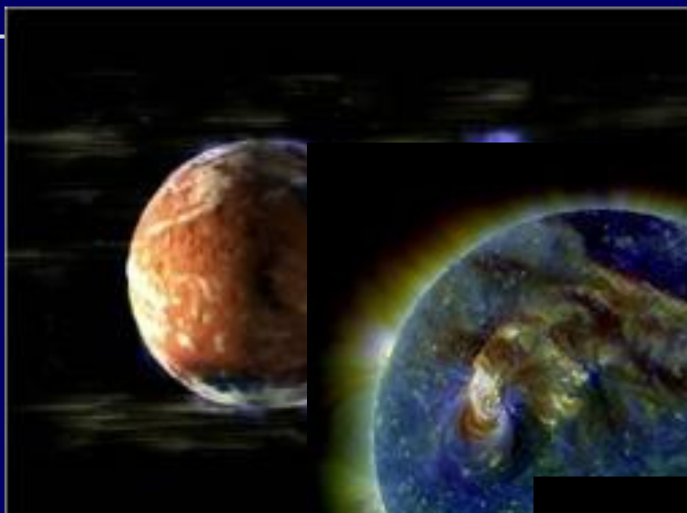
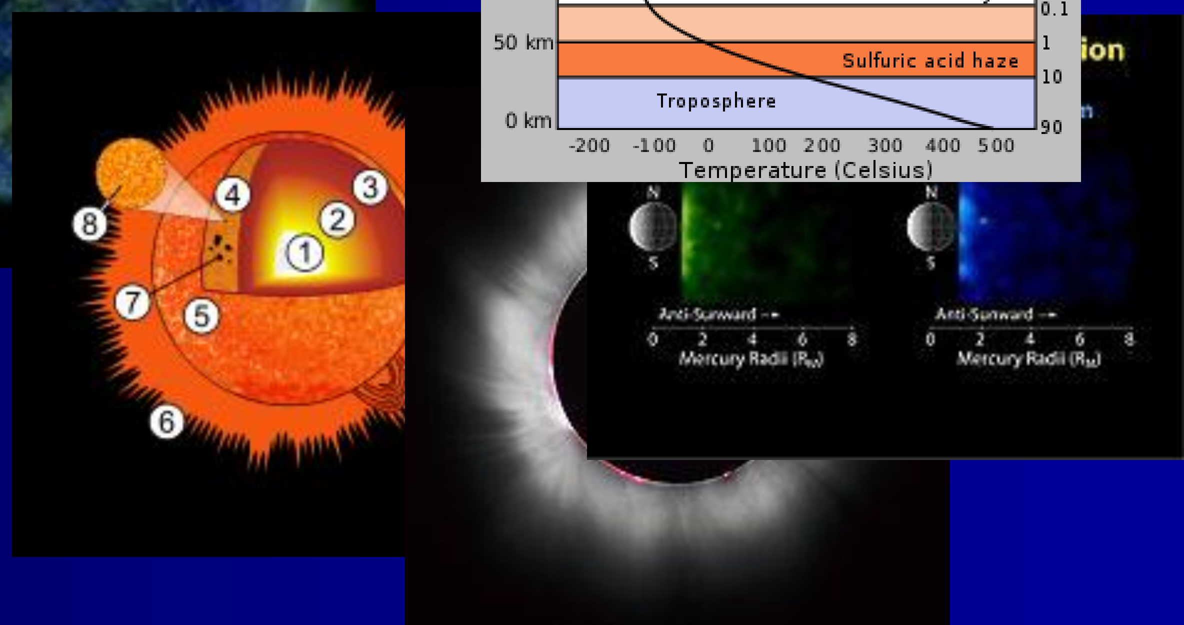
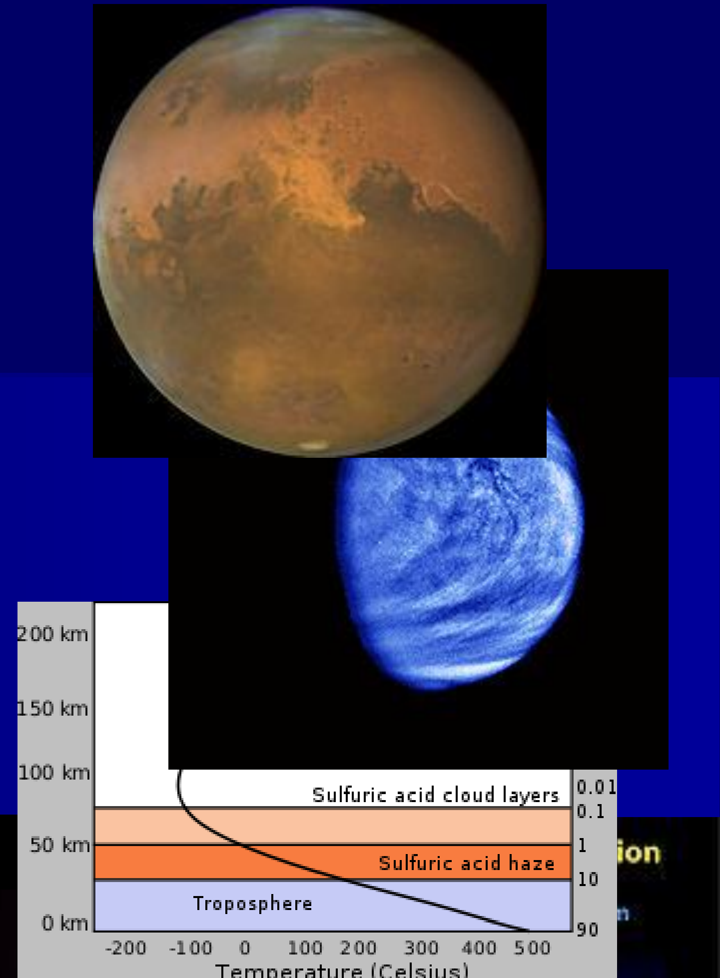
Space Physics

Space Physics







Lecture – 08

The Ionosphere

Introduction
The Chapman Layer Theory
Plasma Frequency
Collision Frequency and Absorption
The Structure of the Ionosphere and the Plasmasphere
Regular and Irregular Variations of the Ionosphere

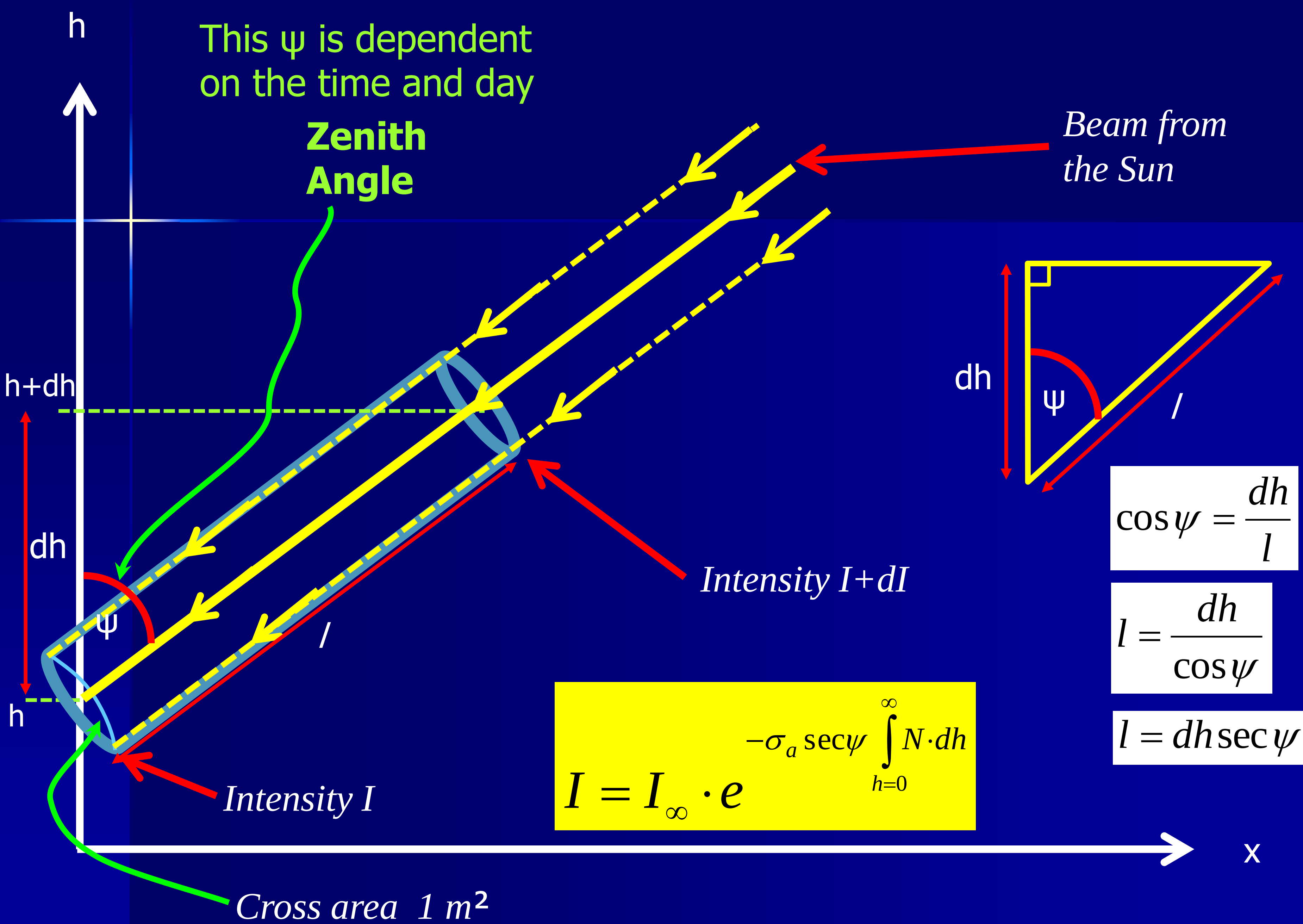
Chapman layer Theory

The Ionization of the atmosphere

Chapman in 1931 produced a very neat theoretical treatment of the problem. In his simplified model, Chapman assumed,

- an isothermal,
- horizontally stratified atmosphere,
- composed of a single gas, which is been ionized by
- monochromatic radiation from the Sun.

It is obvious that this model is an **over simplification** of the actual conditions.



$$\cos\psi = \frac{dh}{l}$$

$$l = \frac{dh}{\cos\psi}$$

$$l = dh \sec\psi$$

$$I = I_{\infty} \cdot e^{-\sigma_a \sec\psi \int_{h=0}^{\infty} N \cdot dh}$$

Electron Production Rate (Q)

Production rate → $$Q = \eta \times dI = \eta \times N \sigma_a I$$

$$\therefore \quad Q = \frac{\eta e^{-Z}}{eH} I_\infty \cdot e^{1-\sec\psi . e^{-Z}}$$

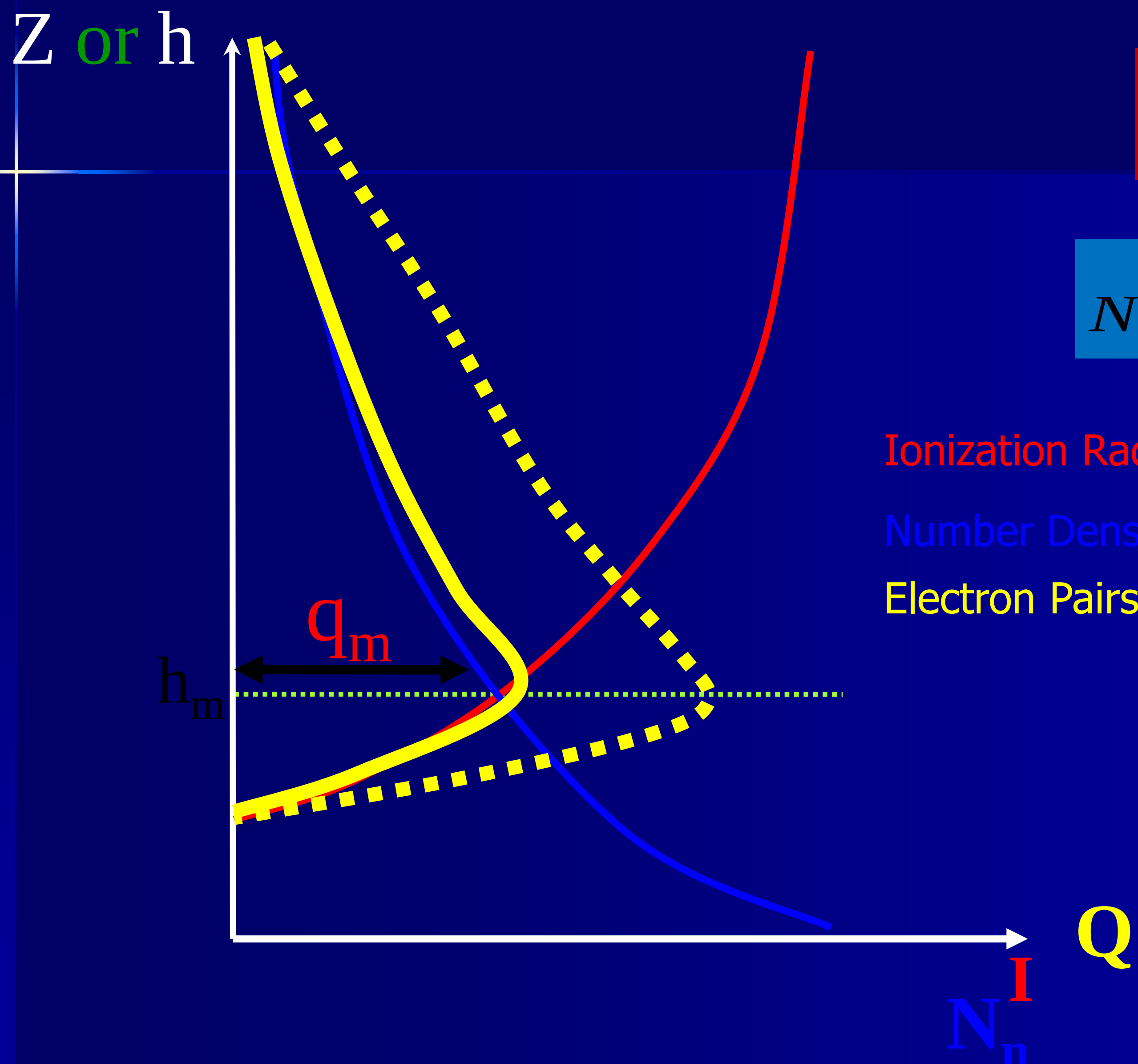
Where N and Z are dependent variables, because

$$e^{-Z} = \sigma_a NH$$

Production rate at any point

$$Q = \frac{\eta \cdot I_\infty}{e H} e^{\left(1 - Z - \sec\psi \cdot e^{-Z}\right)}$$

Ionization Radiation (I), Number Density (N) and Electron Pairs Produced Rate [Q]



$$I = I_{\infty} \cdot e^{-\sigma_a \sec\psi \int_{h=0}^{\infty} N \cdot dh}$$

$$N(h) = N_o \, e^{-\frac{h}{H}}$$

Ionization Radiation (I)

Number Density (N)

Electron Pairs Produced Rate [Q]

$$Q = \frac{\eta \cdot I_{\infty}}{e H} e^{\left(1 - Z - \sec\psi \cdot e^{-Z}\right)}$$

Find the value of Q_m

$$Q = \frac{\eta \cdot I_\infty}{e H} e^{\left(1 - Z - \sec\psi \cdot e^{-Z}\right)}$$

$$\ln[Q] = \ln\left[\frac{\eta \cdot I_\infty}{e H} e^{\left(1 - Z - \sec\psi \cdot e^{-Z}\right)}\right]$$

$$\ln[Q] = \ln\left[\frac{\eta \cdot I_\infty}{e H}\right] + \ln\left[e^{\left(1 - Z - \sec\psi \cdot e^{-Z}\right)}\right]$$

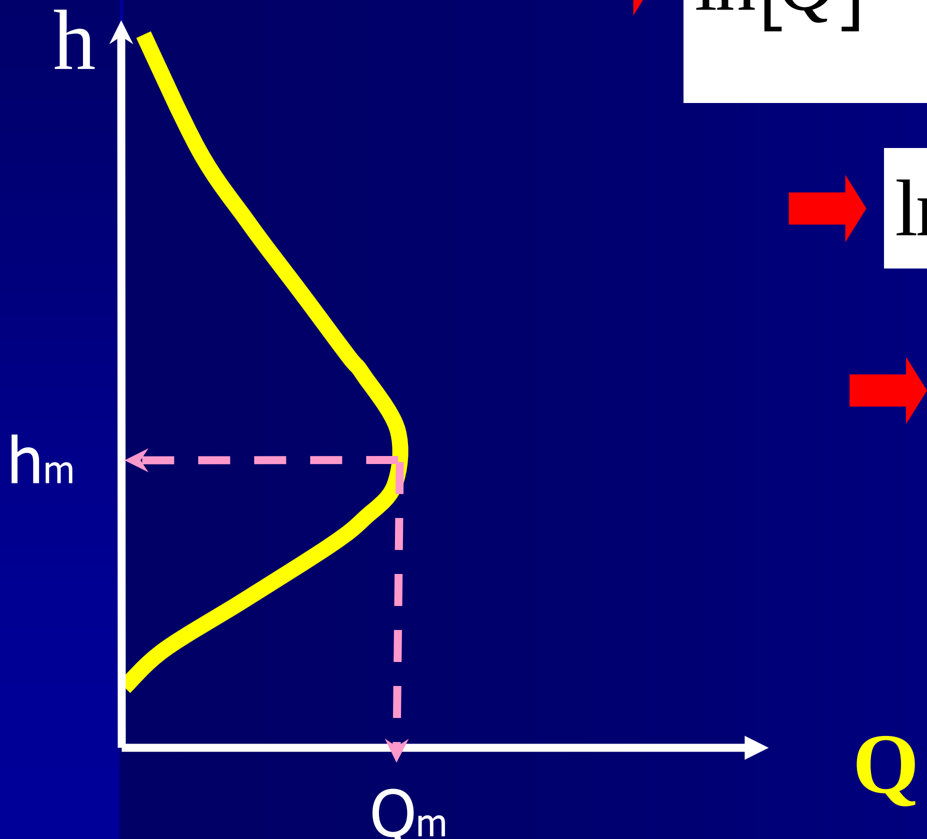
constant, c

$$\ln[Q] = c + 1 - Z - \sec\psi \cdot e^{-Z}$$

constant,

C

$$\ln[Q] = C - Z - \sec\psi \cdot e^{-Z}$$



For find the maximum ;

$$\frac{d\left(\ln[Q]\right)}{dz} = 0$$

Find the value of Q_m

$$\ln[Q] = C - Z - \sec\psi \cdot e^{-Z}$$

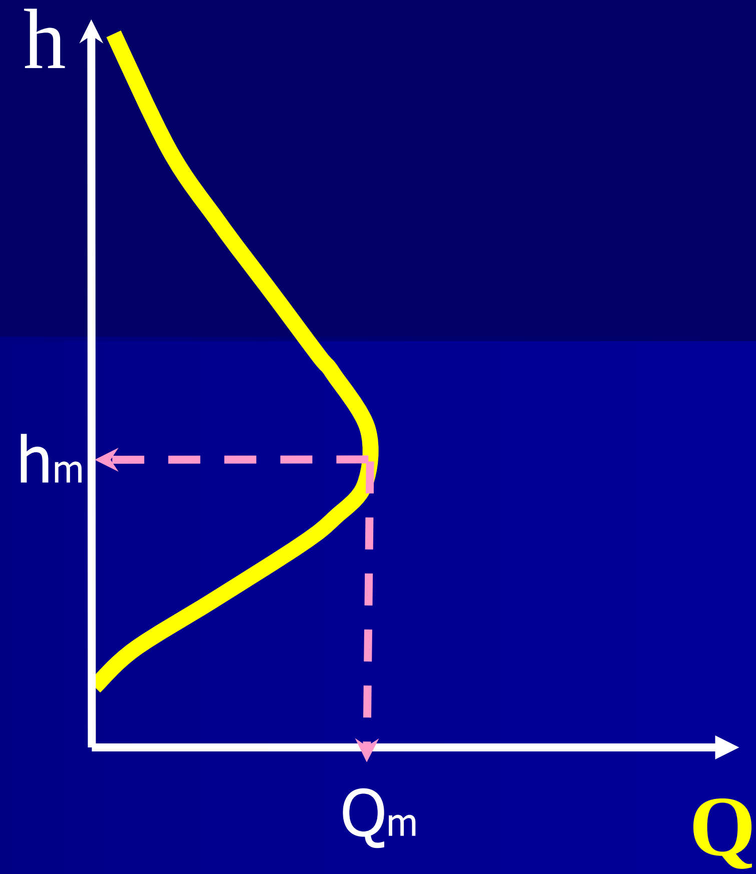
$$\frac{d(\ln[Q])}{dz} = \frac{d\left(C - Z - \sec\psi \cdot e^{-Z}\right)}{dz}$$

$$\frac{d(\ln[Q])}{dz} = -1 - \sec\psi \cdot e^{-Z}(-1)$$

For find the maximum ;

$$\frac{d(\ln[Q])}{dz} = 0$$

$$\Rightarrow \quad \cos\psi = e^{-Z}$$



We know,

$$e^{-Z} = \sigma_a N H$$

Find the value of Q_m

$$Q = \frac{\eta \cdot I_\infty}{e H} e^{\left(1 - Z - \sec\psi \cdot e^{-Z}\right)} \quad \text{— 01}$$

For find the maximum ;

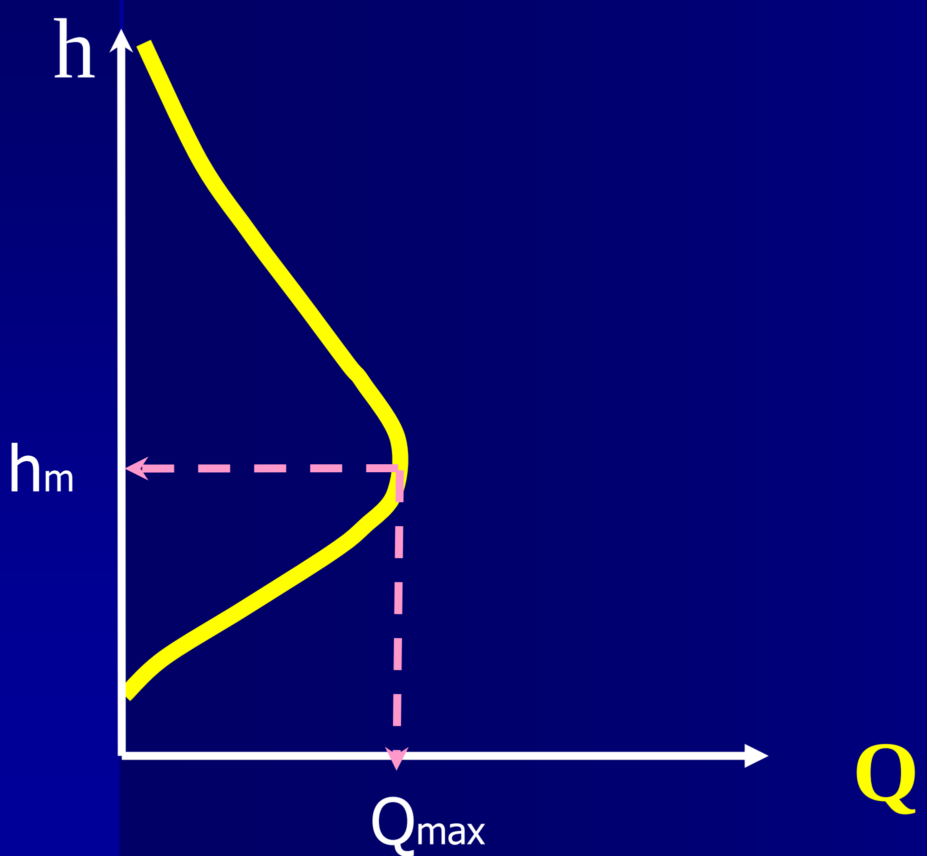
$$\frac{d\left(\ln[Q]\right)}{dz} = 0$$

$$\Rightarrow \cos\psi = e^{-Z}$$

We know, $e^{-Z} = \sigma_a N H$

Using equation – 01 :

$$\Rightarrow Q_{\max} = \frac{\eta \cdot I_\infty}{e H} \cos\psi$$



Find the value of Q_m

$$Q_{\max} = \frac{\eta \cdot I_\infty}{e H} \cos\psi$$

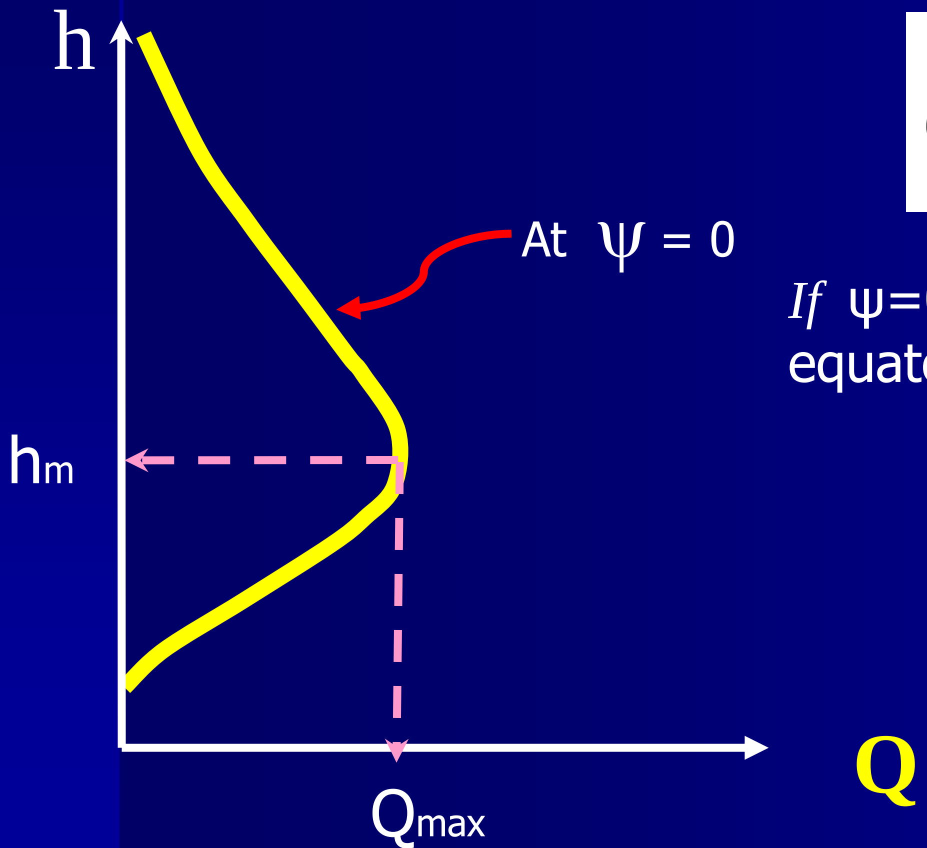
$$\cos\psi = \sigma_a N H$$

Production Rate Q :

$$Q = Q_{\max} e^{\left(1 - \sec\psi \cdot e^{-Z}\right)}$$

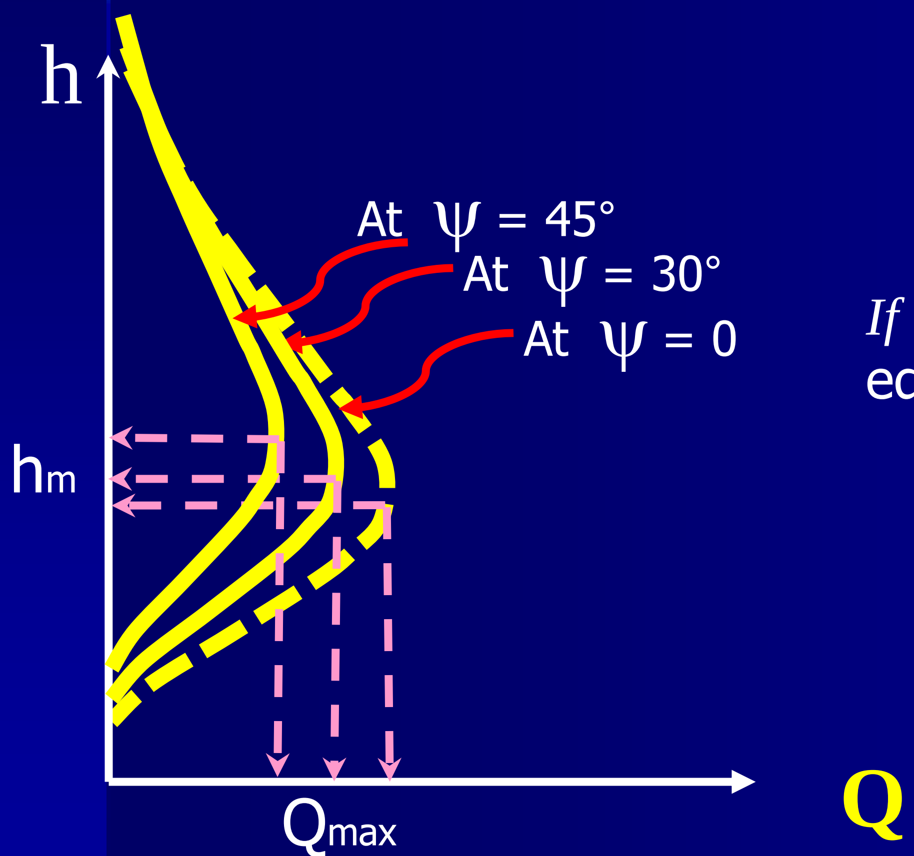
If ψ=0°, Then the Sun is directly up on the equator *:*

$$Q_{\max} = \frac{\eta \cdot I_\infty}{e H}(1)$$



Find the value of Q_m

$$Q_{max} = \frac{\eta \cdot I_\infty}{e\,H} \cos\psi$$



If ψ=30°, Then the Sun is 30° from the equator *:*

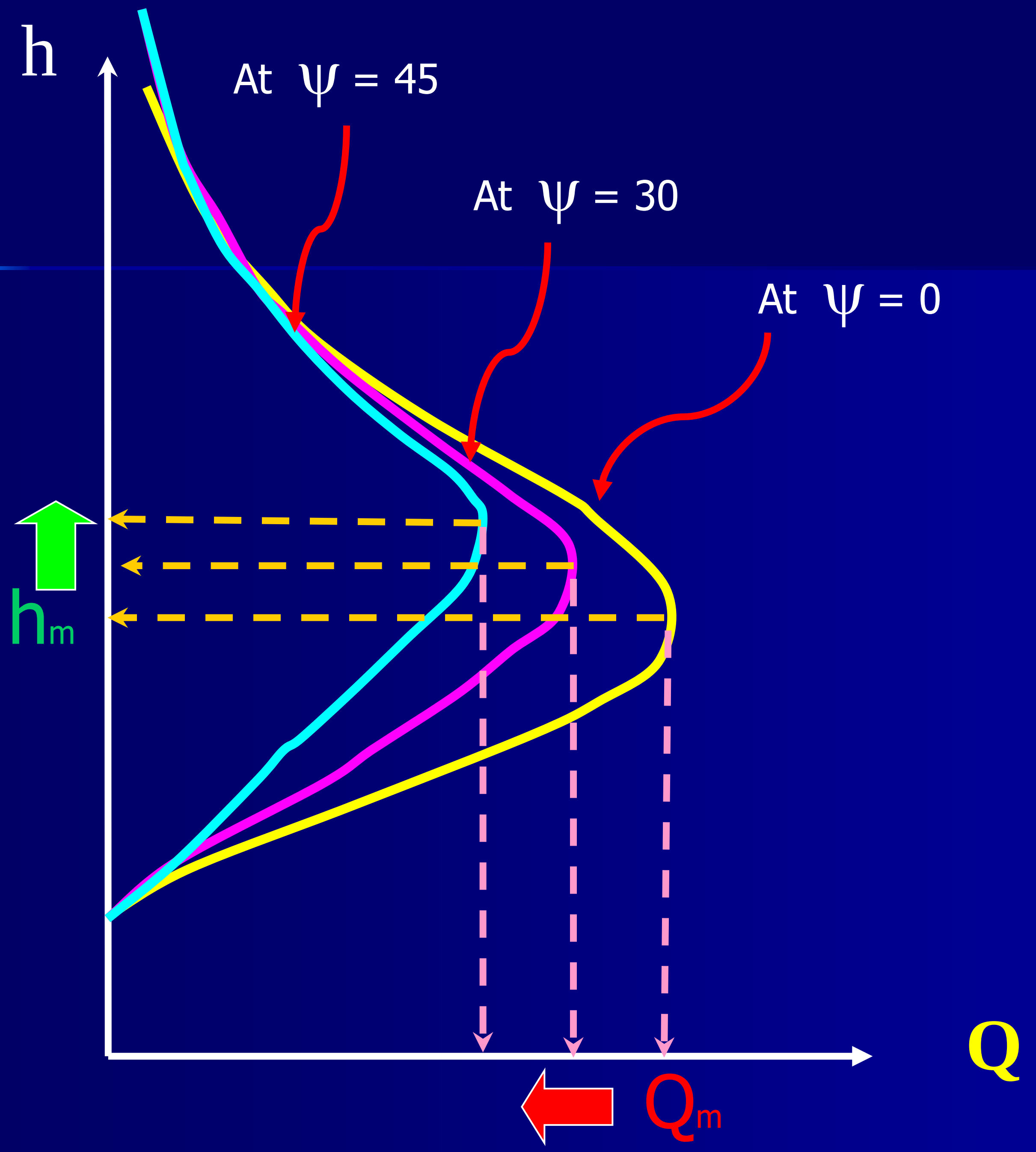
$$\Rightarrow Q_{max} = \frac{\eta \cdot I_\infty}{e\,H}(Cos\,30)$$

$$\Rightarrow Q_{max} = \frac{\eta \cdot I_\infty}{e\,H}(0.8660)$$

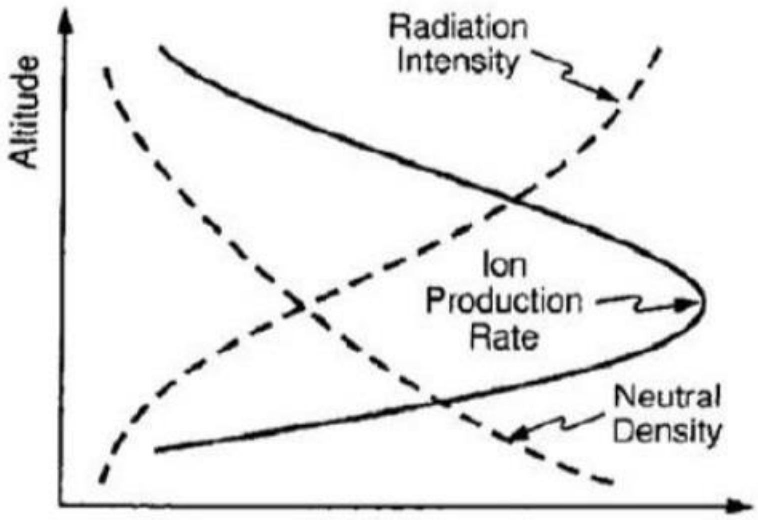
If ψ=45°, Then the Sun is 45° from the equator *:*

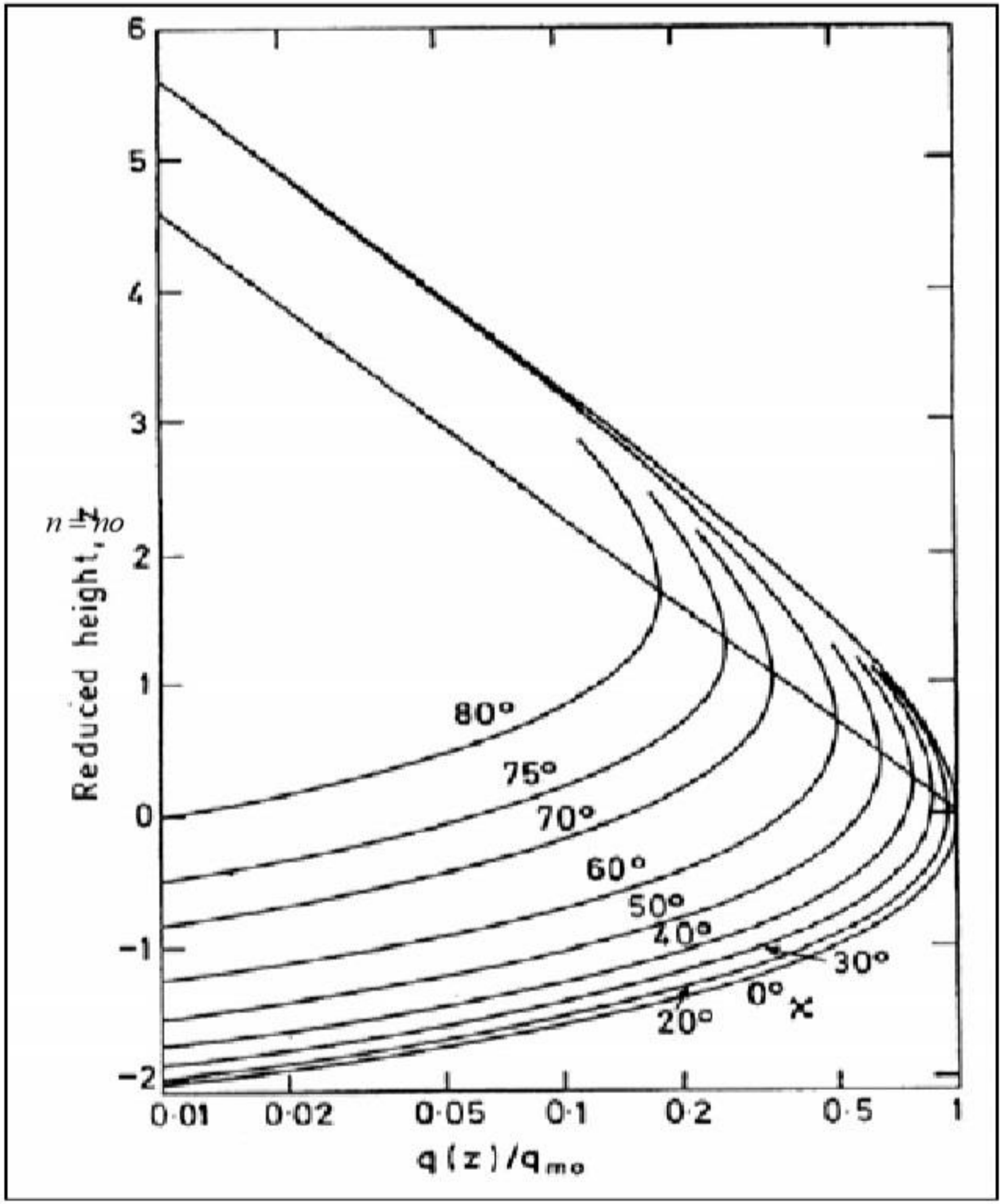
$$\Rightarrow Q_{max} = \frac{\eta \cdot I_\infty}{e\,H}(Cos\,45)$$

$$\Rightarrow Q_{max} = \frac{\eta \cdot I_\infty}{e\,H}(0.7071)$$


h
At ψ = 45
At ψ = 30
At ψ = 0
h_m
Q
Q_m

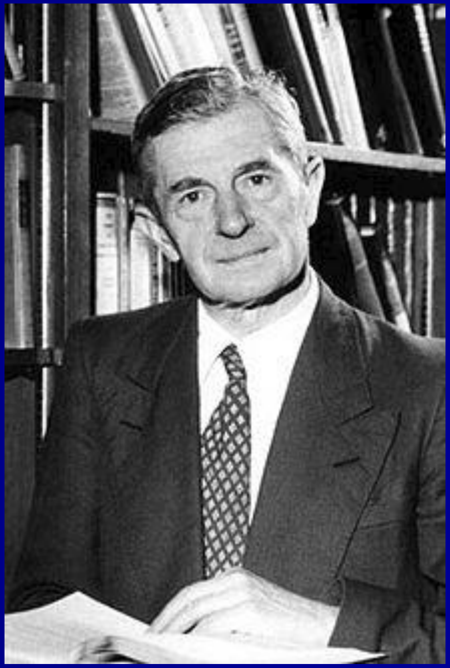
Chapman's Production Profile



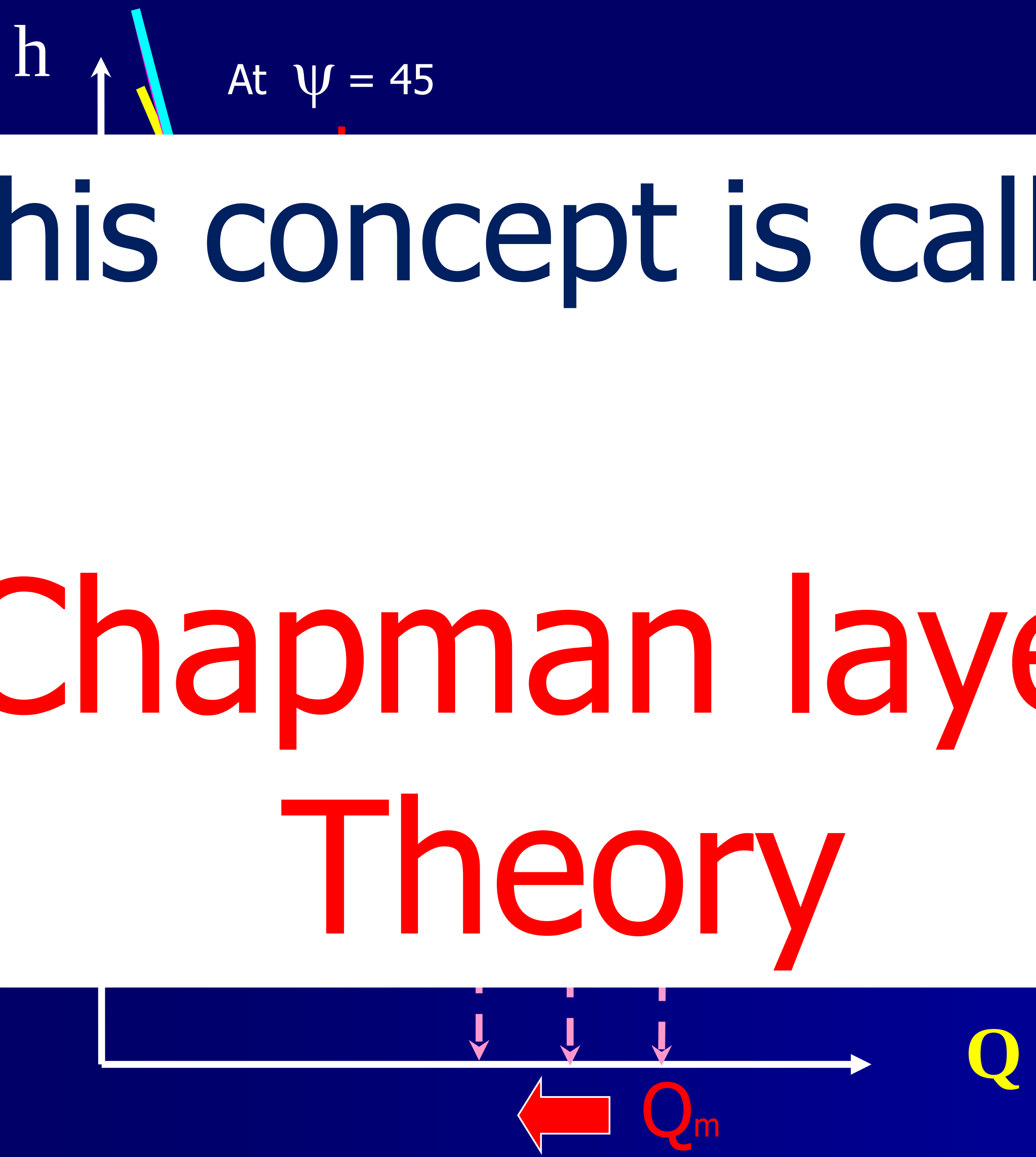


That means ψ is increasing, the maximum value of the Electron Production Rate is decreasing. For that Molecular Number Density of the ionosphere should be decreasing.

.: Region of the Q_{max} is going to far away from the Earth surface. Because N should be decrees. Because h is low, N is high and h is high, N is low.



Sydney Chapman FRS (29 January 1888 – 16 June 1970) was a British mathematician and geophysicist. His work on the kinetic theory of gases, solar-terrestrial physics, and the Earth's ozone layer has inspired a broad range of research over many decades. He was Chief Professor of Mathematics at Imperial College London between 1924 and 1946.



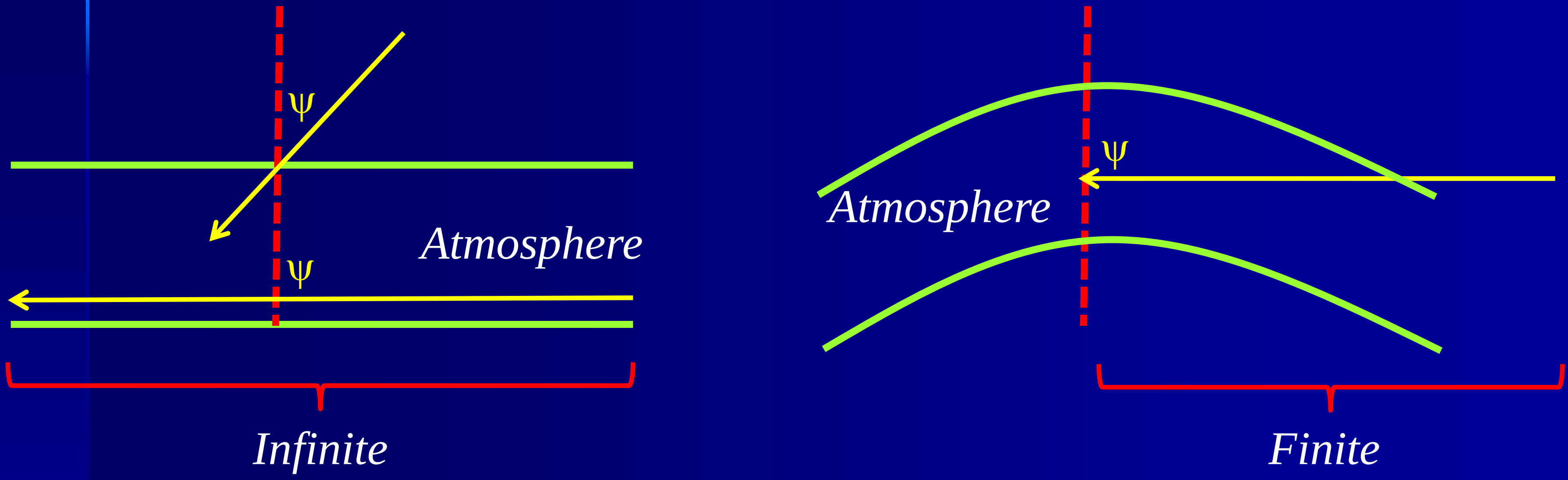
This concept is called

Chapman layer Theory

Chapman layer Theory

Electron Production Rate (Q)

If ψ (**angle of elevation** OR **Zenith Angle**) is high values (~90°), our plate assumption is not corrected.



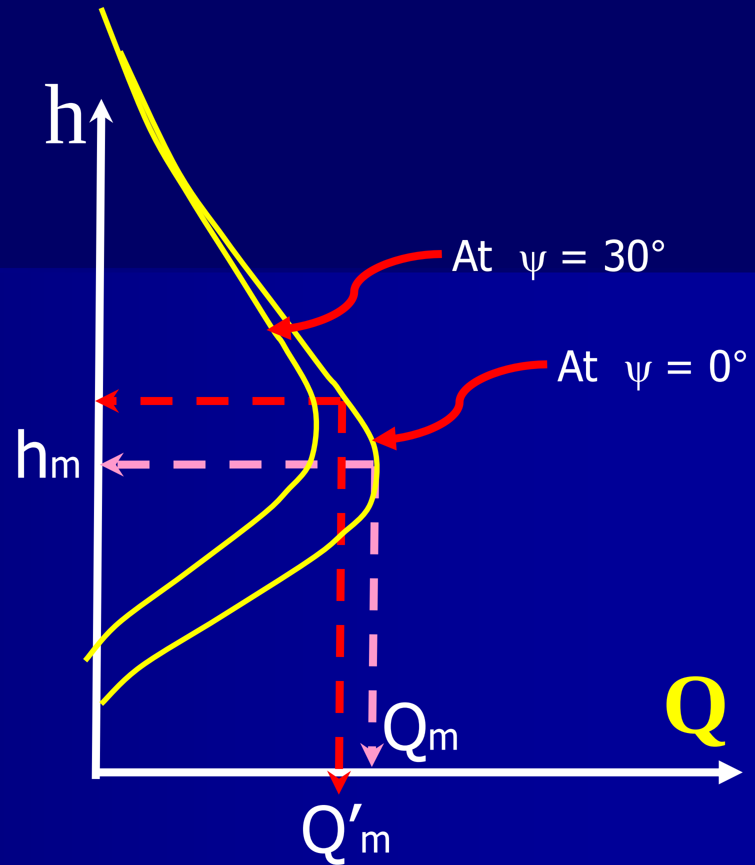
If ψ = 90°, according to our formula and logics, N → 0 !

That means Q_{max} is going to infinity. This is theoretical. But practically this should be large value; but not infinity.

Chapman layer Theory

Electron Production Rate (Q)

If we want to find the value of Q'_m (using the graph), ψ should be zero. Because ψ>0, there is no point on the graph when $Q=Q'_m$ according to the graph.



That means, if we want to find the value of h corresponding Q'_m :
It is depend on the "Time" of the day,

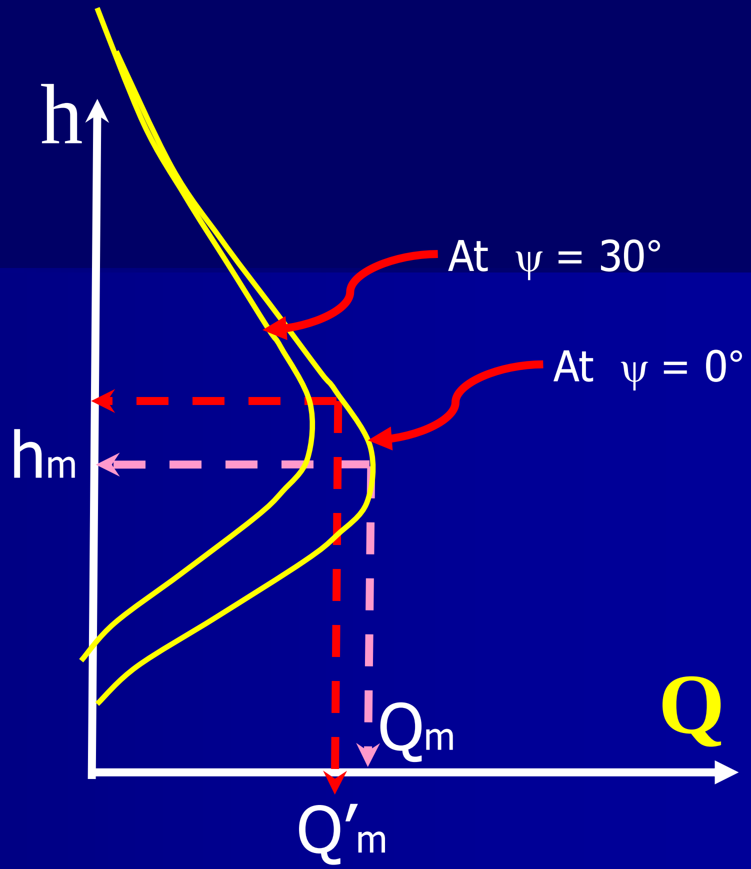
Eg: at 12:00 pm
at 1:00 pm
at 2:00 pm
. . .

- **At the night** there is **no height to corresponding to our value Q'_m** ! Because our graph [according to Chapman Layer Theory] does not exist at night.

Chapman layer Theory

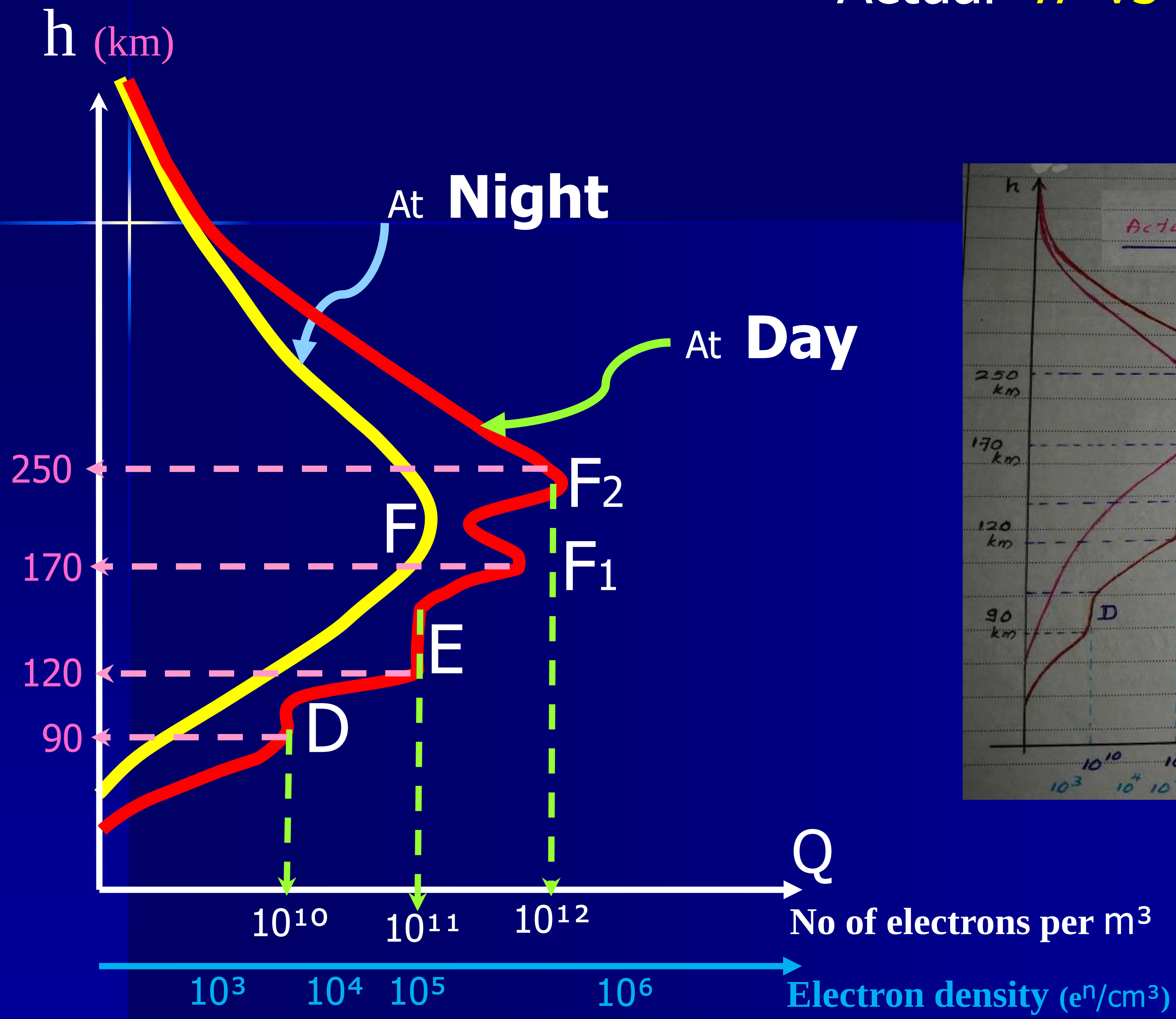
Electron Production Rate (Q)

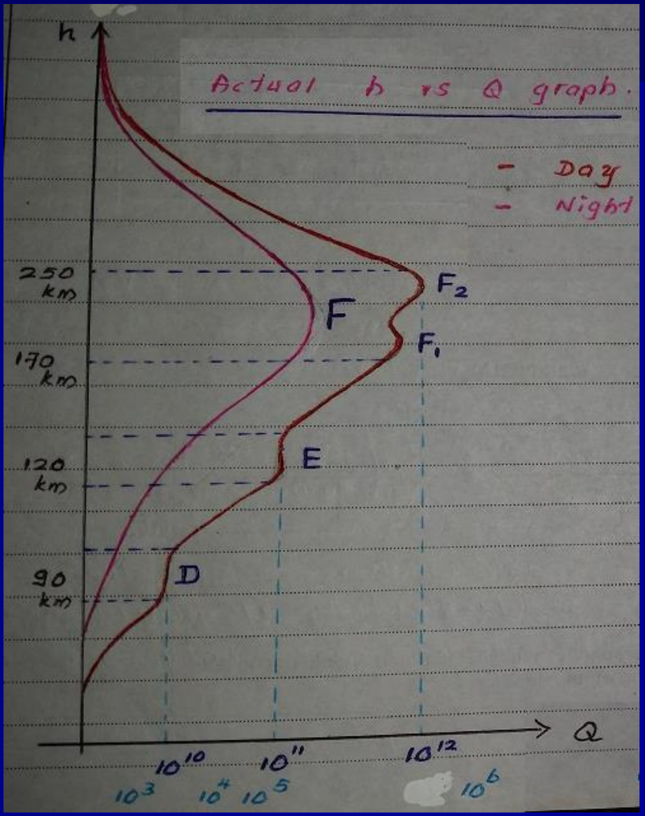
- There are **so many types of gasses in the atmosphere** of the Earth. As a result, the graph of h vs Q **should be contained several peaks**.
- Also if we assume there is a **monochromatic wavelength** comes from the Sun. This is wrong. There should be several peaks of the graph of h vs Q, because of there are **several wavelengths comes from the Sun to ionized the gasses**.



:. We should consider all the effects that we discussed, before plotting the graph of h vs Q.

Actual *h* vs *Q* graph

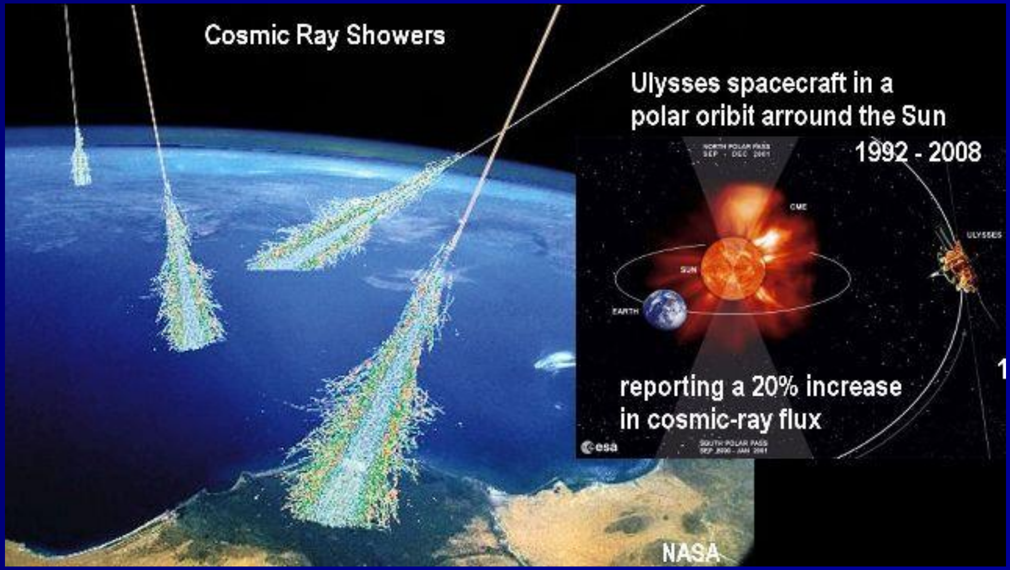




Chapman layer Theory

- We can not find the value of Q (Electron Production Rate) at night using our derived formula. Because, if ψ > 90° our is formula failed !

$$Q = \frac{\eta \cdot I_{\infty}}{e H} e^{\left(1 - Z - \sec\psi \cdot e^{-Z}\right)}$$



- Galactic Cosmic Rays :

Galactic Cosmic Rays comes from the Sun and this radiation is spread all over the Universe. As a result this Galactic Cosmic Radiations comes to the Earth. At night there is no rays comes from the Sun, but Galactic Cosmic Radiations comes to the Earth at night. Therefore, there are several number of ionized electrons may exist at the night !

The Ionosphere

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Plasma Frequency

Let us consider an ionized layer with an uniform electron density N and radio waves of frequency f incident normally (at right angles) upon the layer. If the frequency is above a limiting frequency f_p the waves will pass through the layer, whereas if **$f < f_p$**, the waves will be reflected back. This critical frequency is called the **Plasma Frequency, f_p** and is proportional to the square root of the **electron density, N** of the Layer

$$f_p \; \alpha \; N^{1/2}$$

Plasma Frequency

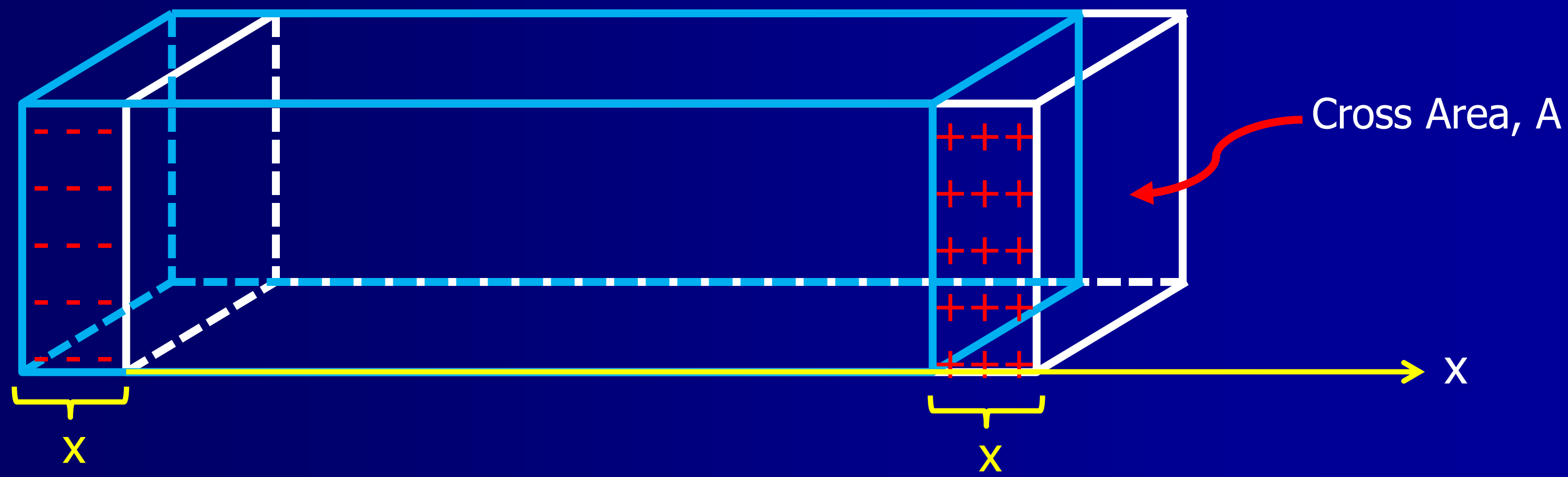
Plasma is the name given to a **mixture of** electrons, ions and neutral particles. When an electromagnetic wave such as the radio wave enters into a plasma, its electric field tends to set the charge particles in motion. The ions, which are about **10^4** times heavier than the electrons, respond very little to the weak field of the wave and can be considered as stationary. The light electrons, on the other hand, react readily to the **-eE** force acting on them. (Where -e is the negative charge of an electron)

Let N_i and N_e be the initial number of densities of the ions and electrons. Since the ionosphere is neutral we can set,

$$N_i = N_e = N$$

Plasma Frequency

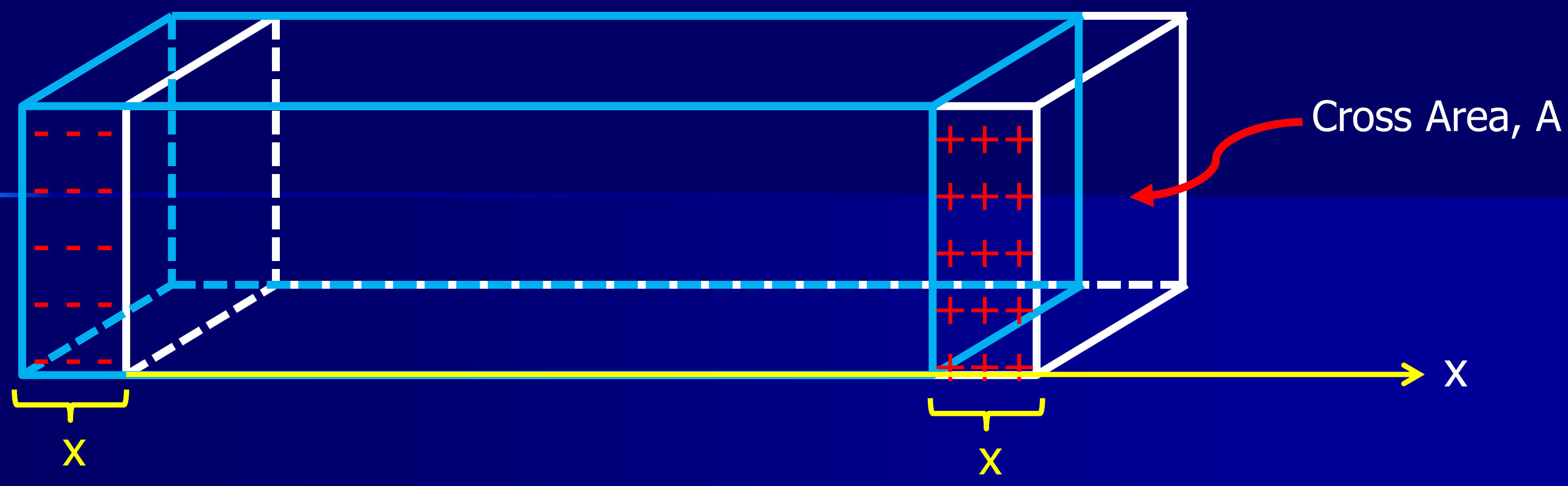
Assuming charge distribution of +ve ions and –ve electrons are separated like the following figure,



For instance, consider a one-dimensional situation in which a slab consisting entirely of one charge species is displaced from its quasi-neutral position by an infinitesimal distance x,

Volume of the charge distribution = $x \times 1 \ m^2$

Plasma Frequency



Number of charges in the Volume = $x \times N$

(Where N is electron (charge) density)

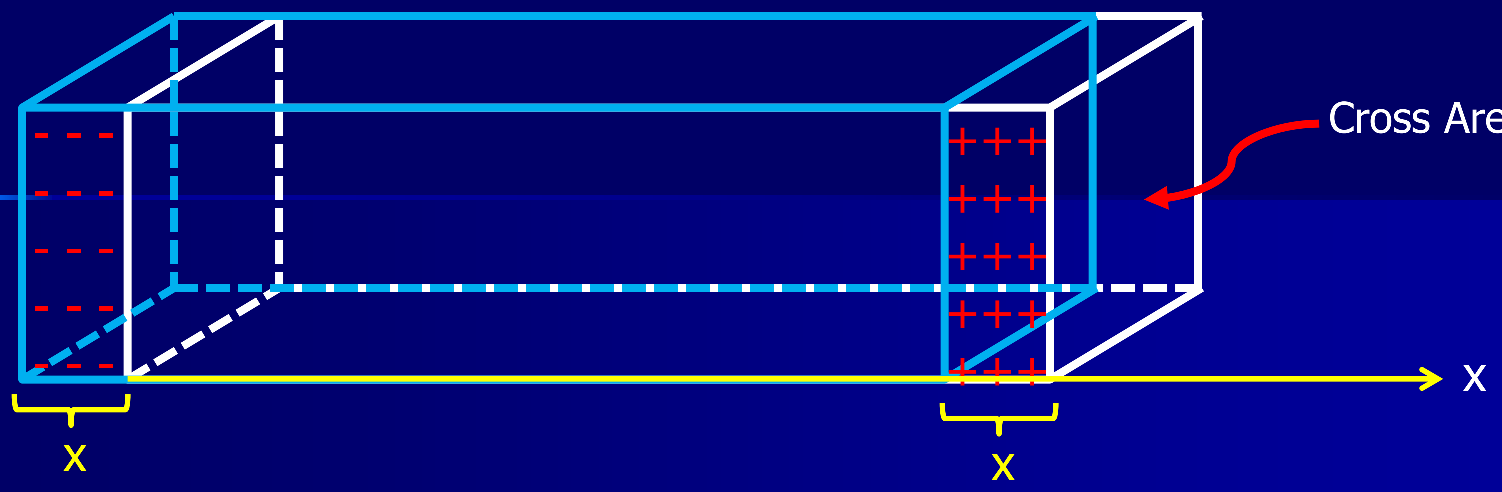
.: Surface charge density = $e \times xN$

(Where e is charge of an electron)

$$\sigma = eNx$$

(The resulting charge density which develops on the leading face of the slab)

Plasma Frequency



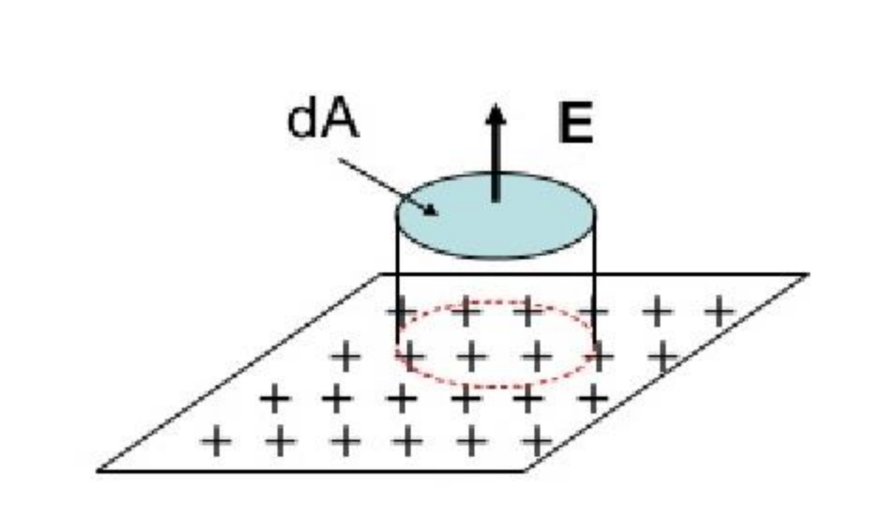
(As equal and opposite charge density develops on the opposite face. The x-direction electric field, generally inside the slab : [Using Gauss law, if we consider this is like a parallel plate situation])

$$E_x = -\frac{\sigma}{\varepsilon_o}$$

(This negative sign for the direction)

Proof -> P. T. O

Plasma Frequency



Using Gauss law,

$$\int_S \mathbf{E}.d\mathbf{S} = \frac{Q_{encl}}{\varepsilon_o}$$

We consider this is like a **parallel plate** situation :

$$E \cdot dA = \frac{\sigma . dA}{\varepsilon_o}$$

$$\mathbf{E} = \frac{\sigma}{\varepsilon_o}$$

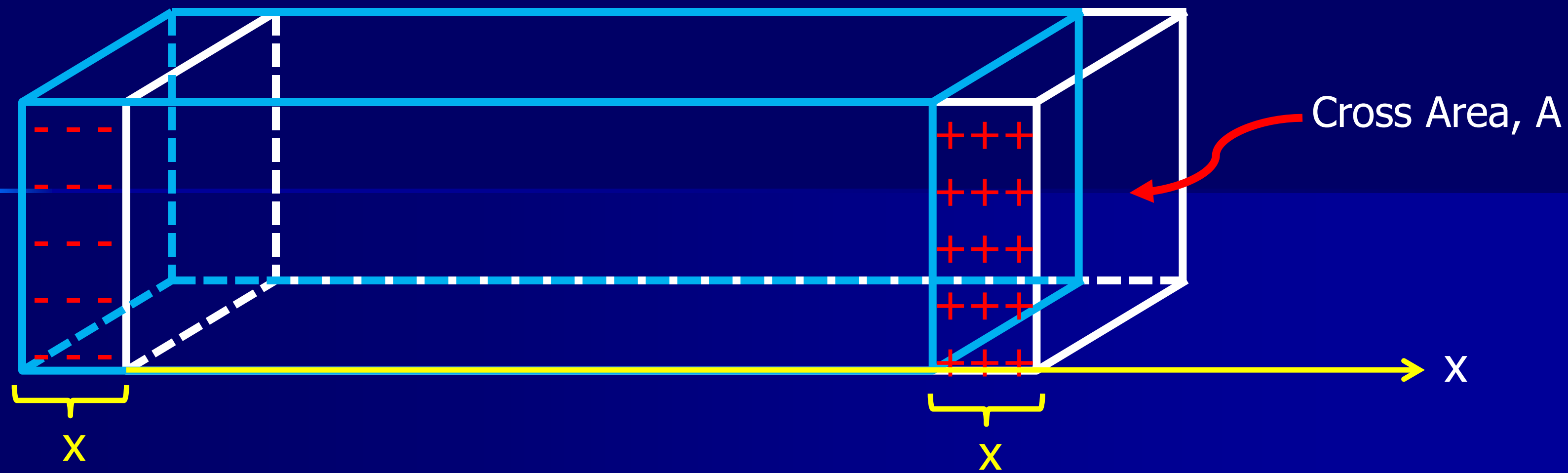
For our case :

$$E_x = -\frac{\sigma}{\varepsilon_o}$$

(This negative sign for the direction)

Force on an electron $F = e \times E$

Plasma Frequency



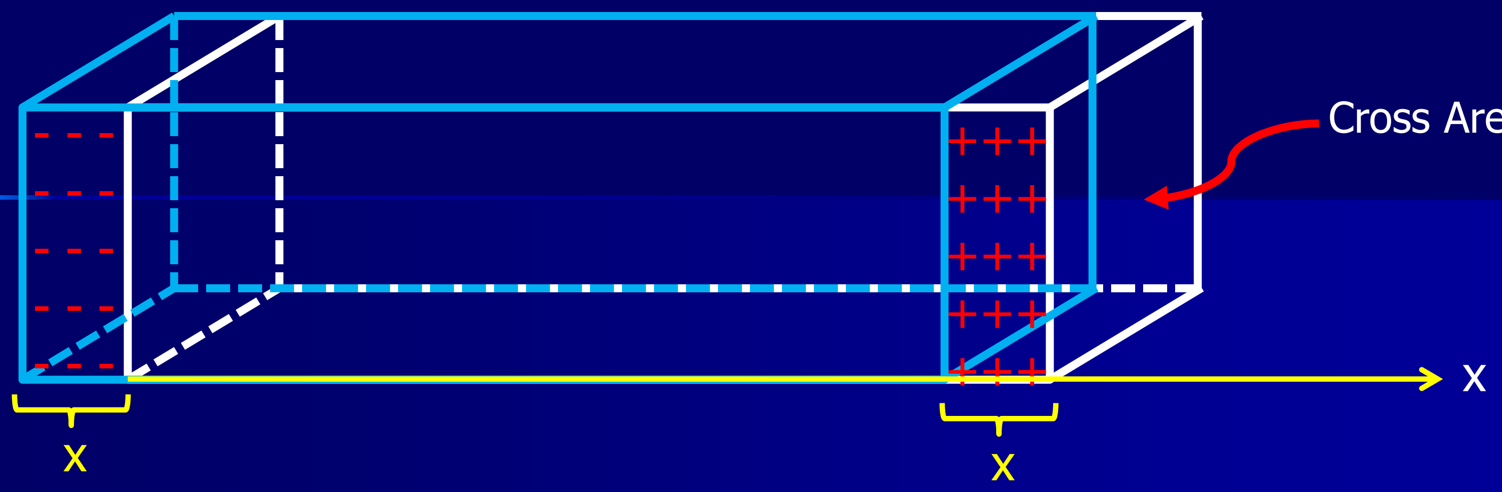
$$F = e \times E \;\Rightarrow\; F = e \times \left(-\frac{\sigma}{\varepsilon_o} \right) \;\Rightarrow\; F = e \times \left(-\frac{eNx}{\varepsilon_o} \right)$$

$$\Rightarrow\; F = -\frac{e^2 Nx}{\varepsilon_o}$$

Thus, Newton's 2nd law applied to an individual particle inside the slab yields,

$$\vec{F} = m\vec{a}$$

Plasma Frequency



$$\vec{F} = m\vec{a} \quad \Rightarrow \quad -\frac{e^2 N x}{\varepsilon_o} = m\frac{d^2 x}{dt^2}$$

$$\Rightarrow \quad \ddot{x} = -\frac{e^2 N}{\varepsilon_o m} x$$

This is the equation of the Simple Harmonic Oscillation;

$$\ddot{x} = -\omega^2 x$$

Plasma Frequency

Then, the Angular Plasma Frequency;

$$\omega_p^{\,2} = \frac{e^2 N}{\varepsilon_o m}$$

and the Plasma Frequency;

$$f_p = \frac{\omega_p}{2\pi}$$

$$\Rightarrow \quad f_p = \frac{e}{2\pi(\varepsilon_o m)^{1/2}} N^{1/2}$$

The *plasma frequency*, is the most fundamental time-scale in plasma physics. Clearly, there is a different plasma frequency for each species. However, the relatively fast electron frequency is, by far, the most important, and references to "the plasma frequency" in text-books invariably mean the *electron* plasma frequency.

Plasma Frequency

$$f_p = \frac{e}{2\pi(\varepsilon_o m)^{1/2}} N^{1/2}$$

A constant !

Where,

$$e = 1.6 \times 10^{-19} C$$

$$m = 9.1 \times 10^{-31} kg$$

$$\varepsilon_o = 8.85 \times 10^{-12} F\, m^{-1}$$

Then,

$$\frac{e}{2\pi(\varepsilon_o m)^{1/2}} = 8.97 \cong 9$$

$$f_p = 9 N^{1/2}$$

Where, f_p is the Plasma Frequency of the medium (is measured in Hz)

N is the Molecular Number Density of the medium (is measured in e^n / m^3)

Eg :

If electron density at some height is 10^{12} e^n/m^3, Find the plasma frequency of the medium at that height.

$$f_p = 9N^{1/2} \rightarrow f_p = 9\times\left(10^{12}\right)^{1/2} \rightarrow f_p = 9\times10^6$$

$$\rightarrow f_p = 9\ MHz$$

That means, if we send a Radio Wave of frequency 9 MHz , it is reflected from the region of the atmosphere when the electron density is 10^{12} e^n/m^3.

That height is situated at **F** region (actually **F2** region)

Ionospheric regions

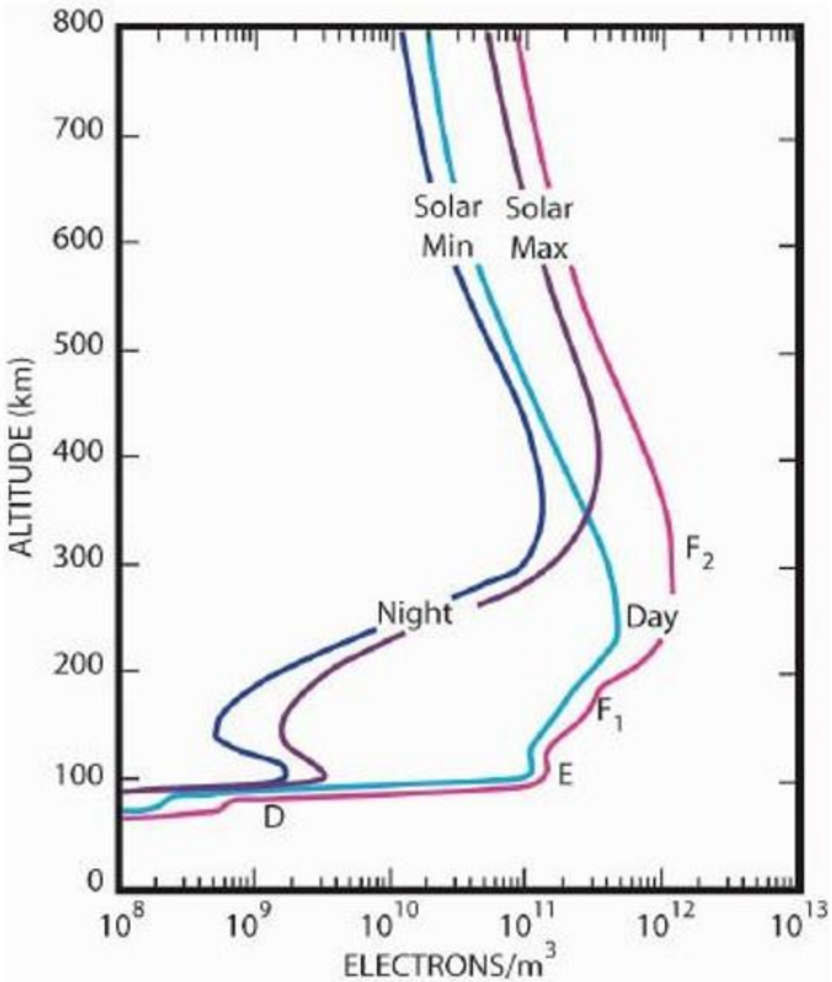


Figure: Typical ionospheric electron density profiles.

Ionospheric regions and typical daytime electron densities:

- D region: 60–90 km, $n_e = 10^8$–10^{10} m^{-3}
- E region: 90–150 km, $n_e = 10^{10}$–10^{11} m^{-3}
- F region: 150–1000 km, $n_e = 10^{11}$–10^{12} m^{-3} .

Ionosphere has great variability:

- Solar cycle variations (in specific upper F region)
- Day-night variation in lower F, E and D regions
- Space weather effects based on short-term solar variability (lower F, E and D regions)

For D region :

- D region: 60–90 km, $n_e = 10^8$–10^{10} m^{-3}

$f_p = 90\ kHz$ to $f_p = 900\ kHz$

That means, if we send a Radio Wave of frequency 90 kHz to 900 kHz, it is reflected from the **D** region; when the electron density is 10^8 - 10^{10} e^n/m^3.

For E region :

- E region: 90–150 km, $n_e = 10^{10}$–10^{11} m^{-3}

$f_p = 900\ kHz$ to $f_p = 2.85\ MHz$

That means, if we send a Radio Wave of frequency 900 kHz to 2.85 MHz, it is reflected from the **E** region; when the electron density is 10^{10} - 10^{11} e^n/m^3.

For F region :

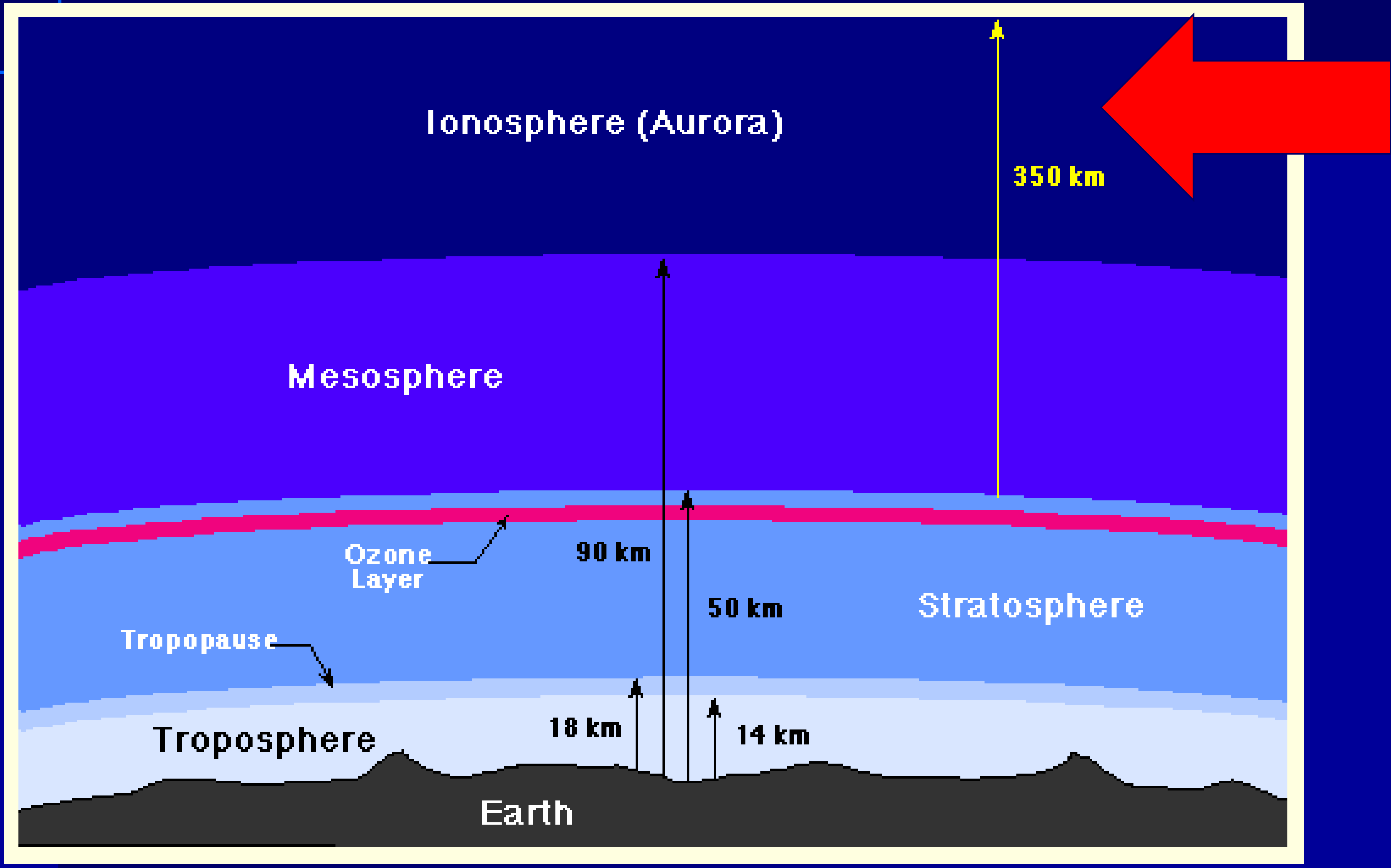
- F region: 150–1000 km, $n_e = 10^{11}$–10^{12} m^{-3} .

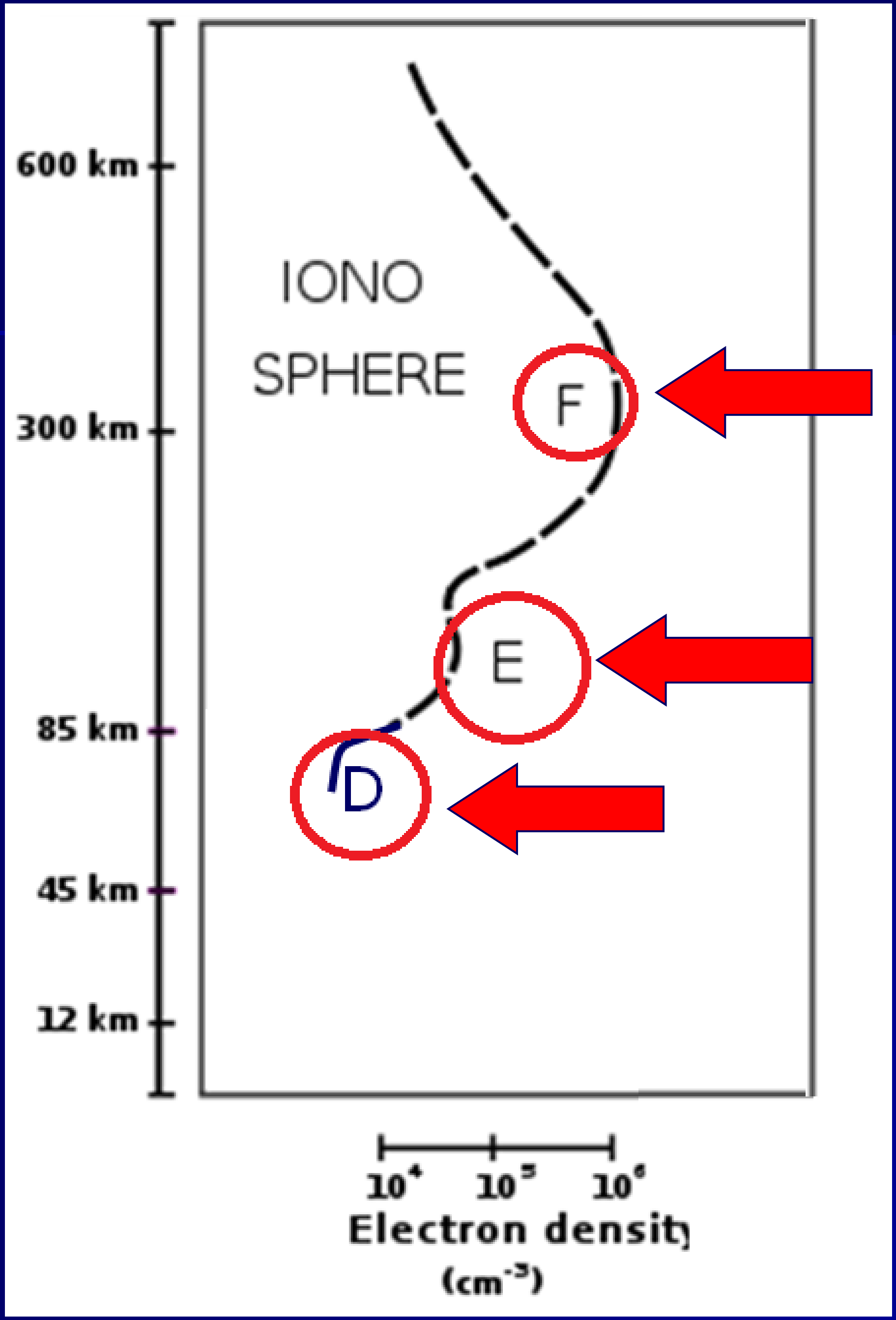
$f_p = 2.85\ MHz$ to $f_p = 9\ MHz$

That means, if we send a Radio Wave of frequency 2.85 MHz to 9 MHz, it is reflected from the **F** region; when the electron density is 10^{11} - 10^{12} e^n/m^3.

But if we send **UHF (300 MHz)** or **VHF (30 MHz)** signal (Radio Wave); the wave **goes through the ionosphere without any reflection** !

The Structure of the Ionosphere

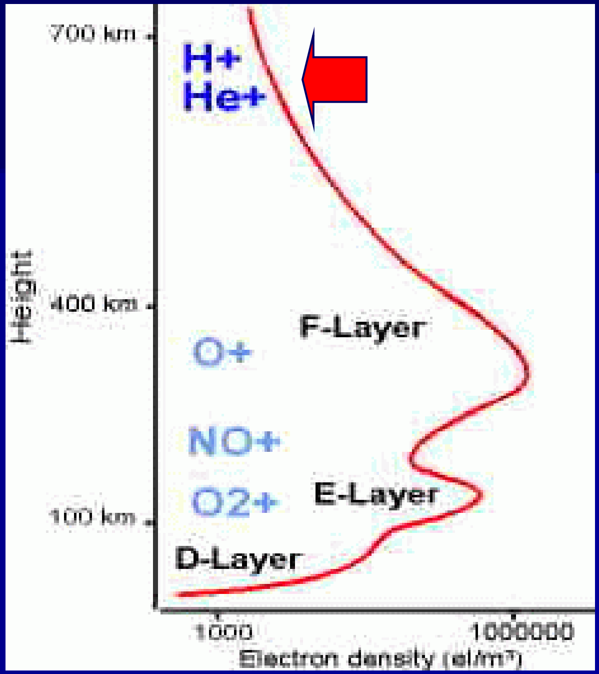



600 km
300 km
85 km
45 km
12 km
IONO
SPHERE
F
E
D
10⁴ 10⁵ 10⁶
Electron density
(cm⁻³)

The Upper Ionosphere

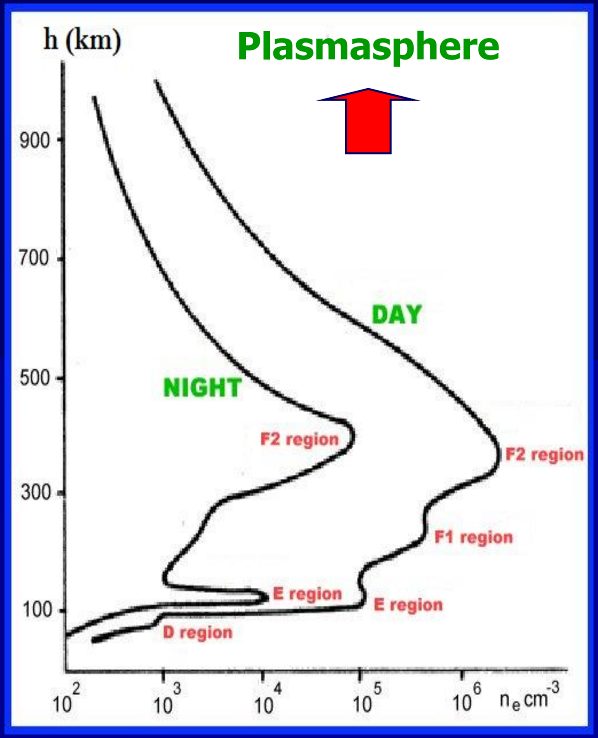
At attitudes above the F_2 peak both the production and the loss of electrons tend to Zero, which means that the upper ionosphere is maintained through the upward diffusion of ionization.

In the presence of the **Earth's Magnetic Field**, which tends to guide the diffusion of the charged particles along the field lines, this becomes a very complicated phenomenon to study.

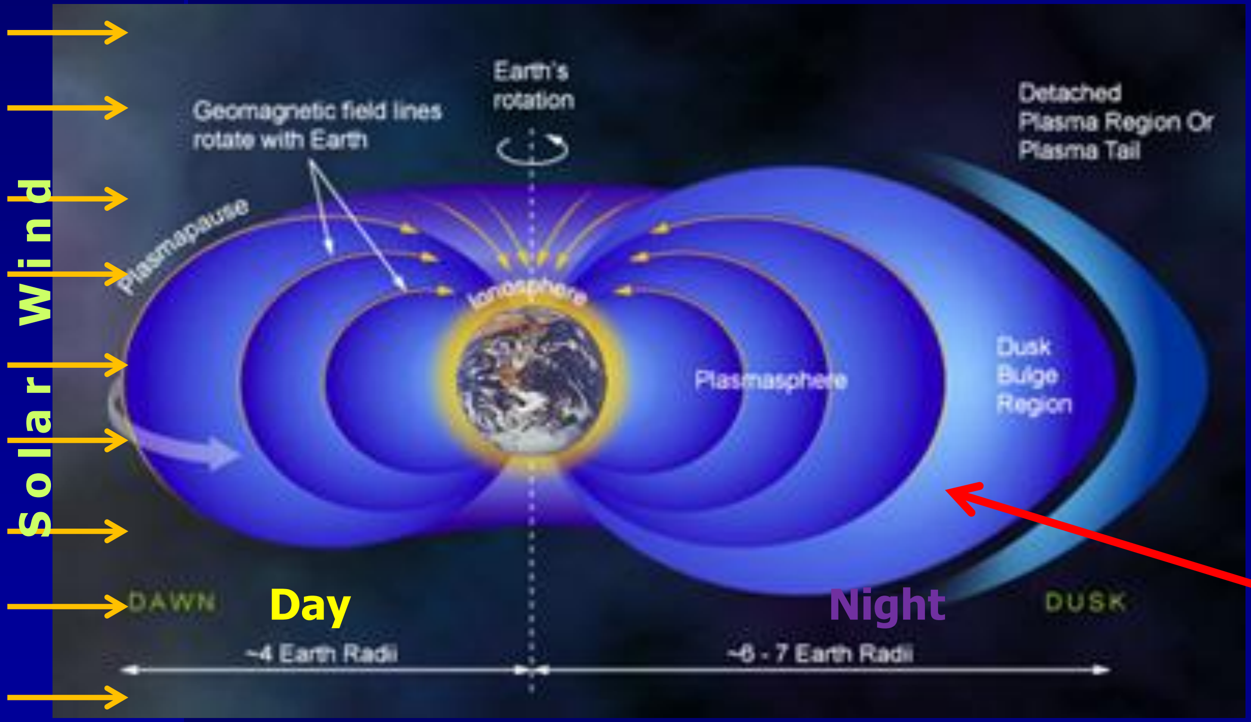


Around 1000 km O+ is replaced by He+ as the predominant ion, and at even higher attitudes (~2500 km) He+ is replaced by H+, i.e.; by free protons. The layer where helium ions dominate is often called **heliosphere** and the region above it is called the **protonosphere**.

The Plasmasphere

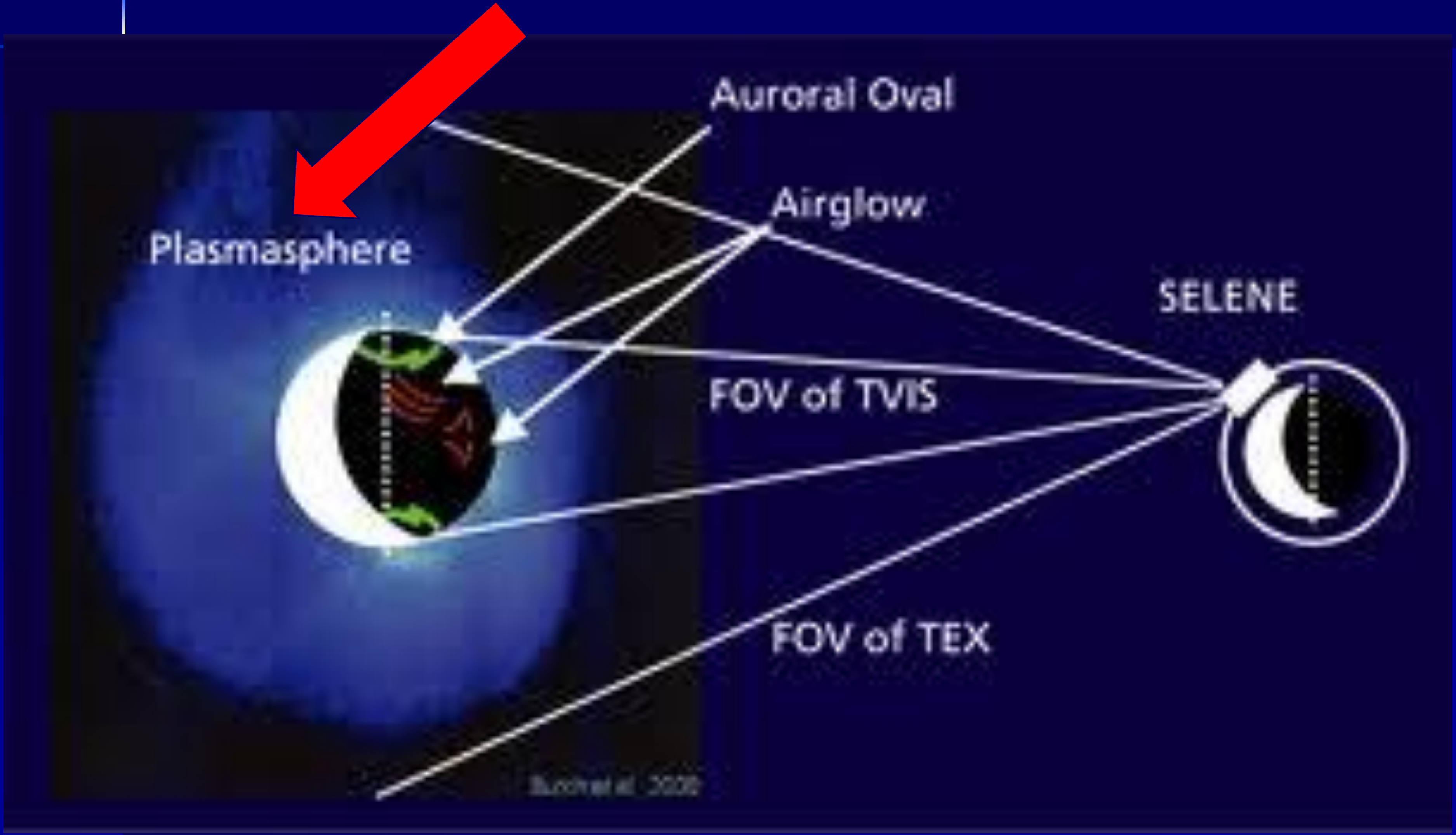


This is the region of the Earth's ionized atmosphere which basically follows the rotation of the Earth. The plasmasphere has the shape of a doughut, very much like the volume formed by the lines of the Earths dipole magnetic field which provides the link that keeps the plasmasphere rotating with Earth.



Shape of a doughnut

The Plasmasphere



Penetration Depth


Thank You !
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