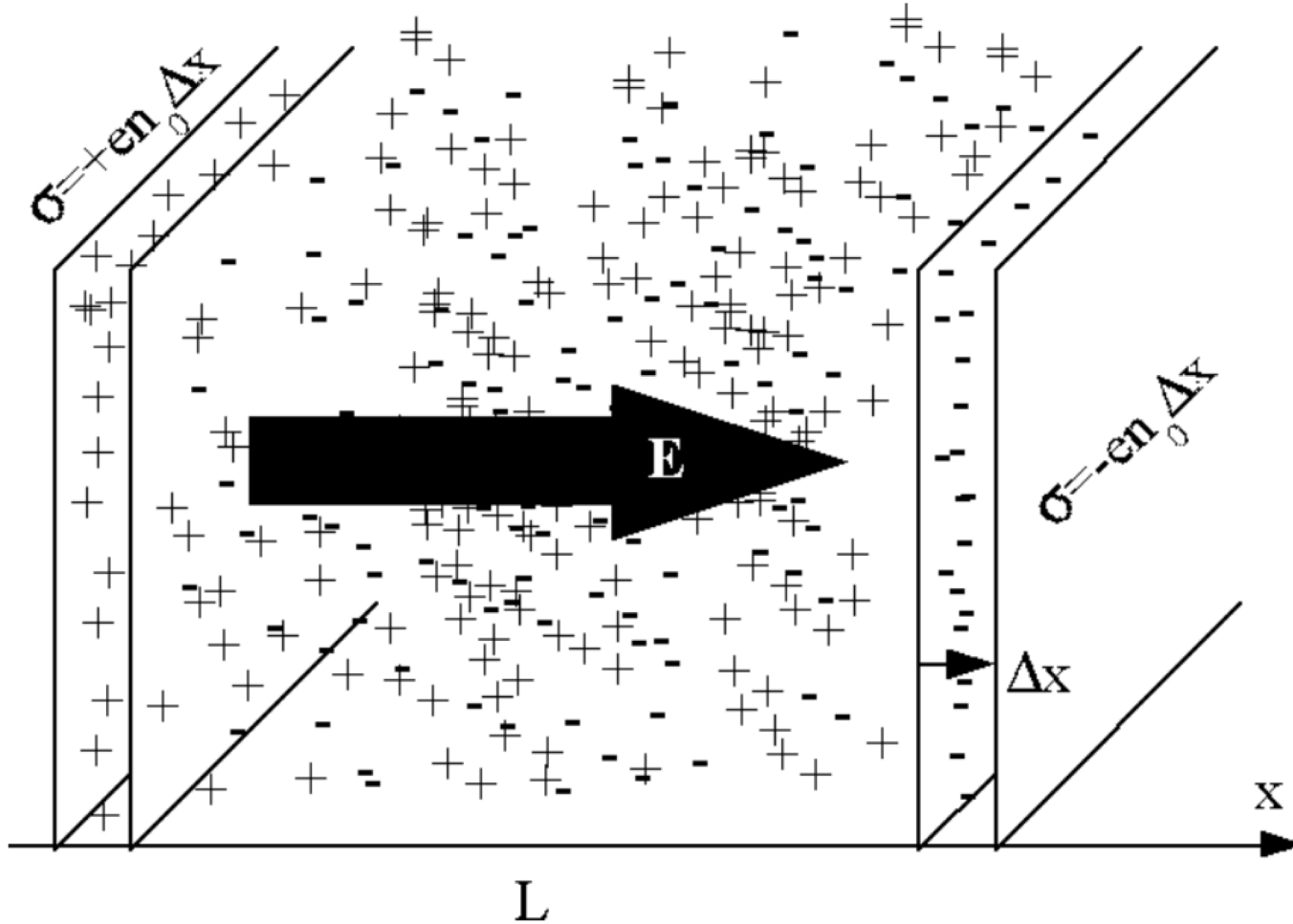


- Assume a plasma of free ions and electrons.
- Perturb the plasma with an external force, accelerating the electrons.
- Separation of electric charges results in a restoring force.
- Frequency of these plasma oscillations is called the plasma frequency:

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

- More rigorous extensions (see e.g. Baumjohann & Treuman Ch 9) give us Langmuir waves and ion acoustic waves.

Plasma Oscillations / Langmuir Waves



$$\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

- In partially ionised plasmas, free charged particles can collide with neutral atoms
- To retain collective plasma behaviour, the average time between electron-neutral collisions (τ_n) should be much larger than the inverse plasma frequency

Third Plasma Criterion

To behave as a plasma, we need

$$\omega_{pe} \tau_n \gg 1$$

What is a Plasma? – Criteria

- **Quasi-neutrality**

- Gas of charged particles with equal positive and negative charge carriers (assuming single unit charge)
- Total positive charge = Total negative charge

⇒ First plasma criterion: $L \gg \lambda_D$

- **Free charges**

- Potential energy due to nearest neighbour is smaller than random kinetic (thermal) energy
- Need thermal energies above a few eV to overcome coupling with neighbours
- A typical plasma is hot and highly ionised

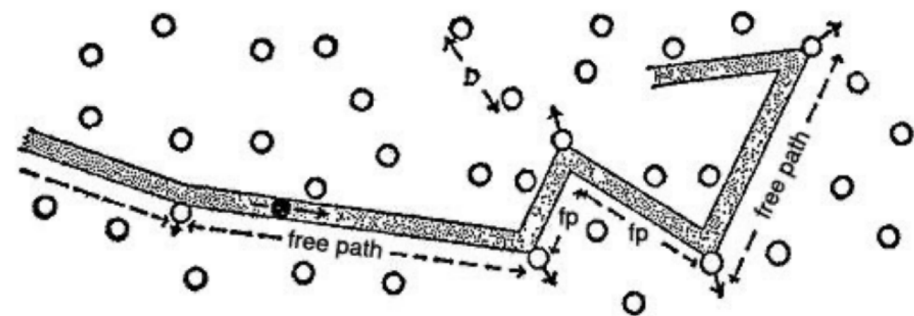
⇒ Second plasma criterion: $n_e \lambda_D^3 \gg 1$

- **Low neutral density**

- A large fraction of neutrals will interfere with the ability to behave as a plasma

⇒ Third plasma criterion: $\omega_{pe} \tau_n \gg 1$

Particle Collisions



Mean free path of a gas molecule

Table 1: Varying Coulomb collisions

Parameter	Chromosphere (1.01 $R_{\odot}$)	Corona (1.3 $R_{\odot}$)	Solar wind (1 AU)
$n(\text{cm}^{-3})$	10^{10}	10^7	10
$T(\text{K})$	10^3	$1 - 2 \times 10^6$	10^5
$\lambda_c(\text{km})$	1	10^3	10^7

Living Reviews in Solar Physics
<http://www.livingreviews.org/lrsp-2006-1>

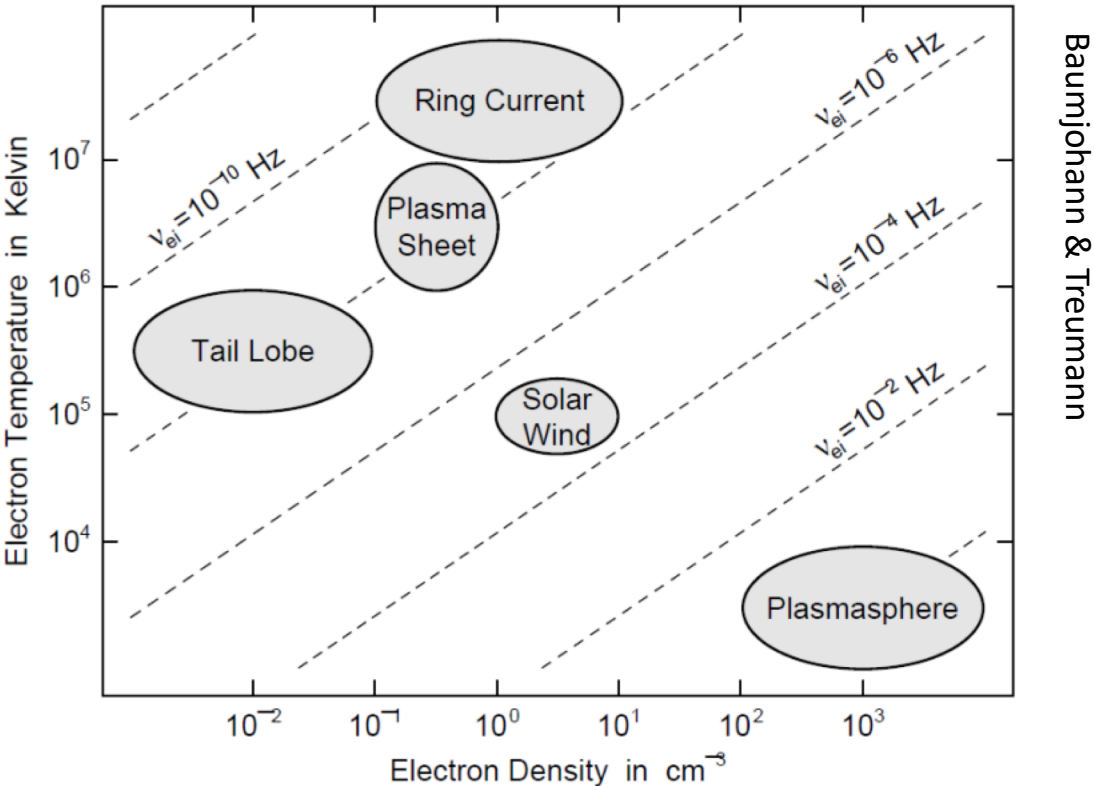


Fig. 4.2. Typical Coulomb collision frequencies for geophysical plasmas.

Collision frequency:
$$\nu_{ei} = \frac{\ln \Lambda_c e^4 n_e}{12 \sqrt{2} \pi^{3/2} \epsilon_0^2 m_e^{1/2} T^{3/2}}$$

<https://farside.ph.utexas.edu/>

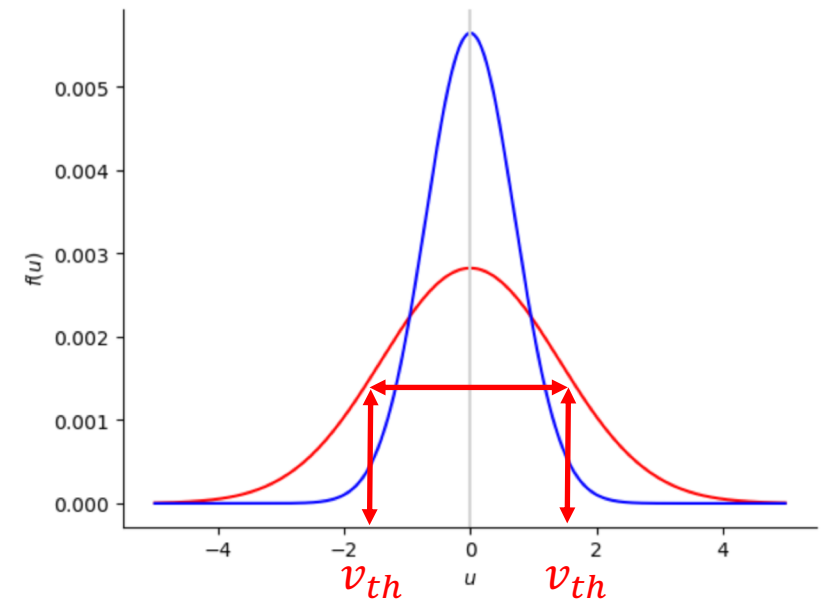
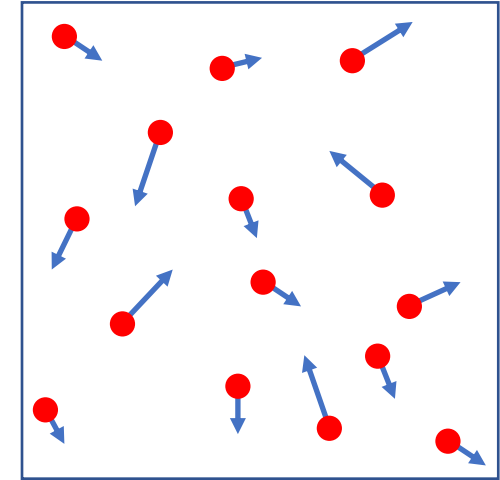
What is the temperature of a plasma?

- In plasma physics, we often consider the **distribution function** $f(\mathbf{v})$, which describes the distribution of electron or ion velocities (and/or positions).

- Consider a simple Maxwellian distribution:

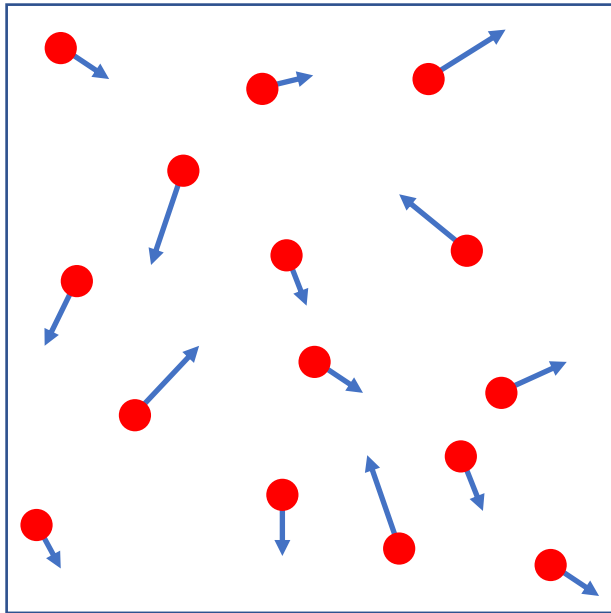
$$f(u) = Ae^{-\frac{1}{2}mu^2/kT}$$

- **Temperature** is related to the random motion of the particles in the plasma – it is a measure of the *variance* of the velocities.
- **Thermal velocity** is comes from the standard deviation of the distribution, i.e. $v_{th} \propto \sqrt{T}$

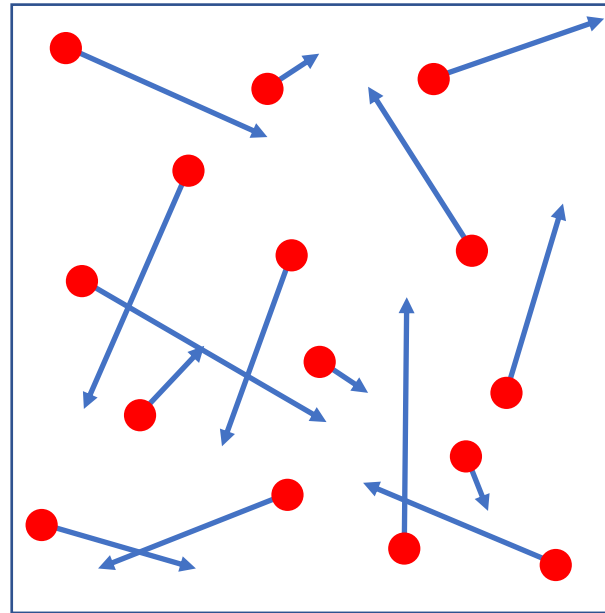


What is the temperature of a plasma?

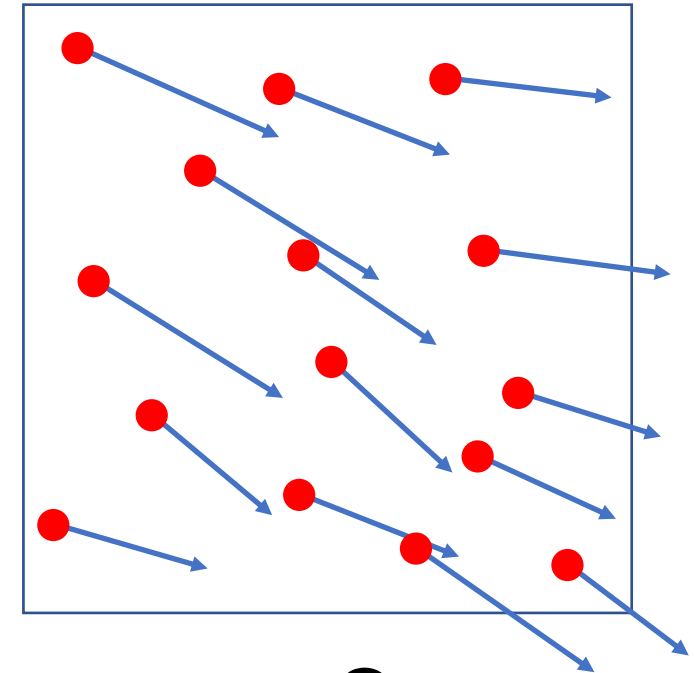
"Hot" or "Cold"?



A

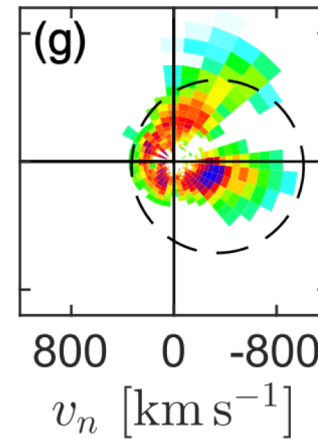
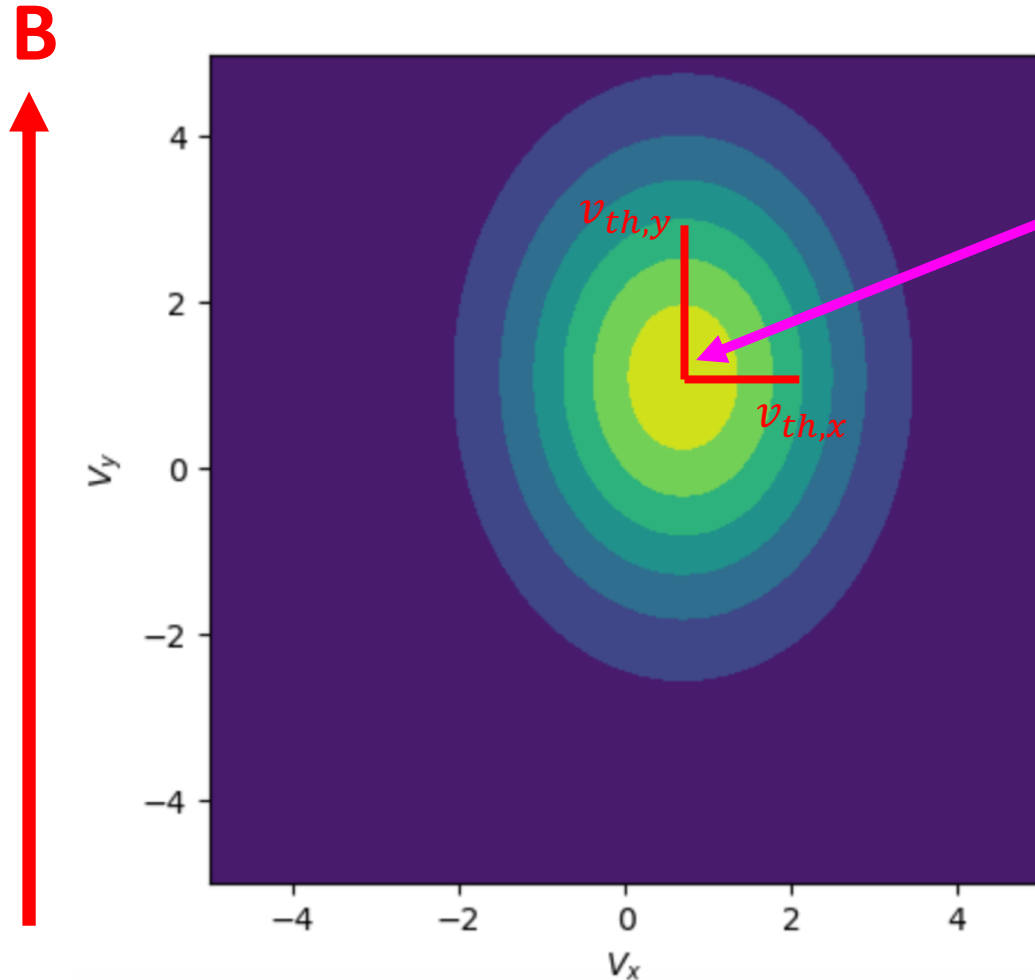


B



C

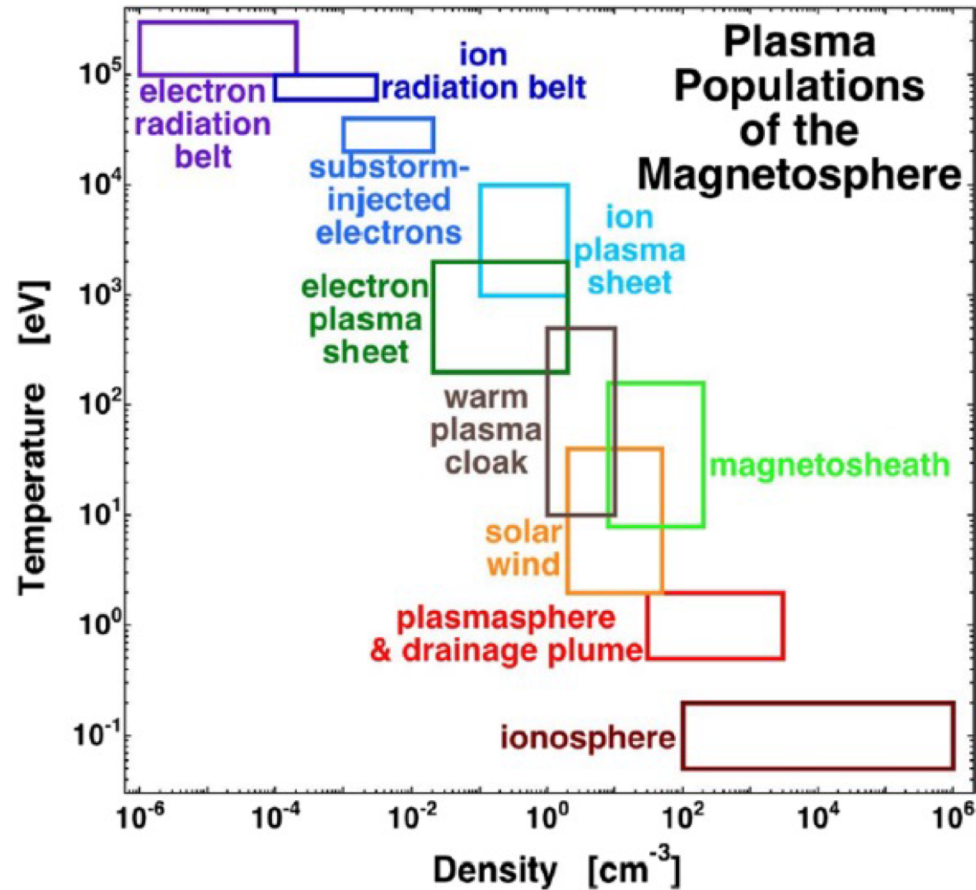
What is the temperature of a plasma?



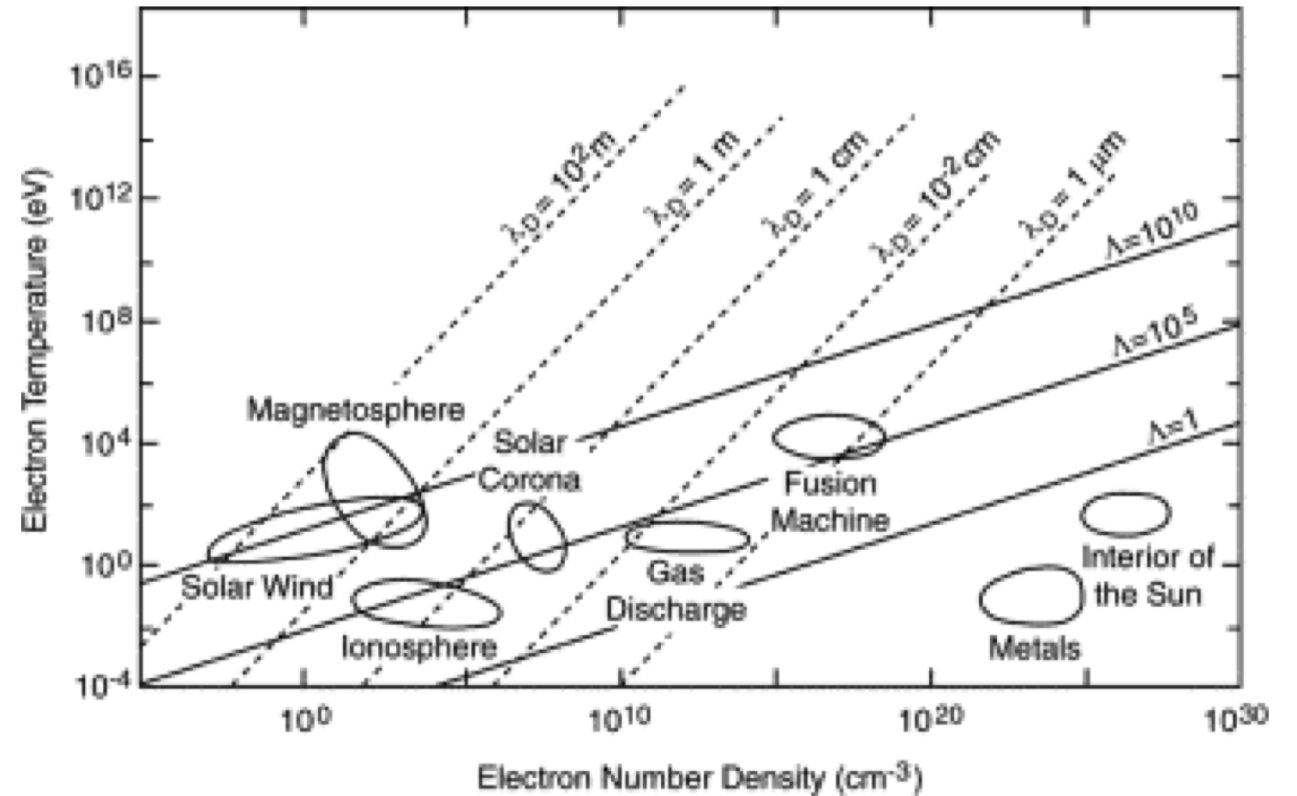
Reflected ions at Earth's bow shock (Johlander et al. 2016)

- We can define temperatures in different directions, i.e. the variance of velocity components.
- Some plasmas have different temperatures in the different directions, particular in the direction parallel and perpendicular to the magnetic field.
- These plasmas have a **temperature anisotropy**.
- It is difficult to meaningfully define temperatures for some plasmas.

Plasmas in the Universe



Borovsky & Valdivia 2018 Surveys in Geophys.
<https://msolss.github.io/MagSeminars/>



C.T. Russell, in Encyclopedia of Physical Science and Technology
 (Third Edition), 2003

Debye Shielding
Plasma Criteria
Collisions
Temperature

Part 2: Single Particle Motions

Gyration
Drifts
Mirroring

Single Particle Motion – Gyration in a uniform B field

Consider the Lorentz force and Newton's second law:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{V} \times \mathbf{B})$$

$$m \frac{d\mathbf{V}}{dt} = q(\mathbf{E} + \mathbf{V} \times \mathbf{B})$$

If $\mathbf{E} = 0$:

$$m \frac{d\mathbf{V}}{dt} = q\mathbf{V} \times \mathbf{B}$$

A static magnetic field, whatever its form, cannot change particle kinetic energy

Single Particle Motion – Gyration in a uniform B field

$$m \frac{d\mathbf{V}}{dt} = q\mathbf{V} \times \mathbf{B}$$

Take $\mathbf{B}$ in z direction ($\mathbf{B} = B\hat{\mathbf{k}}$)

$$\frac{d^2 V_x}{dt^2} = -\left(\frac{qB}{m}\right)^2 V_x$$

$$\frac{d^2 V_y}{dt^2} = -\left(\frac{qB}{m}\right)^2 V_y$$

Define gyrofrequency (units s^{-1})

$$\Omega = \frac{qB}{m}$$

Solution:

$$x(t) = x_0 + \frac{V_{\perp}}{\Omega} \sin(\Omega t + \phi)$$

$$y(t) = y_0 + \frac{V_{\perp}}{\Omega} \cos(\Omega t + \phi)$$

$$z(t) = z_0 + V_{\parallel} t$$

i.e. Motion (gyration) around a “guiding centre” $(x_0, y_0, z(t))$ with gyroradius (“Larmor radius”):

$$r_g = \frac{V_{\perp}}{\Omega} = \frac{mV_{\perp}}{qB}$$

$$V_{\perp} = \sqrt{V_x^2 + V_y^2}$$

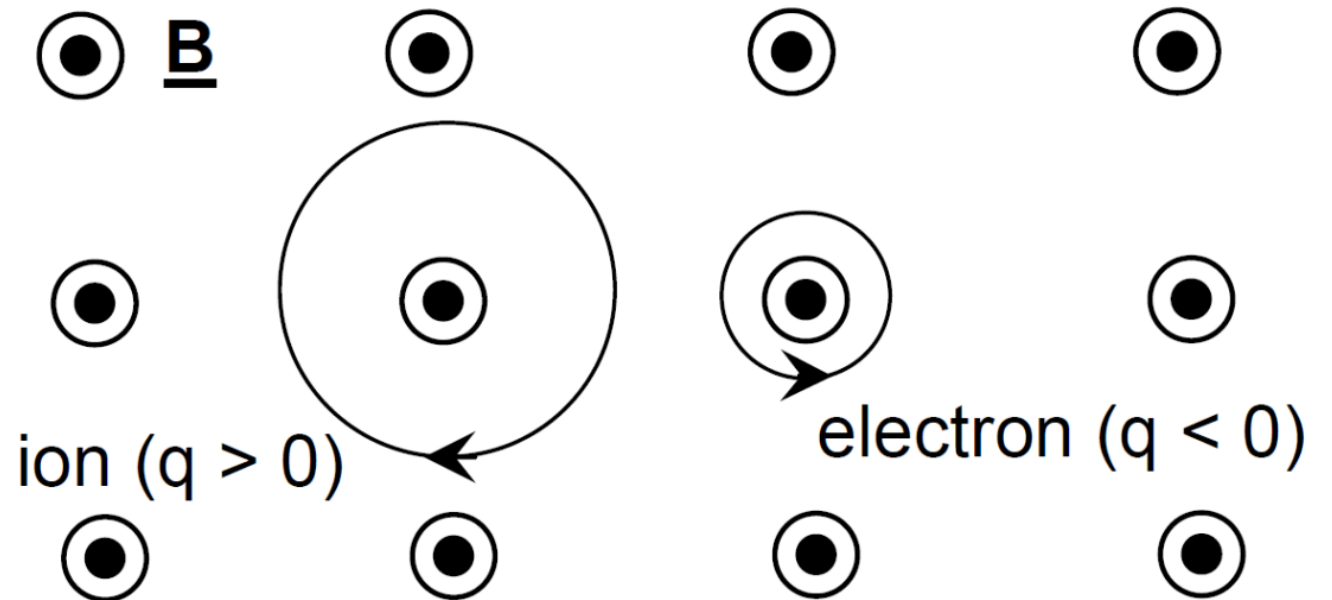
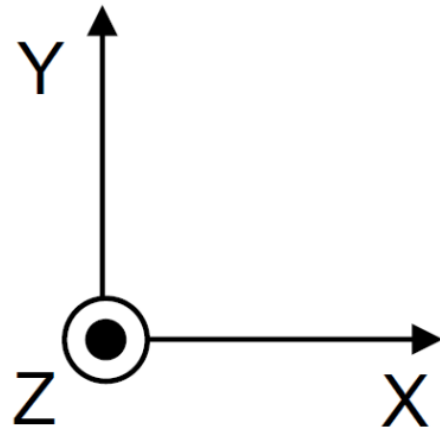
Single Particle Motion – Gyration in a uniform B field

i.e. Motion (gyration) around a “guiding centre” $(x_0, y_0, z(t))$

$$\text{Gyroradius: } r_g = \frac{V_{\perp}}{\Omega} = \frac{mV_{\perp}}{qB}$$

$$\text{Gyrofrequency: } \Omega = \frac{qB}{m}$$

$$V_{\perp} = \sqrt{V_x^2 + V_y^2}$$



Single Particle Motion – Gyration in a uniform B field

Gyrofrequency:

$$\Omega = \frac{qB}{m}$$

Gyroperiod:

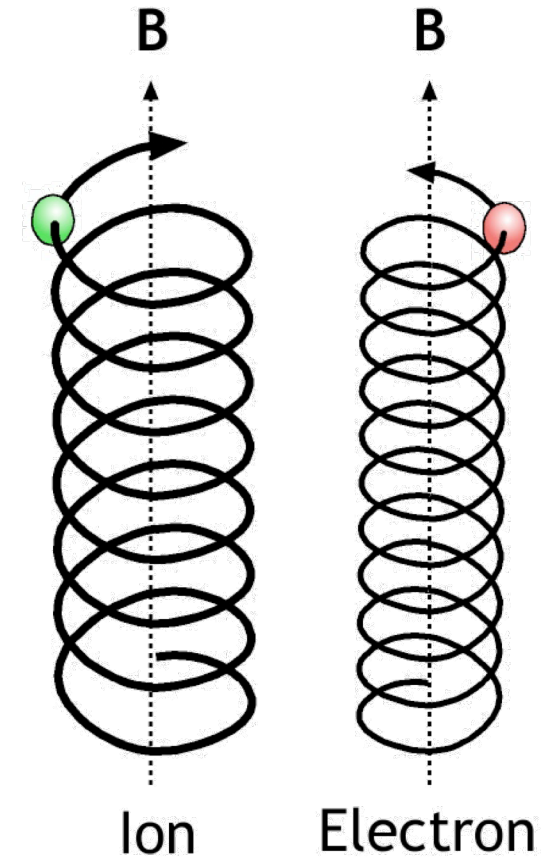
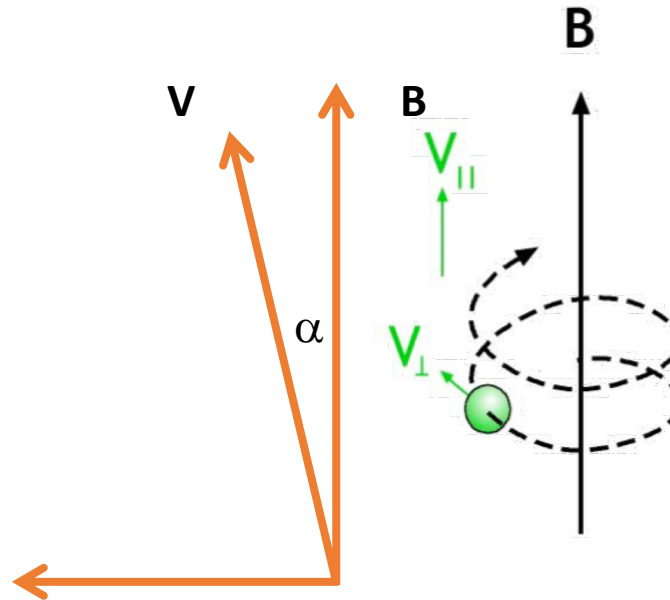
$$\tau = \frac{2\pi}{\Omega}$$

Gyroradius:

$$r_g = \frac{V_{\perp}}{\Omega} = \frac{mV_{\perp}}{qB}$$

Pitch angle:

$$\alpha = \tan^{-1} \frac{V_{\perp}}{V_{\parallel}}$$



Ions and electrons gyrate in opposite directions.

Single Particle Motion – Particle Drifts

What happens if we introduce a uniform external force $\mathbf{F}$, which does not depend on particle position or velocity?

e.g. Gravity or electric field may be considered uniform over limited regions

Start by defining components of external force relative to direction of $\mathbf{B}$:

$$\mathbf{F} = \mathbf{F}_{\parallel} + \mathbf{F}_{\perp}$$

Consider effect on particle motion parallel and perpendicular to $\mathbf{B}$

- **Parallel:** Particle accelerates along field (acceleration = $\mathbf{F}_{\parallel}/m$)
- **Perpendicular:** Particle drifts perpendicular to $\mathbf{F}$ and $\mathbf{B}$

Overall motion: Gyromotion (helix) and constant drift perpendicular to $\mathbf{F}$ and $\mathbf{B}$

General expression for drift velocity:

$$\mathbf{V}_F = \frac{\mathbf{F} \times \mathbf{B}}{qB^2}$$

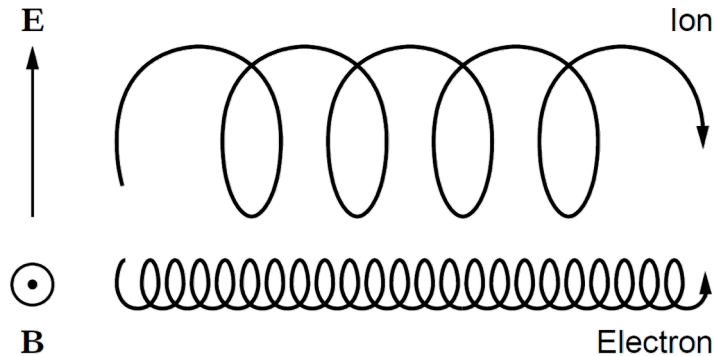
Single Particle Motion – Particle Drifts

ExB Drift

Independent of q , no current
Equivalent to frame transformation

$$\mathbf{F} = q\mathbf{E}$$

$$\mathbf{V}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

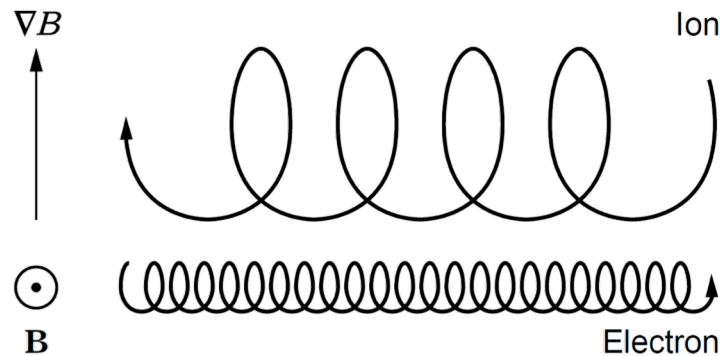


Gradient Drift

Direction depends on charge q , resulting in current

$$\mathbf{F}_{grad} = -\mu_M \nabla B$$

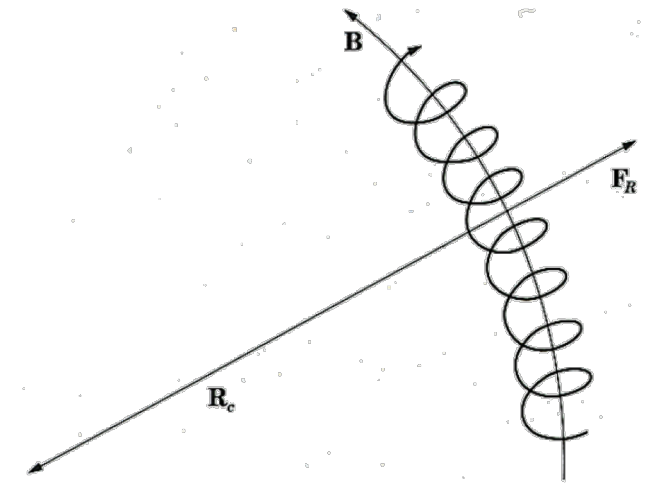
$$\mathbf{V}_{grad} = \frac{W_{\perp} \mathbf{B} \times \nabla B}{qB^3}$$



Curvature Drift

$$\mathbf{F}_{curv} = \frac{mv_{\parallel}^2}{R_c} \hat{\mathbf{R}}_c$$

$$\mathbf{V}_{curv} = \frac{mv_{\parallel}^2}{q} \frac{\mathbf{R}_c \times \mathbf{B}}{R_c^2 B^2}$$



Single Particle Motion – Adiabatic Invariants

- Single particle motion may have a number of “**adiabatic invariants**” depending on symmetries of the system.
- These adiabatic invariants are not strictly conserved, but can be treated as constant under the right conditions.
- The conditions must change slowly in time (i.e. ‘adiabatic’ changes).

Different adiabatic invariants are associated with different types of particle motion:

- Magnetic moment (μ_m) – Gyration around **B**
- Longitudinal invariant (J_L) – Longitudinal motion along **B**
- Drift invariant (Φ) – Perpendicular drift

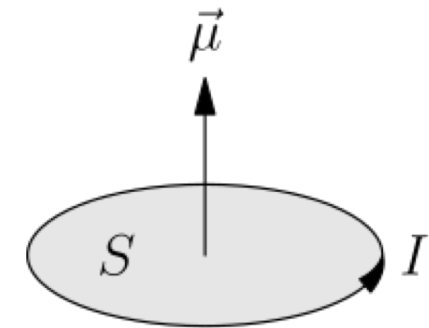
These can each be derived formally from action integrals (but there’s no time for that now!)

Magnetic moment:

$$\mu_M = \frac{W_{\perp}}{B}$$

(or equivalently)

$$\mu_M = IS$$

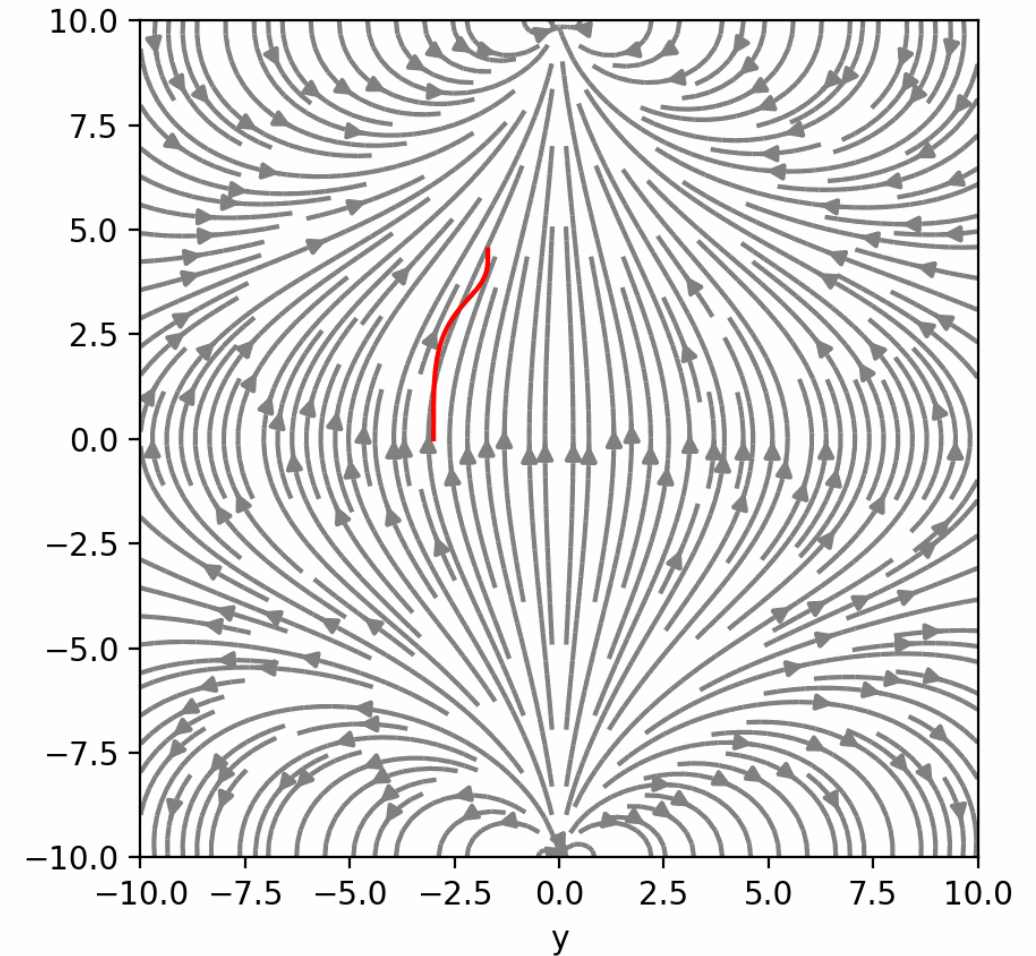
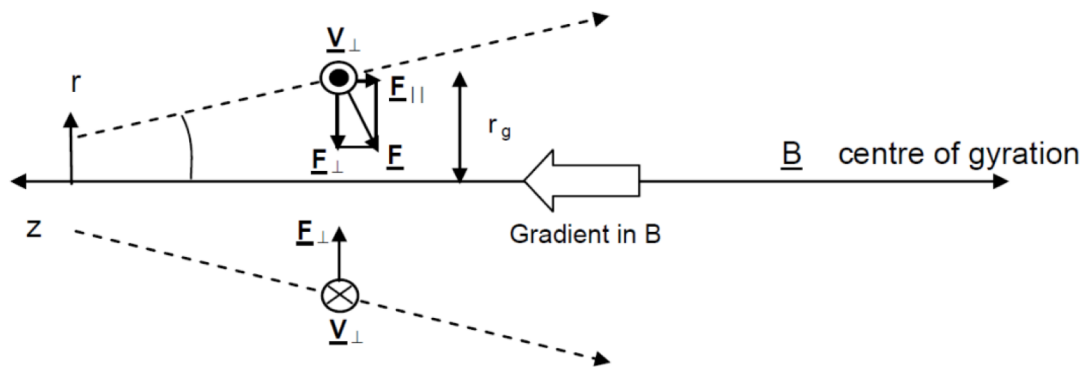


Single Particle Motion – Magnetic Mirroring

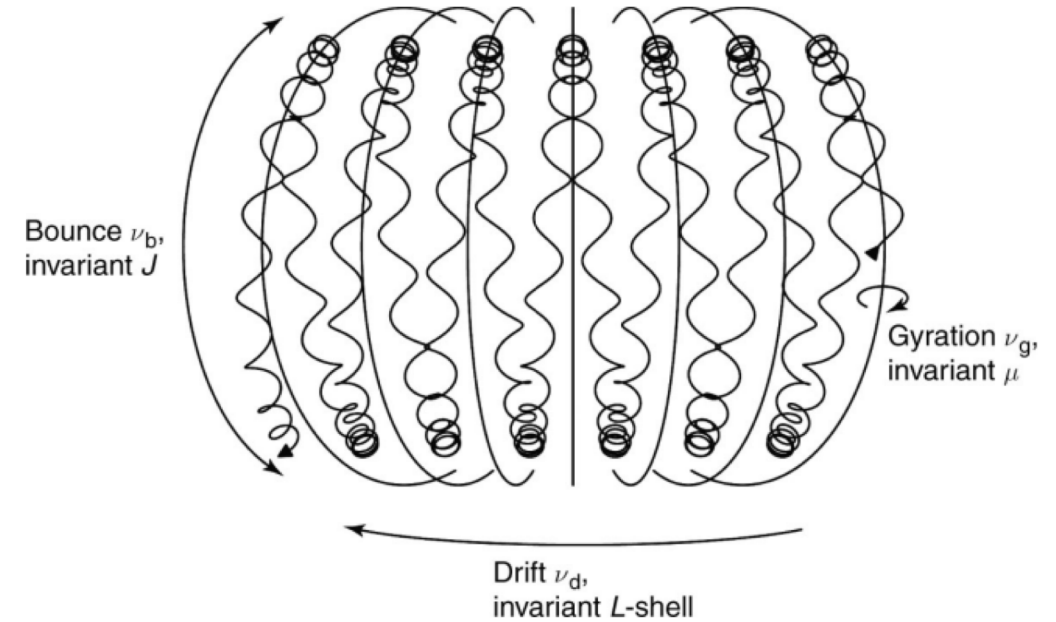
From the conservation of the magnetic moment, particles moving into regions of higher magnetic field strength can mirror if they fulfil the criterion:

$$\alpha_0 > \sin^{-1} \left(\sqrt{\frac{B_0}{B_{max}}} \right) \quad \alpha = \tan^{-1} \frac{V_{\perp}}{V_{\parallel}}$$

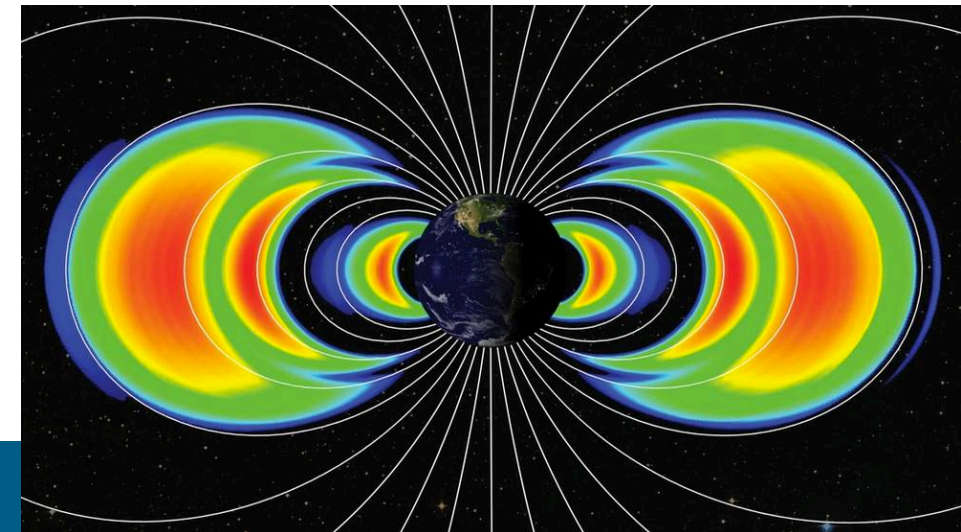
α_0 defines a “loss cone” angle. Particles with smaller pitch angle are not trapped within a given magnetic bottle.



Single Particle Motion – Magnetic Bottle



Earth's radiation belts consist of trapped particles moving according to these drifts.



Gyration
Drifts
Mirroring

Part 3: Plasma Physics Toolkits

Waves
Kinetic Theory
Fluid Theory

Waves in Plasmas – A Generalised Approach

Assume uniform, infinite plasma with no background electric field and uniform background magnetic field.

Maxwell's Equations

$$\begin{aligned}\nabla \cdot \mathbf{E} &= \frac{\rho}{\epsilon_0} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{B} &= \mu_0 \left(\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)\end{aligned}$$

Substitute linear wave solution:
 $e^{i(\mathbf{k} \cdot \mathbf{x} - \omega t)}$

Close the system using a generalised Ohm's law with conductivity tensor $\vec{\sigma}$

$$\mathbf{J} = \vec{\sigma} \cdot \mathbf{E}$$

$$\mathbf{k} \times (\mathbf{k} \times \mathbf{E}) + \frac{\omega^2}{c^2} \mathbf{E} + i\omega\mu_0 \mathbf{J} = 0$$

Re-write as

$$\mathbf{k} \times (\mathbf{k} \times \mathbf{E}) + \frac{\omega^2}{c^2} \vec{\epsilon} \cdot \mathbf{E} = 0$$

$$\vec{\epsilon} = \vec{I} + \frac{i}{\omega\epsilon_0} \vec{\sigma} \text{ is the "Dielectric tensor"}$$

Solutions when $\det|\vec{D}| = 0$

$$\vec{D} \cdot \mathbf{E} = 0$$

with

$$\vec{D} = \mathbf{k}\mathbf{k}^T - k^2 \vec{I} + \frac{\omega^2}{c^2} \vec{\epsilon}$$

"Dispersion relation"
relating $\mathbf{k}$ and ω

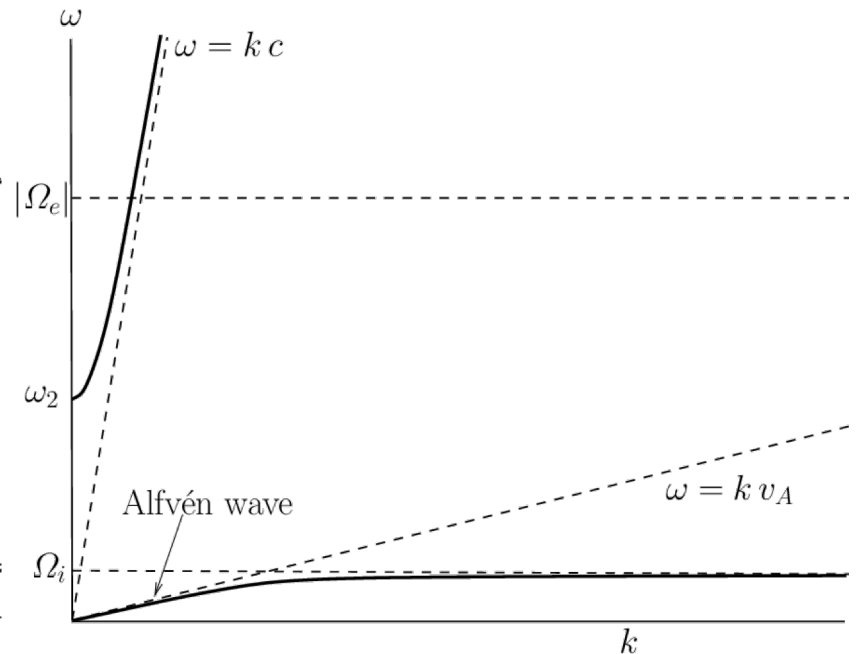
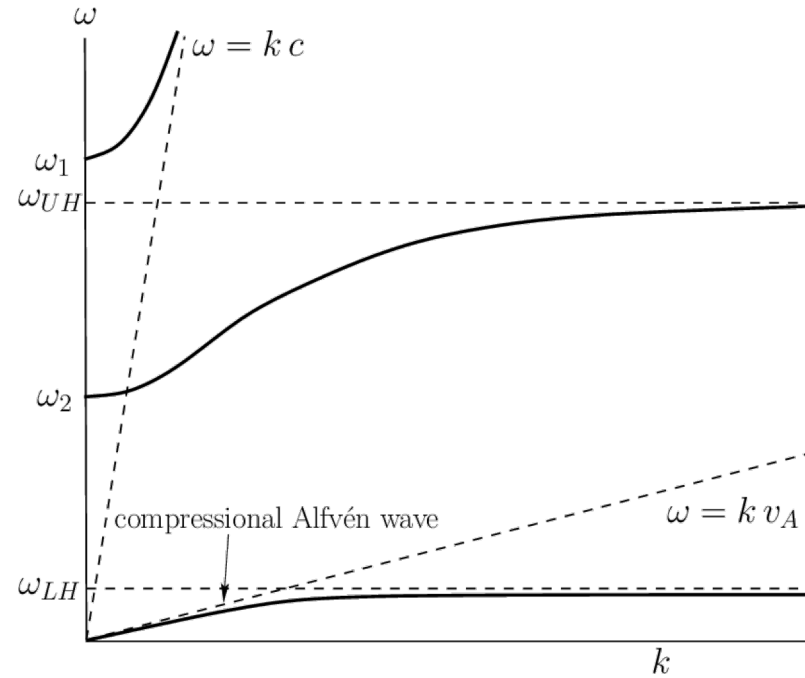
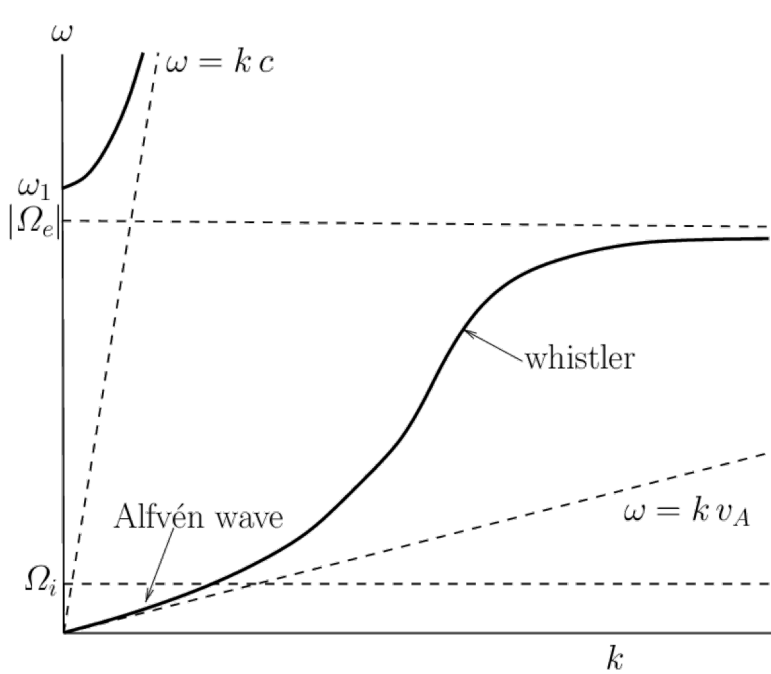
Cold, Magnetised Plasma Dispersion Relations

Parallel propagation

Perpendicular propagation

Right-handed waves

Left-handed waves



The zoo of plasma waves is complex and varied!
You will hear more about waves in MHD later today...

<https://farside.ph.utexas.edu>

Waves in MHD

Plasmas support many different kinds of wave mode, which you can derive using the MHD equations (an exercise for the reader!)

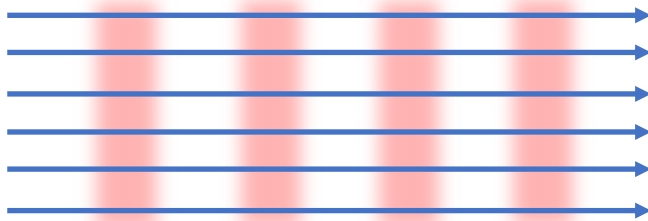
In ideal MHD (zero resistivity), it's easy to show three different kinds of wave modes, which arise from magnetic pressure and magnetic tension:

Slow Magnetosonic Waves

Longitudinal
Compressive

$$\mathbf{k} \parallel \mathbf{B}$$

$$V_{slow} \approx c_s$$

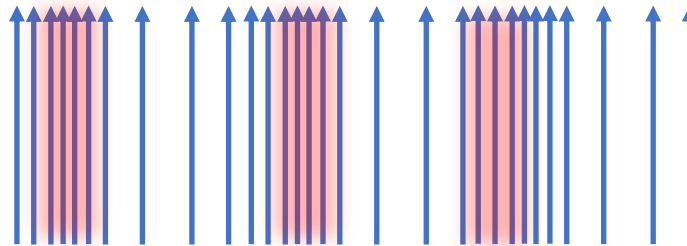


Fast Magnetosonic Waves

Longitudinal
Compressive

$$\mathbf{k} \perp \mathbf{B} \text{ (preferentially)}$$

$$V_{fast} \approx \sqrt{V_A^2 + c_s^2}$$

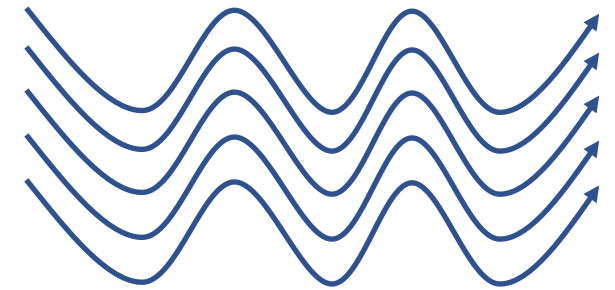


Alfvén Waves

Transverse
Incompressible

$$\mathbf{k} \parallel \mathbf{B}$$

$$V_A \approx B / \sqrt{\mu_0 \rho}$$



See also: whistler waves, cyclotron waves, upper and lower hybrid waves, kinetic Alfvén waves, Bernstein waves, X and O mode electromagnetic waves,....

Modelling Plasmas – Kinetic Theory

Let's set the stage for your upcoming lectures on magnetohydrodynamics!

Looking at the distribution function again (more rigorously this time), we define:

$$f(\mathbf{x}, \mathbf{v}, t) d^3\mathbf{x} d^3\mathbf{v} = dN(\mathbf{x}, \mathbf{v}, t)$$

dN is the number of particles in the phase space volume $dV = d^3\mathbf{x} d^3\mathbf{v}$

We can "take moments" of the distribution function (integrate over $\mathbf{v}$) to derive macroscopic quantities of the plasma:

$\int \dots$	0 th moment	Number density:	$n(\mathbf{x}, t) = \int f(\mathbf{x}, \mathbf{v}, t) d^3\mathbf{v}$
--------------	------------------------	-----------------	--

$\int \mathbf{v} \dots$	1 st moment	Bulk flow velocity:	$\mathbf{V} = \frac{1}{n} \int \mathbf{v} f d^3\mathbf{v}$
-------------------------	------------------------	---------------------	--

$\int v^2 \dots$	2 nd moment	Pressure tensor:	$\mathbf{P}_{ij} = \int m (v_i - V_i)(v_j - V_j) f d^3\mathbf{v}$
------------------	------------------------	------------------	---

Modelling Plasmas – Kinetic Theory

We can consider the time evolution of the distribution function $f(\mathbf{x}, \mathbf{v}, t)$ using the Boltzmann equation:

$$\frac{df(\mathbf{x}, \mathbf{p}, t)}{dt} = \frac{\partial f}{\partial t} + \frac{d\mathbf{p}}{dt} \cdot \frac{\partial f}{\partial \mathbf{p}} + \frac{d\mathbf{x}}{dt} \cdot \frac{\partial f}{\partial \mathbf{x}} = \cancel{\left(\frac{\partial f}{\partial t}\right)_{coll}} = 0$$

We can often (not always) treat space plasmas as collisionless

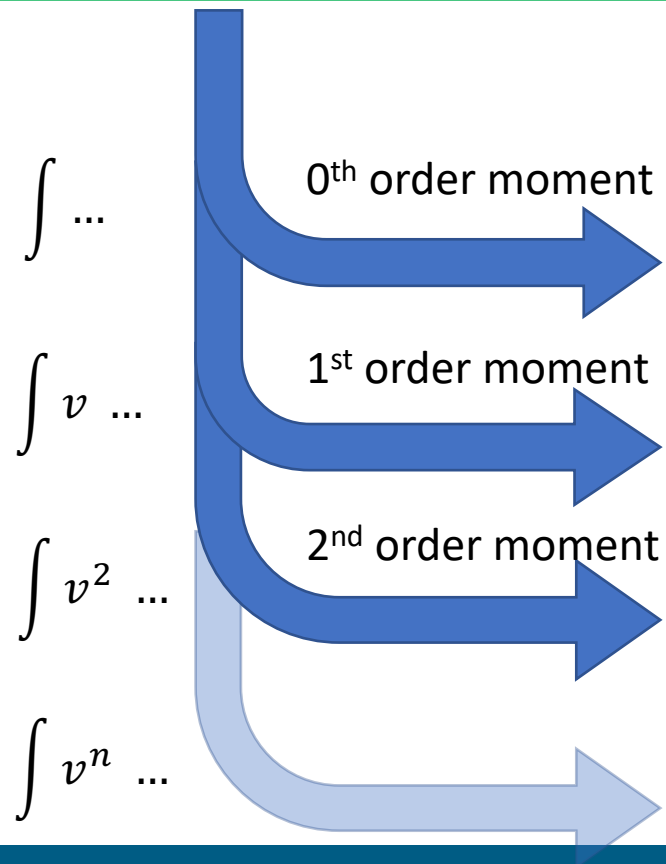
Substitute the Lorentz force: $\frac{d\mathbf{p}}{dt} = q (\mathbf{E} + \mathbf{v} \times \mathbf{B})$ to arrive at the Vlasov equation:

$$\frac{\partial f}{\partial t} + \frac{q}{m} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \nabla_{\mathbf{v}} f + \mathbf{v} \cdot \nabla_{\mathbf{x}} f = 0$$

Modelling Plasmas – Towards Fluid Theory

$$\frac{\partial f}{\partial t} + \frac{q}{m} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \nabla_{\mathbf{v}} f + \mathbf{v} \cdot \nabla_{\mathbf{x}} f = 0$$

Over long space and time scales, we can take moments of the Vlasov equation to derive the continuity equations of a fluid plasma:



0th order moment

Continuity of Mass

Fluid Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

1st order moment

Momentum Equation

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = \mathbf{J} \times \mathbf{B} - \nabla p$$

2nd order moment

Energy Equation

$$\left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) p = -\gamma p \nabla \cdot \mathbf{v} + (\gamma - 1) \frac{J^2}{\sigma}$$

$$\int v^n \dots$$

Electromagnetism

Maxwell's Equations

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

Continuity of Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

Momentum Equation

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = \mathbf{J} \times \mathbf{B} - \nabla p$$

Energy Equation

$$\left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) p = -\gamma p \nabla \cdot \mathbf{v} + (\gamma - 1) \frac{J^2}{\sigma}$$

Ohm's Law

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \frac{\mathbf{j}}{\sigma} + \frac{1}{ne} (\mathbf{j} \times \mathbf{B} - \nabla \cdot \mathbf{P}_e) + \frac{m_e}{ne^2} \left(\frac{\partial \mathbf{j}}{\partial t} + \nabla \cdot \left(\mathbf{u} \mathbf{j} + \mathbf{j} \mathbf{u} - \frac{\mathbf{j} \mathbf{j}}{ne} \right) \right)$$

Fluid Equations

Electromagnetism

Maxwell's Equations

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

low frequency approximation

Ohm's Law $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \mathbf{J} / \sigma$

Fluid Equations

Continuity of Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

Momentum Equation

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = \mathbf{J} \times \mathbf{B} - \nabla p$$

Energy Equation

$$\left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) p = -\gamma p \nabla \cdot \mathbf{v} + (\gamma - 1) \frac{J^2}{\sigma}$$

Summary

What is a plasma?

Quasi-neutrality

Debye Shielding

Plasma Criteria:

- Length scales far above Debye length
- Many particles in Debye sphere
- Neutral collision frequency much less than plasma frequency

Single Particle Motion

Gyration

ExB drift, Gradient drift,
Curvature drift)

Adiabatic Invariants

Magnetic Mirroring

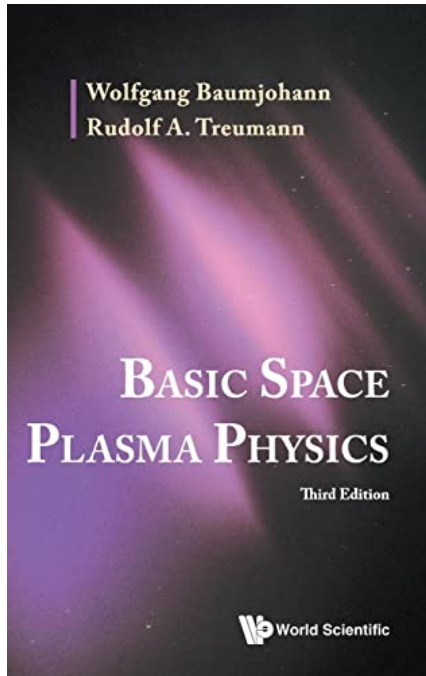
Plasma Physics Toolkits

Waves in Plasmas: Dielectric Tensor

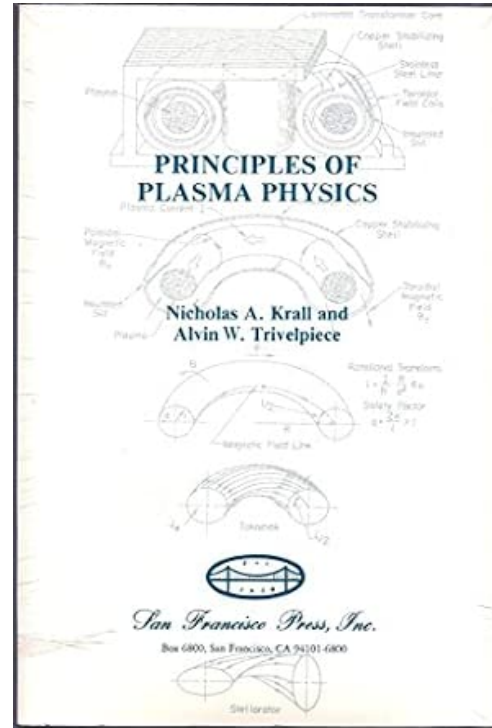
Kinetic Theory: Vlasov Equation

Fluid Theory: Moments

References

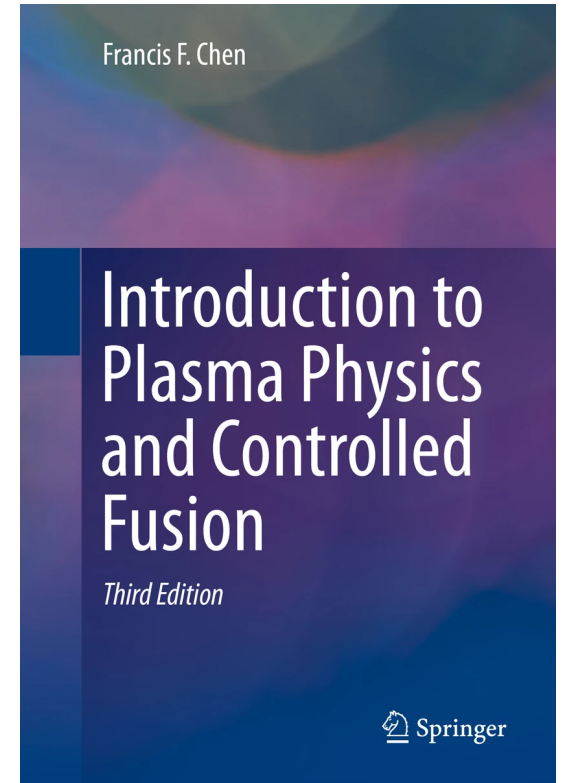


Basic Space Plasma Physics
Baumjohann & Treumann



Principles of Plasma Physics
Krall & Trivelpiece

**Introduction to
Plasma Physics &
Controlled Fusion**
Francis Chen



Fitzpatrick:
<https://farside.ph.utexas.edu/teaching/plasma/plasma.html>