Collisional Processes in Ionospheric Plasmas: Advanced Concepts

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Abstract

Earth's ionosphere is an open laboratory that enable to study plasma in situ. Composed of a myriads of chemical species subject to ionization and recombination, it plays an important role for earth's environment. The ionosphere is stratified composed of many layers that is responsible of protecting earths from solar extreme radiations, meteorites and is crucial for communication by using satellites or wave reflection from ground.

NATIONAL HIGHER SCHOOL OF MATHEMATICS
المدرسة الوطنية العليا في الرياضيات

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What is atmosphere?

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
- regulating temperature
- protecting from harmful space radiation and meteors.

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

Atmospheric Layers

Based on thermal profile the atmosphere can be divided into layers:

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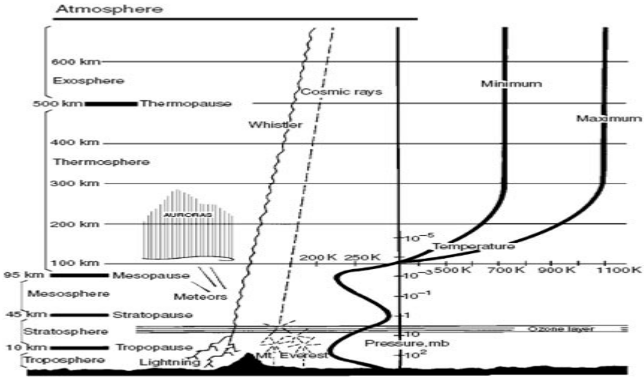

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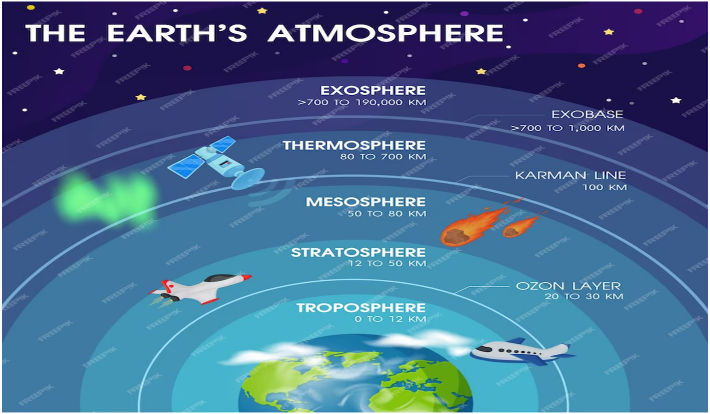

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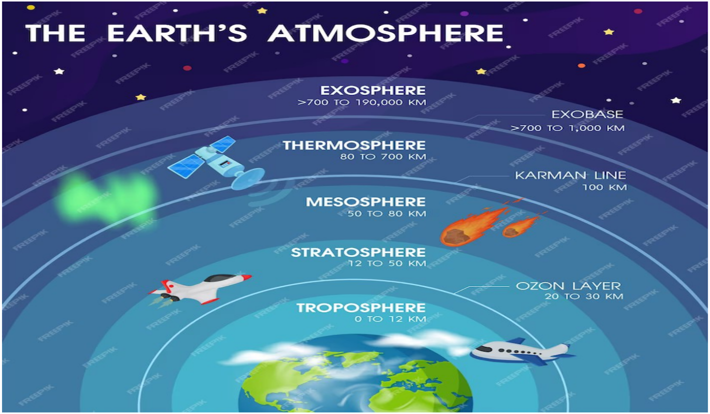

The ionosphere is ionized part of the atmosphere

Earth's Ionosphere

The ionosphere is a layer of Earth's upper atmosphere (spanning from ~ 60 to $1,000$ km in altitude) where solar and cosmic radiation ionize atoms and molecules, creating a dense population of free electrons and ions. Important

- Radio communication
- satellite navigation
- and space weather phenomena.

Open laboratory

Ionosphere is a natural laboratory without walls, where plasma can be studied *in situ*.

The ionosphere is also divided into three parts which can change between day and night depending on UV flux and may disappear.

Ionosphere layers

Gaseous envelope common to all solar system planets.

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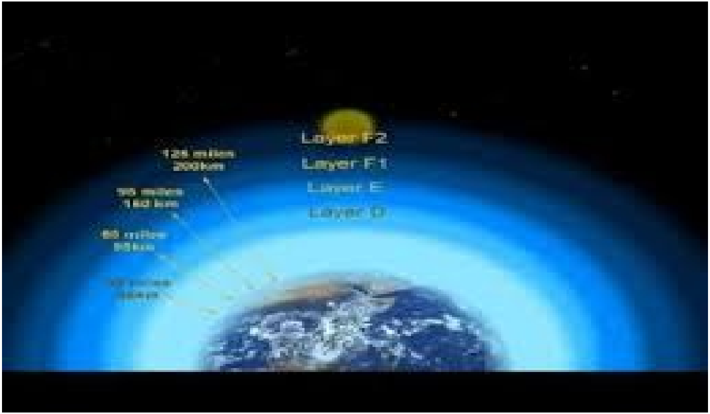

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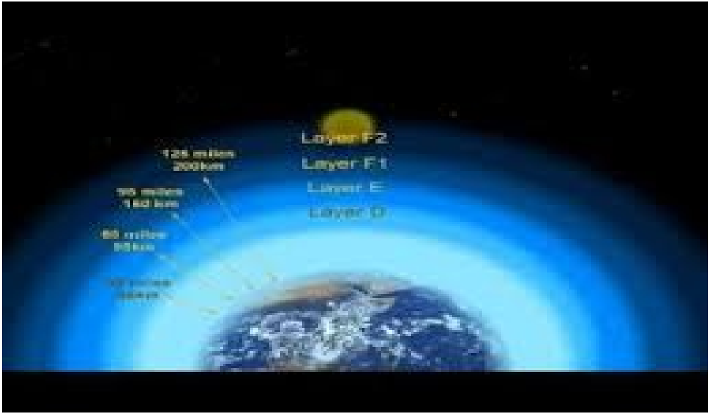

Ionosphere is the ionized part of the high atmosphere which contains: neutral atoms, electrons, ions (named upon them) and impurities 'dust'

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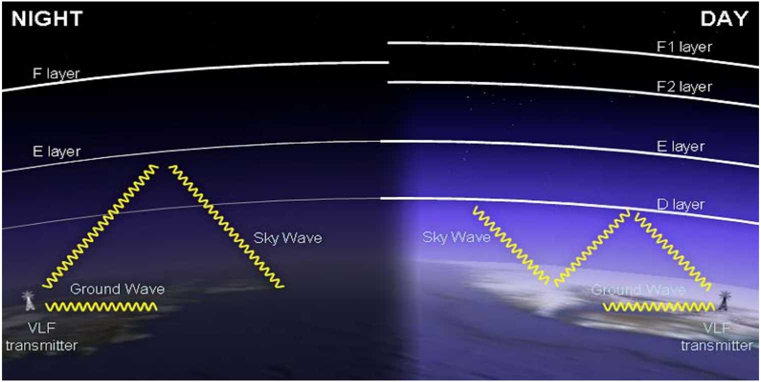
- Absorb part of (UV) radiations and heat the Earth surface.
- Reduce the temperature gradient between day and night
- Recycle the water.

Ionospheric Layers characteristics

- **D region:** (60-90 *km* altitude), electron density $10^8 - 10^{10} m^{-3}$ and dominated by negative many-atomic ions. Exists only in the presence of sun rays. Absorb waves less than $\sim$ *MHz* and reflects low frequency waves (30 to 300*kHz*).
- **E region:** (90-120 *km*), electron density $\sim 10^{11} m^{-3}$. Contains metallic ions, NO^+ and O_2^+.
- **F region:** (150-500 *km*) the most ionized part of the ionosphere, electron density can reach 10^{11} to $10^{12} m^{-3}$ at altitude 250 *km*. The attitude change depending on the daytime. reflects high frequency radio waves (3 to 30 *MHz*). The region where the lighter atomic ions (H^+ and He^+) dominate.

Importance of Layers



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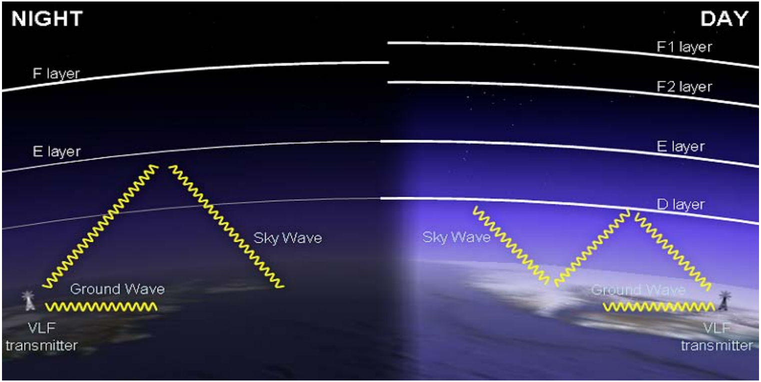

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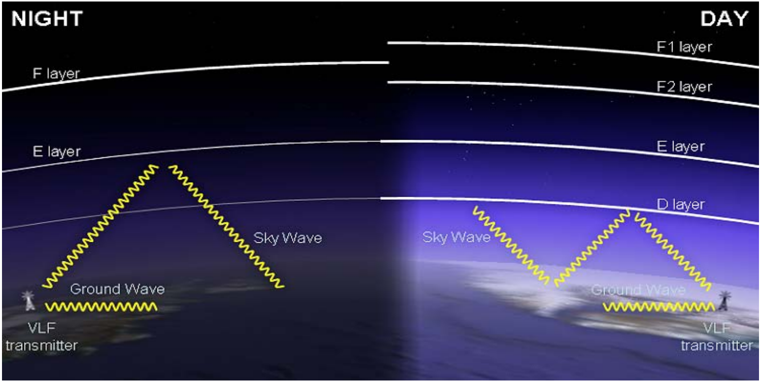

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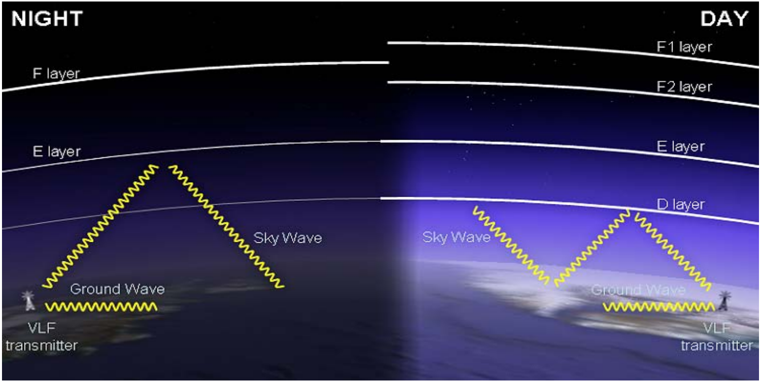

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F:

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

Collision in Earth's ionosphere

play a fundamental role in the dynamics and energetics, as they are

- are responsible for the production of ionization, the diffusion of plasma.
- conduct heat from hot to cold regions by exchange of energy.
- govern the interactions with radio waves and satellites.

Two classes of collisional processes

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- When the relative kinetic energy increases, inelastic collisions are important.

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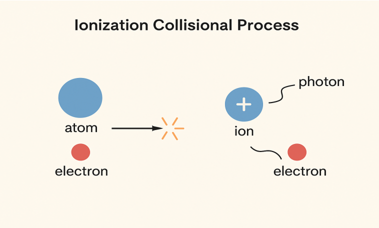


Ionization

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

$$h\nu + A \xrightarrow{\text{source}} A^{+n} + ne$$

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.

$$O + e \to O^{+} + 2e; \qquad N_2 + e \to N_2^{+} + 2e$$

Recombination

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

$$A^{+n} + ne \longrightarrow A+$$

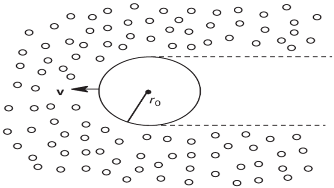
In the Earth's ionosphere the main recombination mechanisms involve the recombination of O^{2+} and NO^{+} ions with free electrons.
Dissociative recombination occurs when electrons attach positively charged molecular ions to form highly energetic leading to electron removal.

Balance

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

Collision frequency

Let us consider a large particle of radius r_0 (atom) surrounded by a gas of small particles (electrons of density 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):

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

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

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

Cross section of binary Coulomb collision

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 on 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 $(r,\ \phi)$.

For a central force like Coulomb interaction between two charges

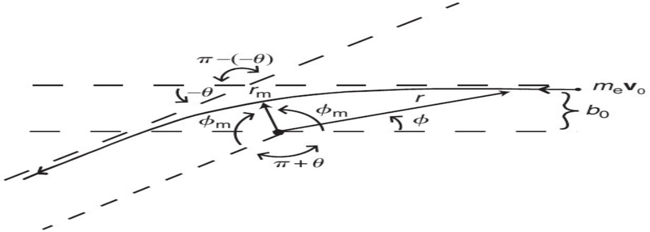
$$\vec{F} = -\frac{1}{4\pi\varepsilon_o}\frac{e^2}{r^2}\vec{e}_r; \qquad V = -\frac{1}{4\pi\varepsilon_o}\frac{e^2}{r}$$

The scattering angle corresponds to

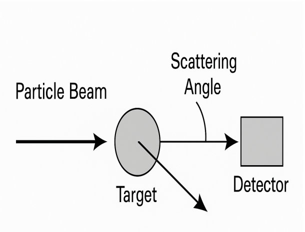
$$\theta = \pi - 2b_0\int_{r_m}^{\infty}\frac{dr}{r^2}\left[1-\frac{b_0^2}{r^2}-\frac{2\alpha_0}{r}\right]^{-1/2}$$

where $\alpha_0 = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e v_0^2}$; $\quad r_m = \frac{b_0^2}{-\alpha_0+(\alpha_0^2+b_0^2)^{1/2}}$ and $\quad b_o = .$

v_o is the initial speed and b_o 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.