

Collisional Processes in Ionospheric Plasmas: II. Advanced Concepts

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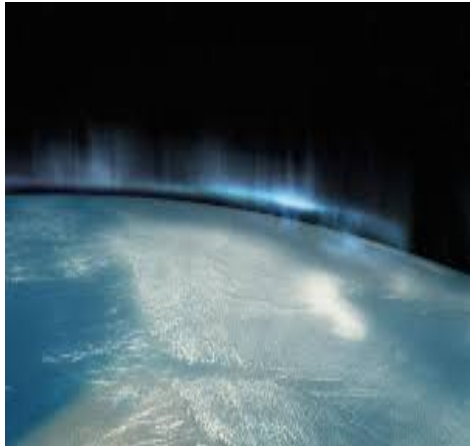
The Earth's ionosphere represents a vast open laboratory to study naturally occurring plasmas. This ionized plasma, consisting of a myriad of chemical species in the process of ionization and recombination, assumes a crucial role in the Sun-Earth connection and the near-Earth space environment. The ionosphere consists of different layers such as the D, E, and F regions. These layers extend up to several hundred kilometers, ranging from 60 to 100 km. These layers are controlled by different physical processes and control the absorption, reflection, and transmission of radio waves. These radio waves are necessary for long-range communication and satellite navigation. In this part of the talk, we outline the process by which collisions of charged particles and neutral species control the structure and dynamics of the ionosphere.

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Earth's atmosphere is the layer of gases that surrounds the planet and is held in place by Earth's gravity. It plays a critical role in:

- Supporting life (supplying oxygen, nitrogen, ...).

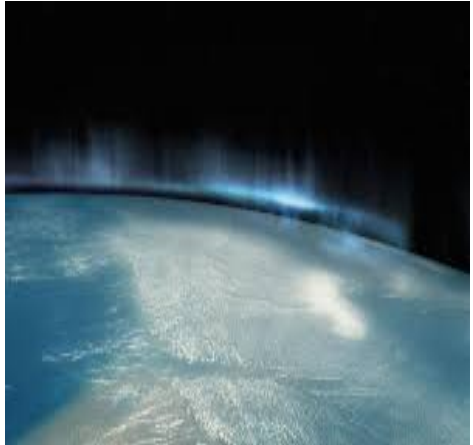


<https://www.youtube.com/watch?v=5C6hbf5rgjE>

What is the atmosphere?

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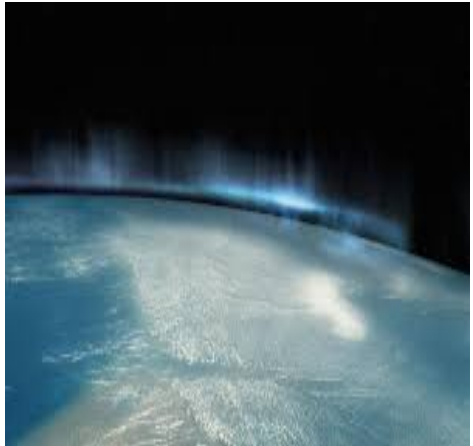
- Supporting life (supplying oxygen, nitrogen, ...).
- Regulating temperature (via the greenhouse effect and heat redistribution).



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- Supporting life (supplying oxygen, nitrogen, ...).
- Regulating temperature (via the greenhouse effect and heat redistribution).
- Protecting the surface from harmful solar radiation and small meteoroids.



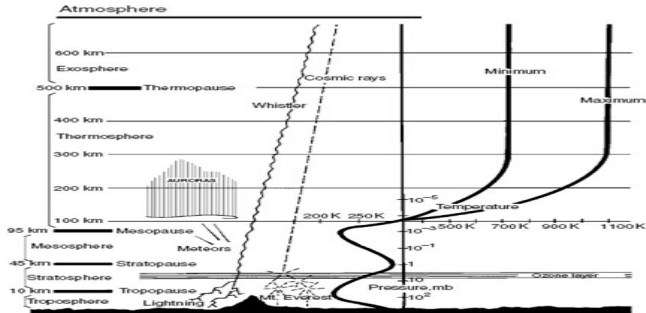
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Atmospheric layers

Based on the thermal profile, Earth's atmosphere can be divided into several distinct layers: **troposphere**, **stratosphere**, **mesosphere**, **thermosphere**, and **exosphere**.

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The ionosphere is the ionized part of the upper atmosphere, embedded within the mesosphere and thermosphere, where solar EUV and X-ray radiation create a layer of free electrons and ions that strongly affects radio-wave propagation.

Earth's ionosphere

The ionosphere is the ionized part of Earth's upper atmosphere, spanning roughly from ~ 60 to about 1000 km in altitude, where solar EUV, X-ray, and cosmic radiation ionize neutral atoms and molecules, creating a dense population of free electrons and ions.

This region is important for:

- Radio communication (e.g., HF skywave propagation).
- Satellite navigation (GNSS signal propagation and delay).
- Space weather phenomena (e.g., scintillation, ionospheric storms).

Open laboratory

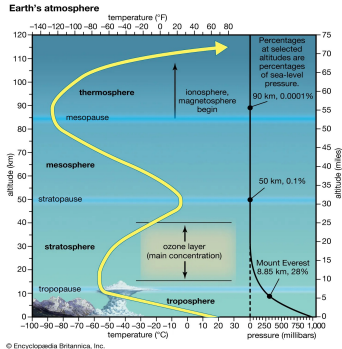
The ionosphere is a natural laboratory without walls, where plasma can be studied *in situ* by ground-based instruments, rockets, and low-Earth-orbit satellites.

The ionosphere is conventionally divided into several layers (D, E, and F regions) whose structure and electron density vary strongly with time of day, solar zenith angle, and solar activity; some regions (such as the D layer) can effectively disappear at night.

The upper atmosphere, ionized by solar and cosmic radiation, is a feature common to many planets in the Solar System. Earth's ionosphere is the ionized part of this high-altitude gaseous envelope, embedded in the mesosphere and thermosphere.

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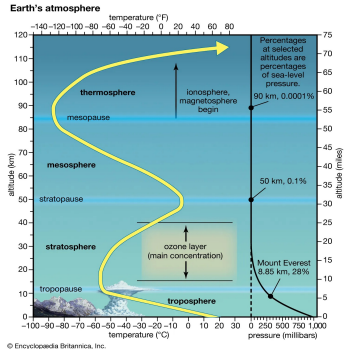
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Composition:

The ionosphere is a partially ionized gas containing:

- Neutral atoms and molecules (mainly N_2 , O_2 , O),
- Free electrons,
- Positive ions (e.g., O^+ , NO^+ , O_2^+ , N_2^+),



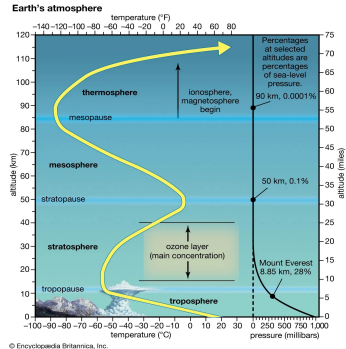
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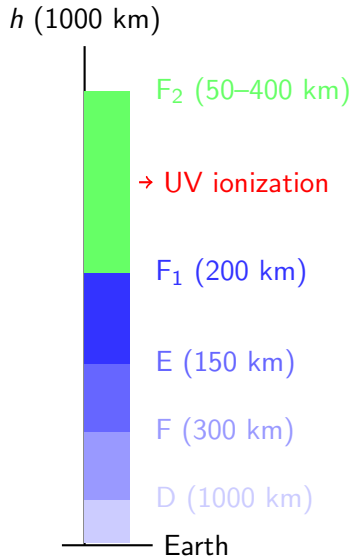
In some regions, small charged dust particles and impurities are present.

Properties of Earth's Atmosphere and Ionosphere

- The **ionosphere** surrounds Earth at 50–1000 km altitude.

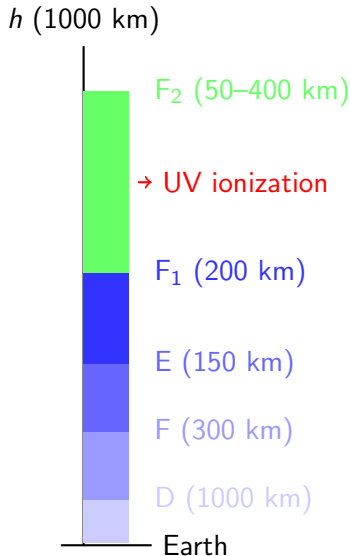
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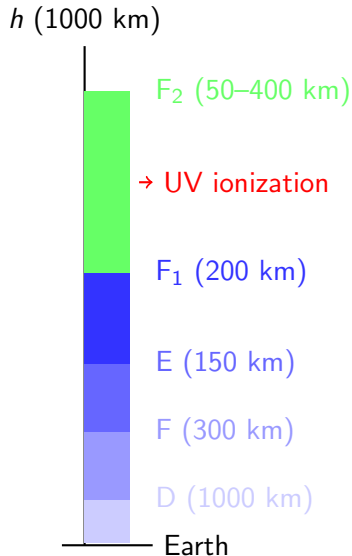
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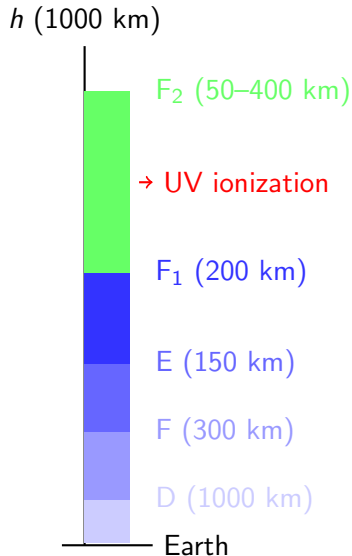
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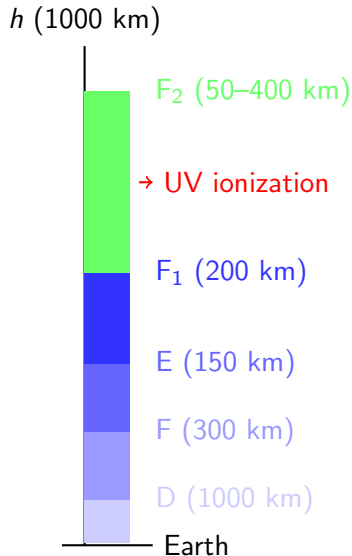
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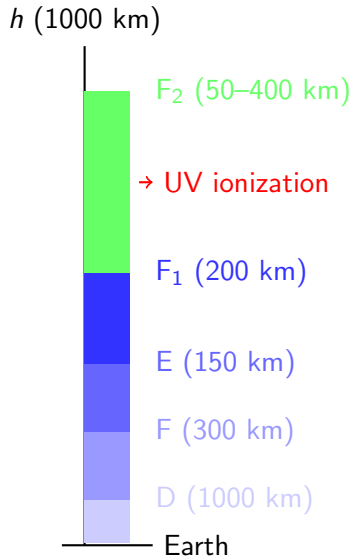
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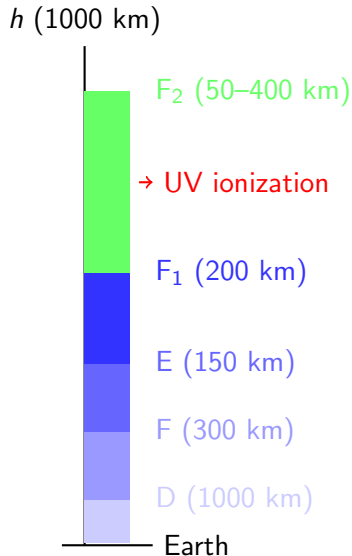
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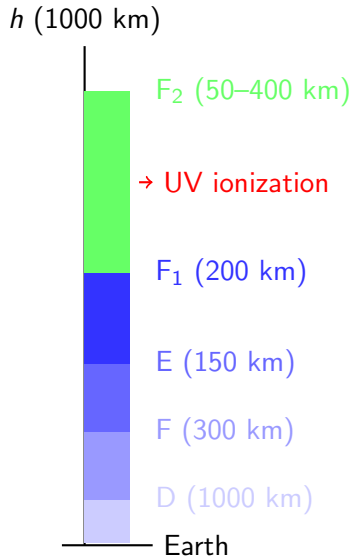
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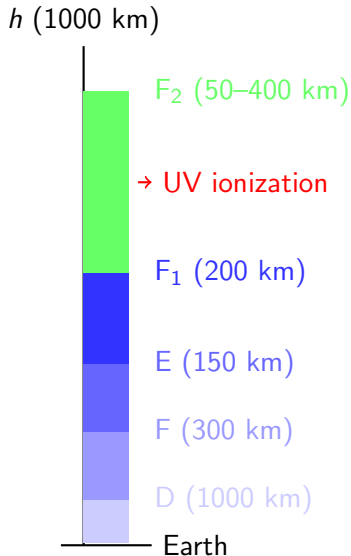
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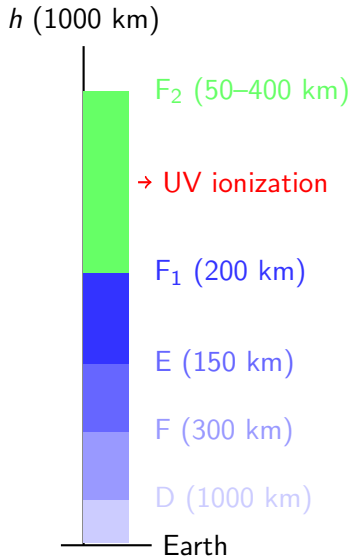
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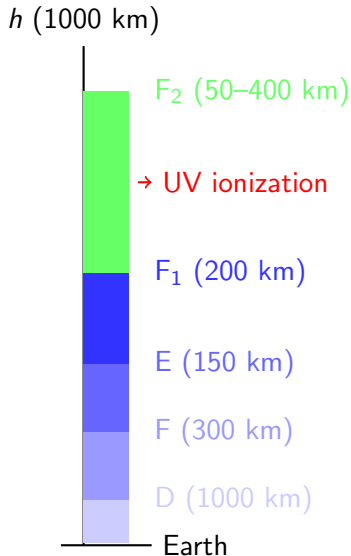
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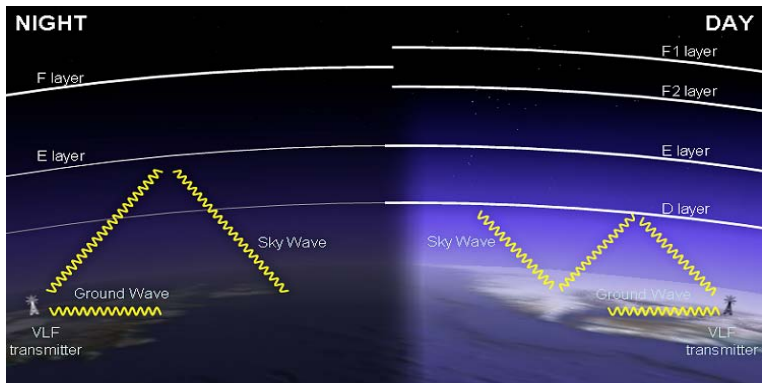


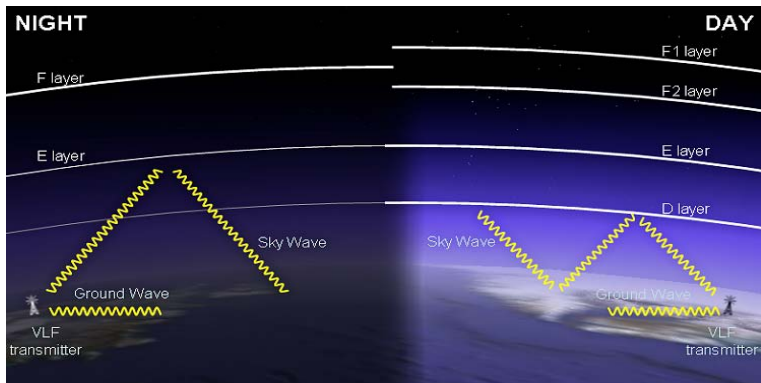
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 - Variable: H_2O (0–4%), CO_2 ($\sim 0.04\%$).



Importance of Layers

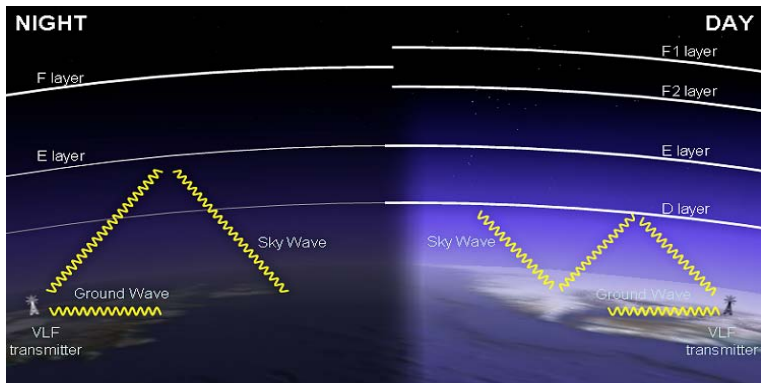




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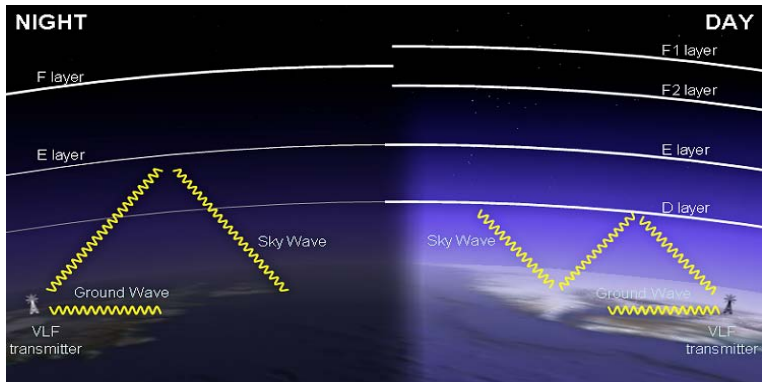


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F:

- 150 – 500 km
- $n_e \sim 10^{11} - 10^{12} m^{-3}$
- HF are reflected
- species O, N, H

Ionosphere as a “collisional” plasma

The ionosphere is a low-temperature, partially ionized plasma where collisions between charged particles (electrons, ions) and neutrals occur frequently, especially at low altitudes.

These collisions:

- Control the effective conductivity and resistivity of the plasma.
- Govern radio-wave absorption (mainly in the D and lower E regions).
- Mediate energy and momentum transfer between the ionized and neutral components.
- Responsible of the production of ionization, the diffusion of plasma.
- Conduct heat from hot to cold regions by energy exchange .

Two classes of collisional processes

- Low energies: elastic collisions dominate.
- Higher energies: inelastic collisions are important.

Ionosphere as a “collisional” plasma

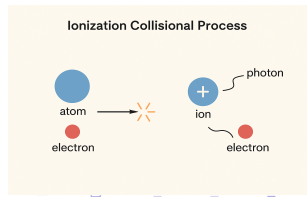
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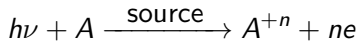
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A process in which an atom or molecule loses at least one electron or more



Many sources are responsible of the ionization in the ionosphere:

- ① Photo-ionization: a daytime process. The Sun's radiations (UV, X-rays, strip electron from neutral species and creating a sea of electrically charged particles with ions.
- ② Cosmic rays: during nighttime, ionization is due to high-energy particles or clusters of particles that travel through space at nearly the speed of light (from Sun or stars) to lead to secondary electron emission.
- ③ Superthermal electrons; high-energy electrons which travel significant distances and are a dominant heat source for the low and mid-latitude ionosphere.



Ion captures a free electron (or more) and forms a neutral atom, molecule or a species with reduced degree of ionization.



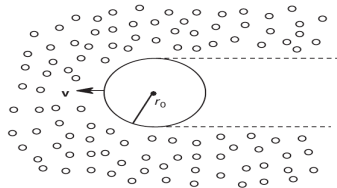
In the Earth's ionosphere the main recombination mechanisms involve the recombination of O^{2+} and NO^+ ions with free electrons.

Dissociative recombination occurs when electrons attach positively charged molecular ions to form highly energetic leading to electron removal.

Balance

between ionization and recombination processes determines the quantity of ionization present in the ionosphere.

Let us consider a large particle of radius r_0 (atom) surrounded by a gas of small particles (electrons of density n). Let v be the relative speed. In the hard-sphere model the collision cross-section is $\sigma = \pi r_0^2$.



At a given time Δt the swept volume is: $V = \sigma \times (v\Delta t)$

Number of collisions in Δt : $n \times \sigma v \Delta t$

Collision frequency (collisions per unit time):

$$\nu = \frac{\text{Collisions}}{\Delta t} = n\sigma v; \quad \sigma = \sigma(v)$$

The Mean-Free-Path (Distance traveled between two consecutive collisions):

$$\lambda_{\text{mfp}} = v \times \tau = \frac{1}{\sigma n}$$

represents the effective area that a target particle presents for collisions with incident particles. It has units of area (1 barn = $10^{-28} m^2$). Based on

- Conservation of momentum (linear and angular).
- Conservation of kinetic energy for elastic collision.
- Working in a frame which belongs to the center of mass.
- Using the polar coordinates (r, ϕ) .

For a central force like Coulomb interaction between two charges

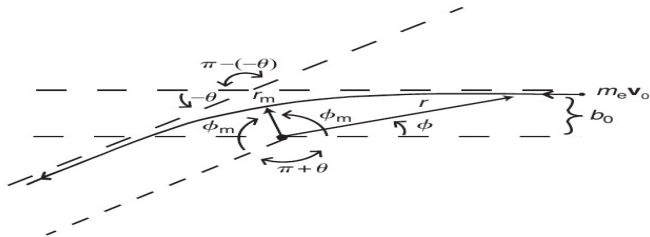
$$\vec{F} = -\frac{1}{4\pi\epsilon_0} \frac{e^2}{r^2} \vec{e}_r; \quad V = -\frac{1}{4\pi\epsilon_0} \frac{e^2}{r}$$

The scattering angle corresponds to

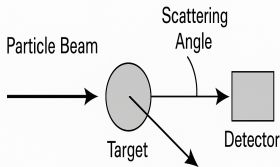
$$\theta = \pi - 2b_0 \int_{r_m}^{\infty} \frac{dr}{r^2} \left[1 - \frac{b_0^2}{r^2} - \frac{2\alpha_0}{r} \right]^{-1/2}$$

where $\alpha_0 = -\frac{1}{4\pi\epsilon_0} \frac{e^2}{m_e v_0^2}$; $r_m = \frac{b_0^2}{-\alpha_0 + (\alpha_0^2 + b_0^2)^{1/2}}$ and $b_0 =$.

v_0 is the initial speed and b_0 the impact parameter

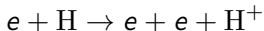


Collision between an electron and a heavy ion
(for more details see Ionospheres Physics, Plasma Physics, and Chemistry P75)



The differential cross section $\frac{d\sigma}{d\Omega}$ gives the probability per unit solid angle $d\Omega$ that a particle is scattered into a particular direction.

Consider ionization of atomic hydrogen:



- Ionization occurs only if the electron energy exceeds the threshold:

$$E \geq I = 13.6 \text{ eV}$$

- The process is characterized by the **energy-dependent cross section**:

$$\sigma(E) \quad [\text{m}^2]$$

- Typically:
 - $\sigma(E) = 0$ for $E < I$
 - $\sigma(E)$ rises above threshold, peaks, then slowly decreases

The ionization rate is obtained from kinetic theory:

$$R = n_e \int_I^{\infty} \sigma(E) v(E) f(E) dE$$

- R : reaction rate per neutral atom [s^{-1}]
- n_e : electron density [m^{-3}]
- $v(E) = \sqrt{\frac{2E}{m_e}}$: electron speed
- $f(E)$: normalized electron energy distribution:

$$\int_0^{\infty} f(E) dE = 1$$

Interpretation:

- σv = collision probability per unit time
- Integral = averaging over all electron energies

For a Maxwellian electron population:

$$f(E) = \frac{2}{\sqrt{\pi}} \frac{1}{(k_B T_e)^{3/2}} \sqrt{E} e^{-E/(k_B T_e)}$$

Define the **rate coefficient**:

$$\langle \sigma v \rangle = \int_0^{\infty} \sigma(E) v(E) f(E) dE$$

- Units: [m³/s]
- Encodes all microscopic physics (cross section + distribution)

The ionization rate per unit volume is:

$$\frac{dn_{H^+}}{dt} = n_e n_H \langle \sigma v \rangle$$

Physical Interpretation of $\langle \sigma v \rangle$

- Strong dependence on electron temperature T_e
- Two competing effects:

- **Threshold effect:**

$$\exp\left(-\frac{I}{k_B T_e}\right)$$

Only high-energy electrons contribute

- **Velocity effect:**

$$v \sim \sqrt{T_e}$$

Faster electrons increase collision rate

- **Result:**
 - Very small ionization at low T_e
 - Rapid increase when $k_B T_e \sim I$
 - Broad maximum at higher energies

A commonly used approximation:

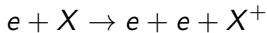
$$\langle \sigma v \rangle \sim T_e^{1/2} \exp\left(-\frac{I}{k_B T_e}\right)$$

- Valid for qualitative analysis
- Not accurate for precise modeling

Important:

- Real calculations use tabulated or fitted cross sections
- Example datasets:
 - Lotz formula
 - ADAS database

For a general species X :



- Same formalism applies:

$$\frac{dn_{X^+}}{dt} = n_e n_X \langle \sigma v \rangle_X$$

- Differences come from:
 - Ionization energy I_X
 - Cross section $\sigma_X(E)$
- $\langle \sigma v \rangle_X(T_e)$ must be:
 - computed numerically, or
 - taken from databases

Connection to fluid models:

Source term in continuity equation