Space & Atmospheric Physics

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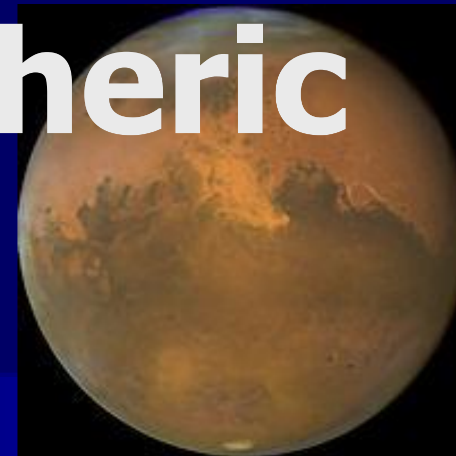
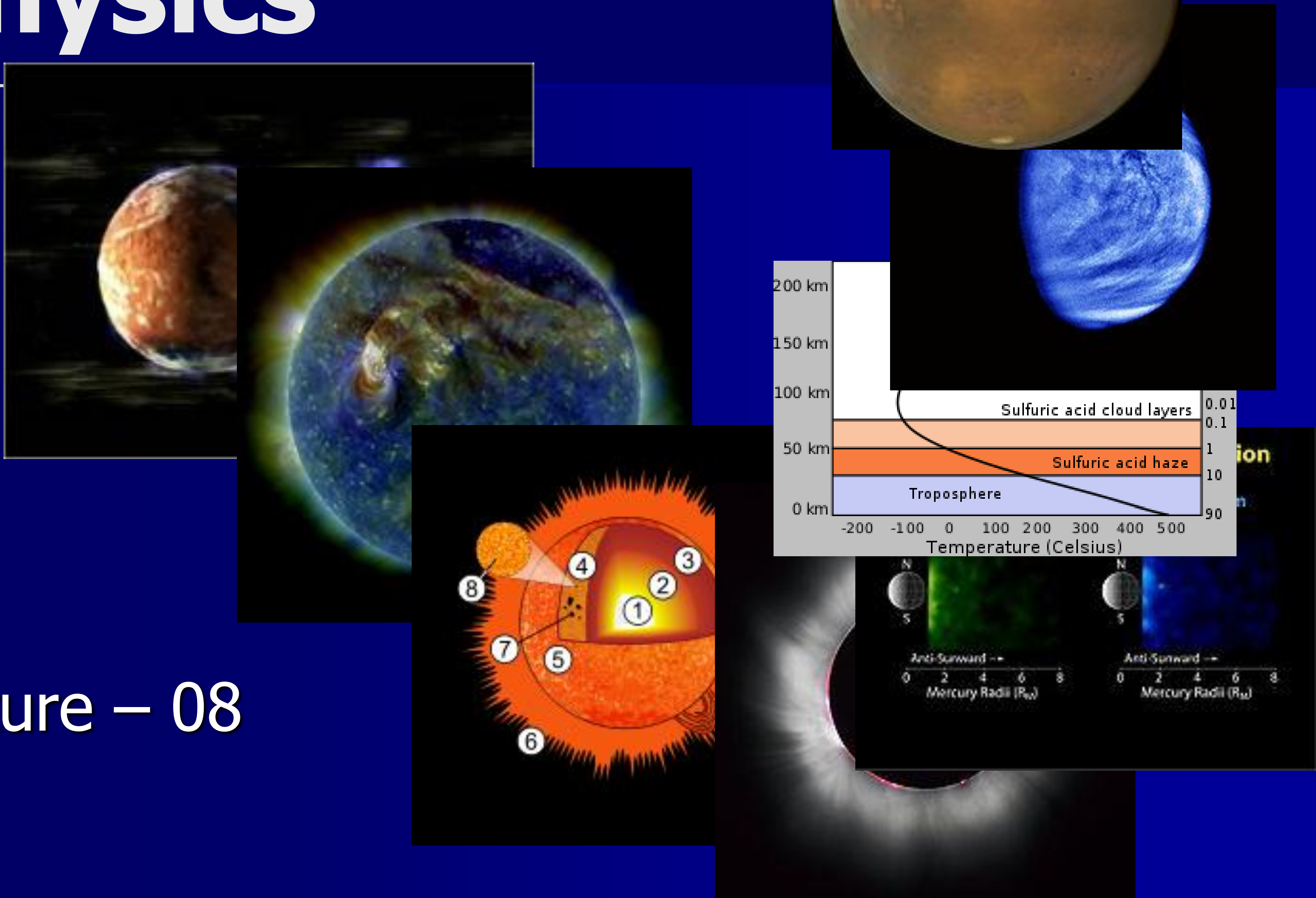




Lecture – 08

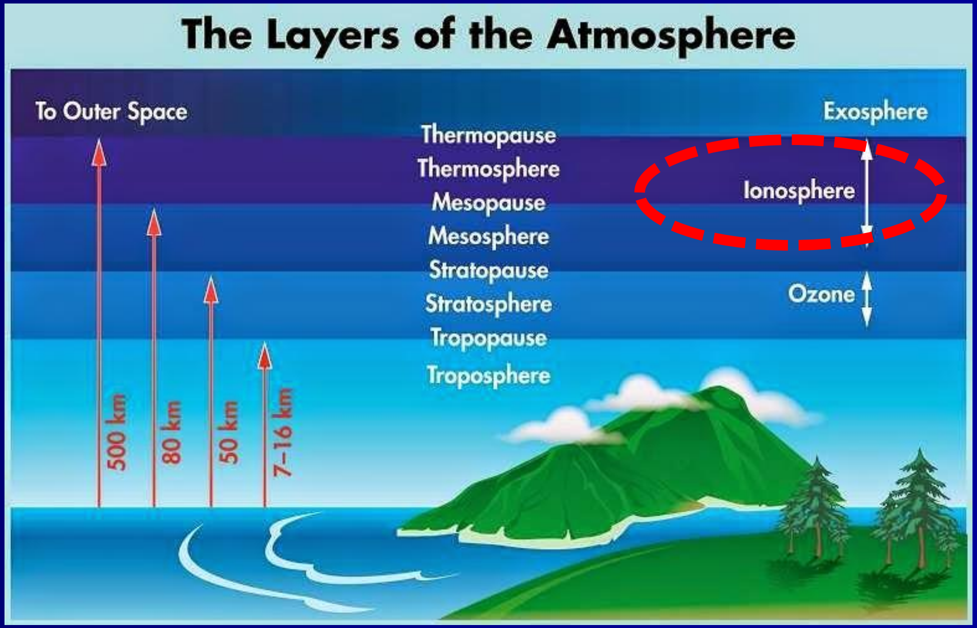
The Ionosphere

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

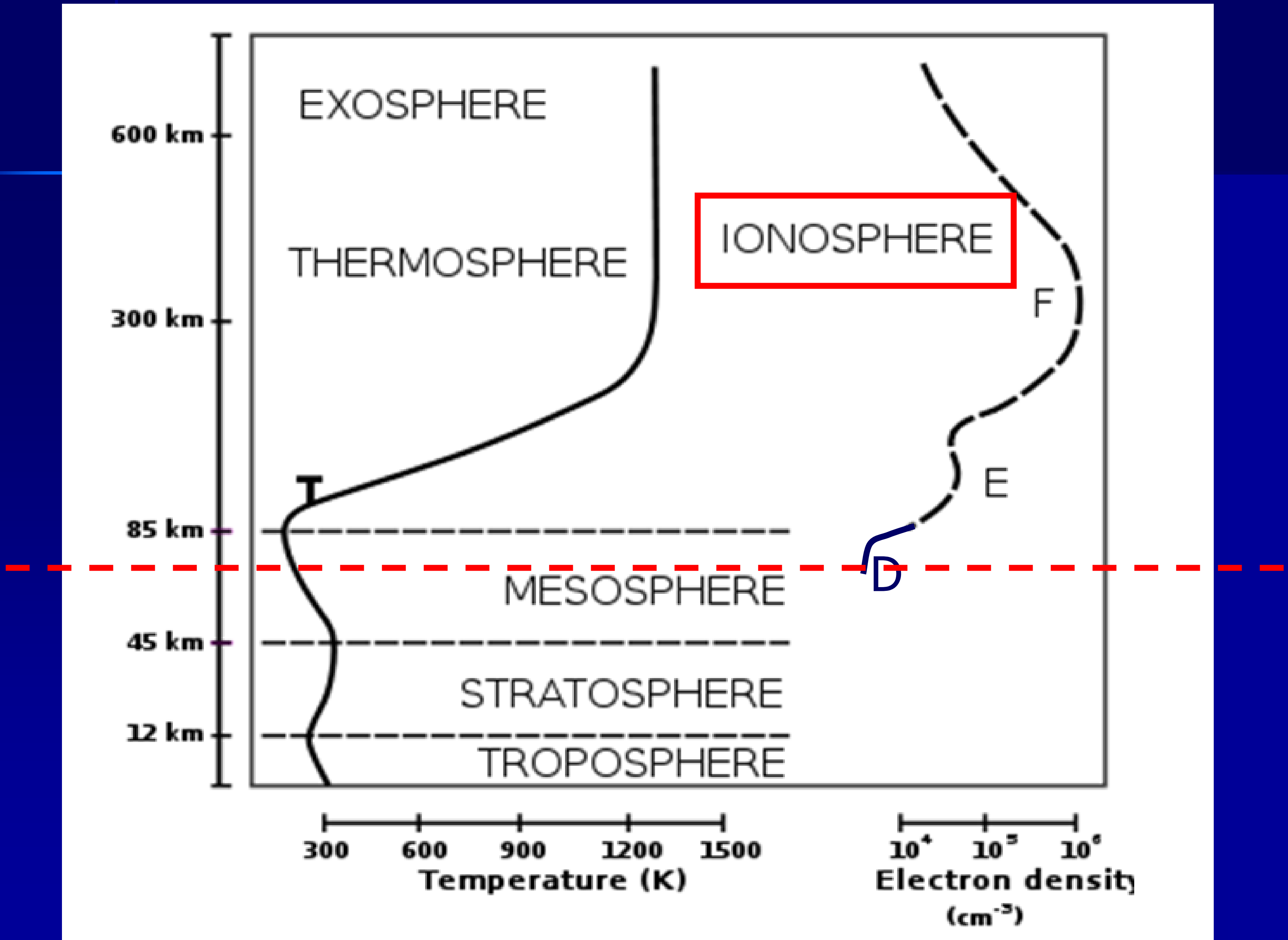
Introduction – A video

Introduction

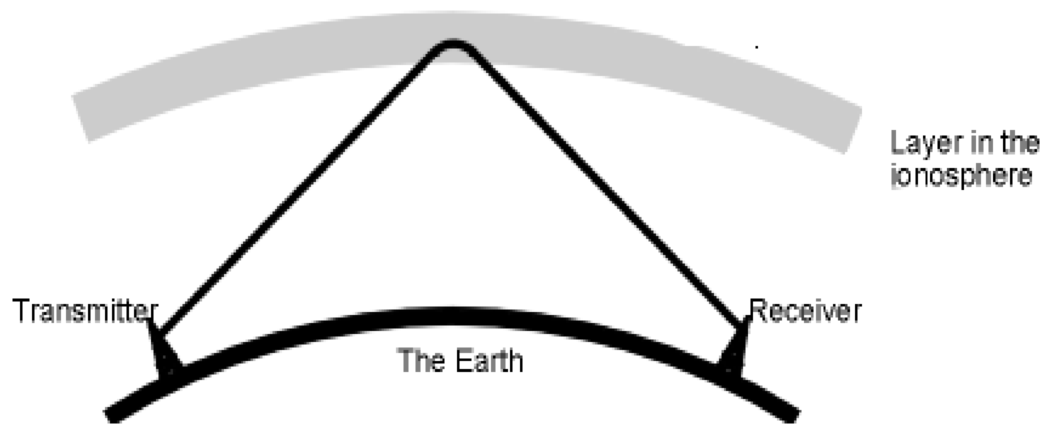
The ionosphere is a portion of the upper atmosphere, between the thermosphere and the exosphere, distinguished because it is ionized by solar radiation.
The ionosphere is a shell of **electrons** and **electrically charged atoms** and **molecules** that surrounds the Earth, stretching from a height of about 70 km on up.



Relationship of the atmosphere and ionosphere



The existence of the ionosphere, as an electrically conducting region of the atmosphere, was first suggested by the Scottish meteorologist Belfour Stwart in 1883. It has practical importance because among other functions, it influences Radio Propagation to distant places on Earth.

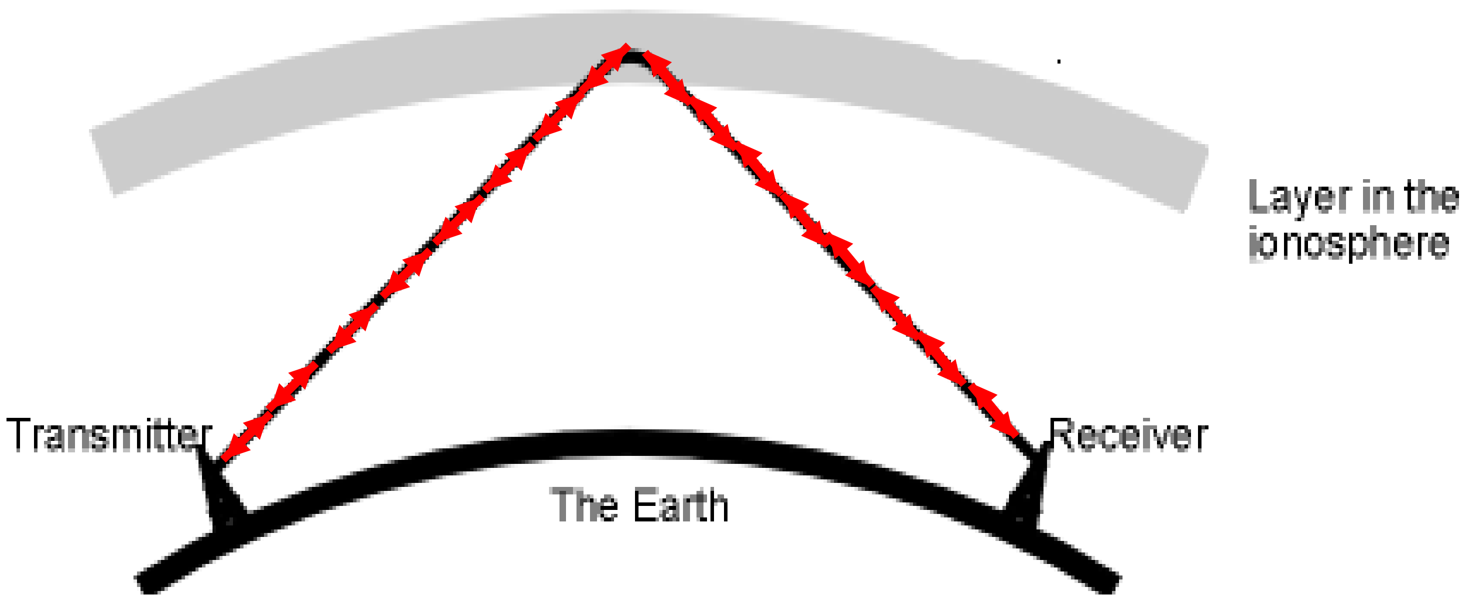


Refraction of a radio signal as it enters an ionised region

Marconi's successful experiments in 1901 of wireless communication across the Atlantic prompted **Heaviside** and **Kennelly** to postulate independently the existence of an ionized layer in the atmosphere. This electrically conducting layer was originally called the **Heaviside** Layer and later the E-Layer because of its many free elections.

The E-layer as seen in the following figure, acts as a **reflector** and makes it possible for Radio Signals to bridge large distance over the spherical Earth. The E-layer is an altitude of approximately 110 km.

The Ionosphere acting as a reflector of radio waves making possible radio telecommunication over the horizon.



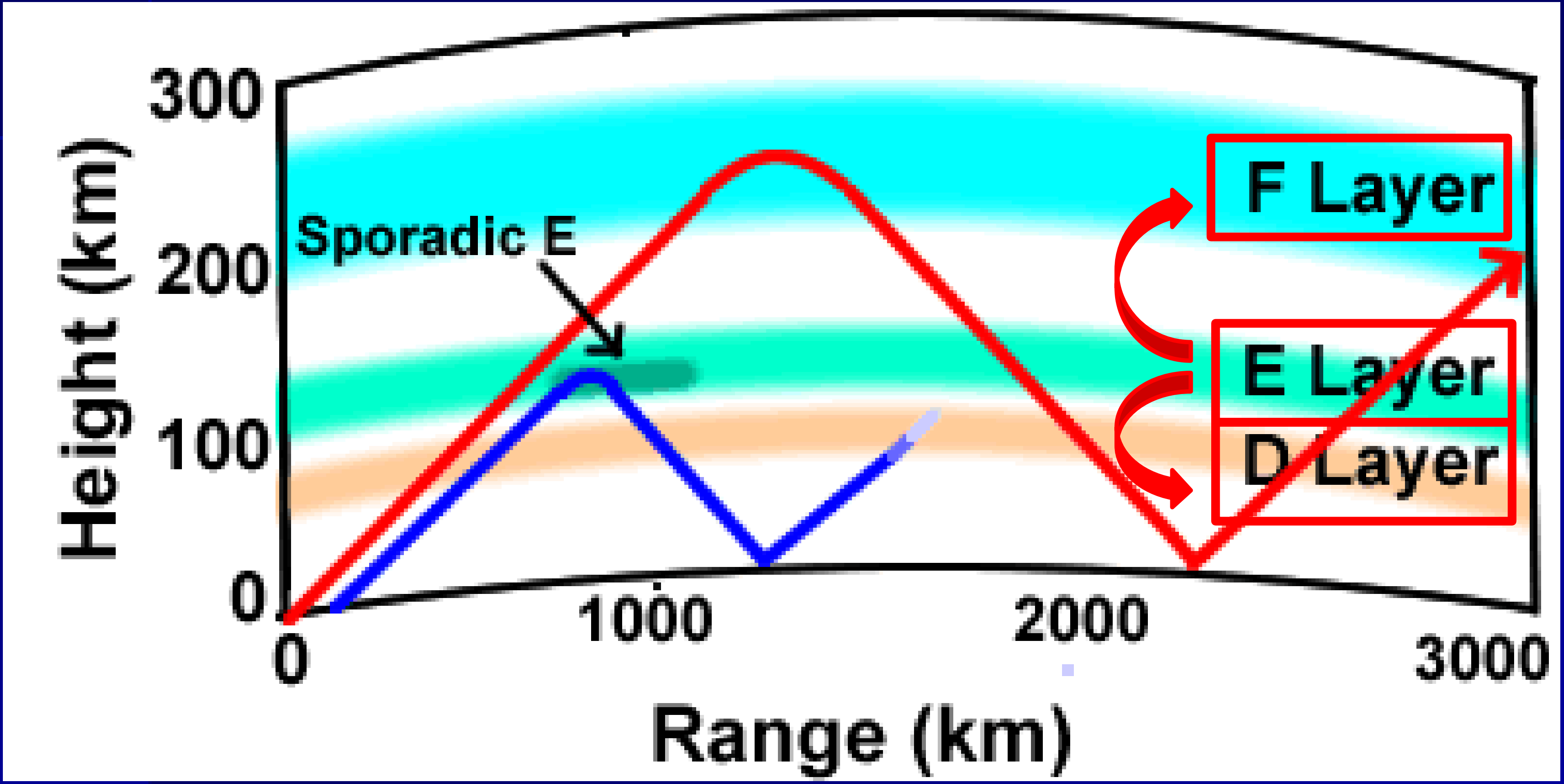
Refraction of a radio signal as it enters an ionised region

The First attempts to **study the structure of the ionosphere with Radio signals bounced back from the ionosphere** were made in **1925** by Appleton and Barnett in England.

Similar ionospheric sounding experiments were performed also in America in **1928** by Brest and Tuve.

An ionospheric sounder consists basically of a **Radio Transmitter** and a **Radio Receiver** connected in a way which allows them to **measure the time interval** between the transmission and the return of the Radio Pulse.

By multiplying one half of this time interval, which is of the order of a millisecond, with the speed of light, we obtain the **heights of the Reflection Layer.**



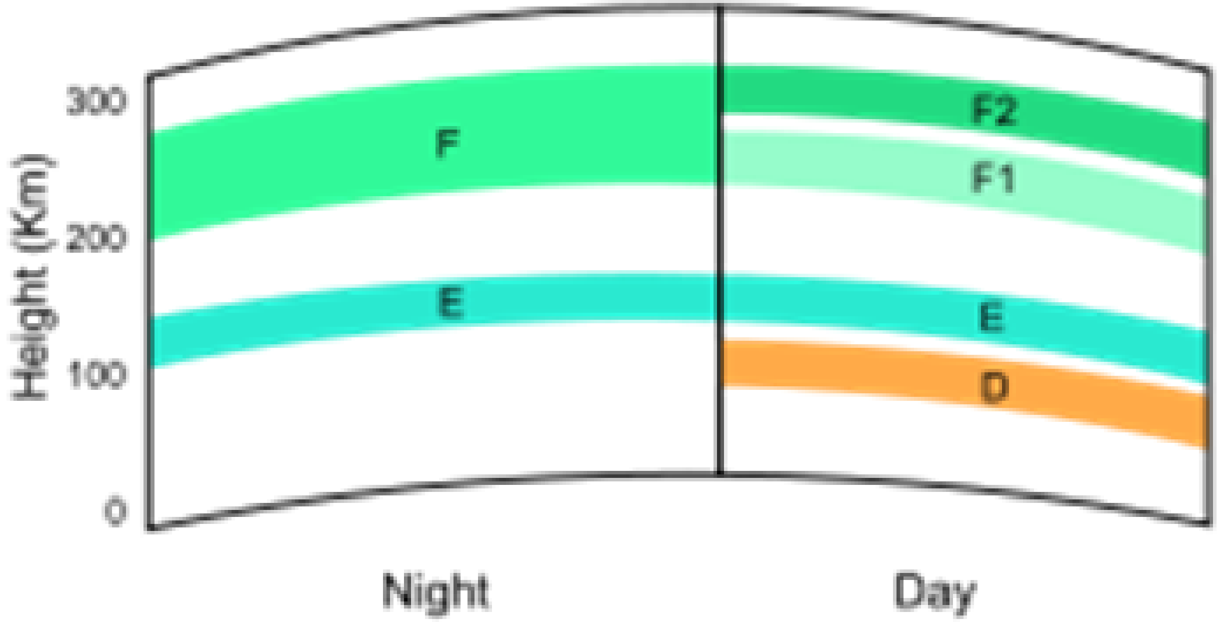
Height (km)
300
200
100
0
Sporadic E
F Layer
E Layer
D Layer
0
1000
2000
3000
Range (km)

The ionospheric layers

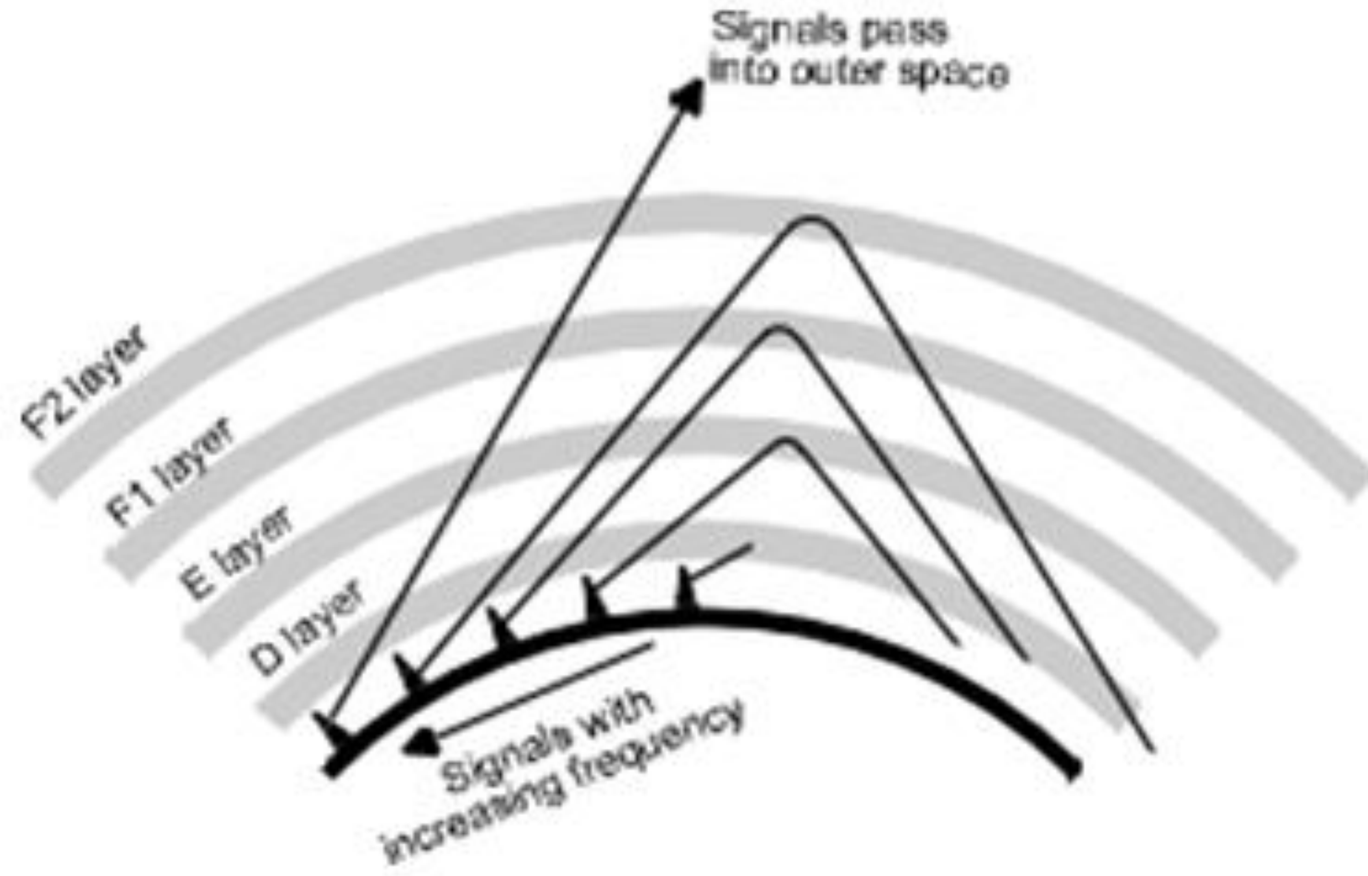
At night the F layer is the only layer of significant ionization present, while the ionization in the E and D layers is extremely low.

During the day, the D and E layers become much more heavily ionized, as does the F layer, which develops an additional, weaker region of ionisation known as the F1 layer. The F2 layer persists by day and night and is the region mainly responsible for the refraction of radio waves.

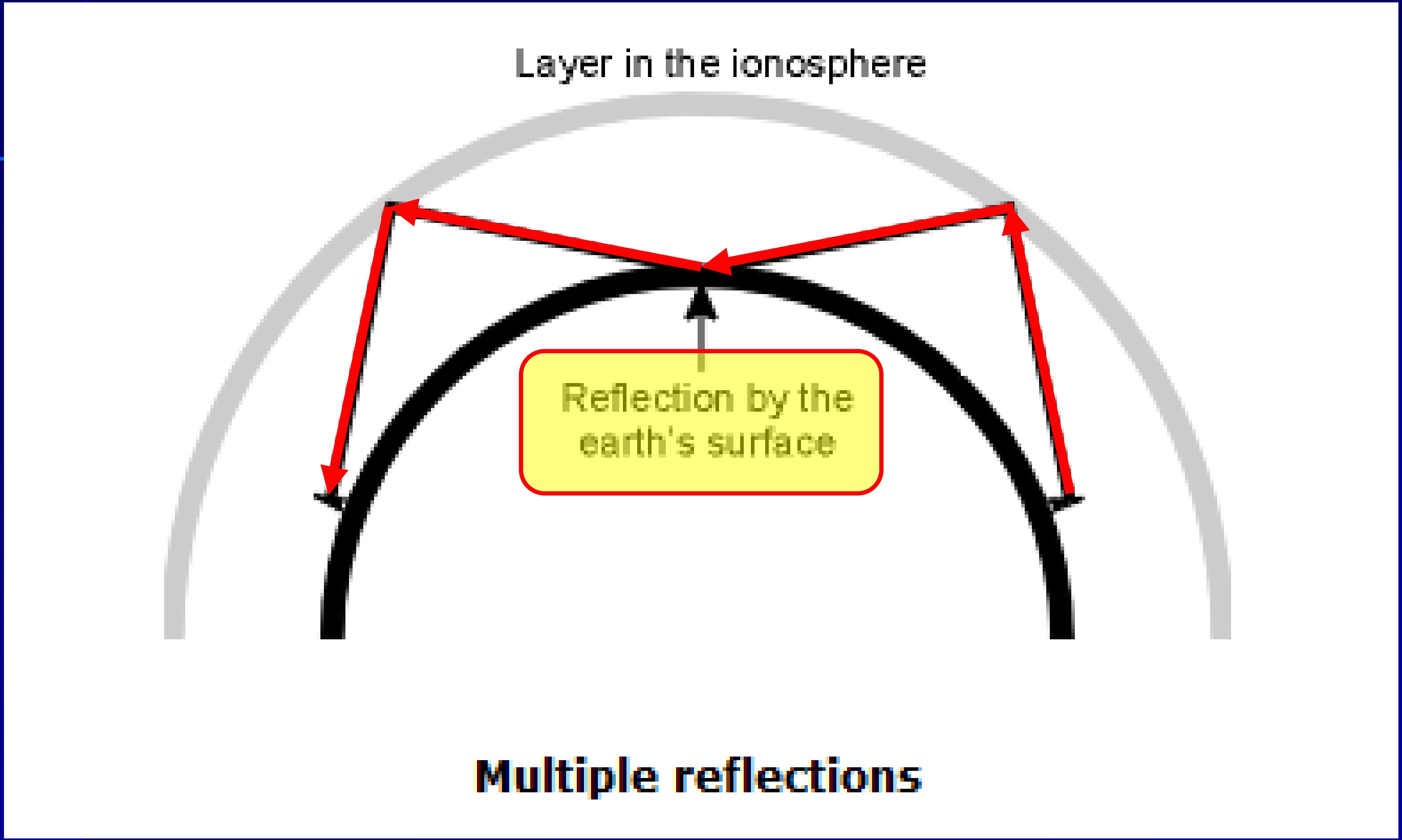
The ionospheric layers



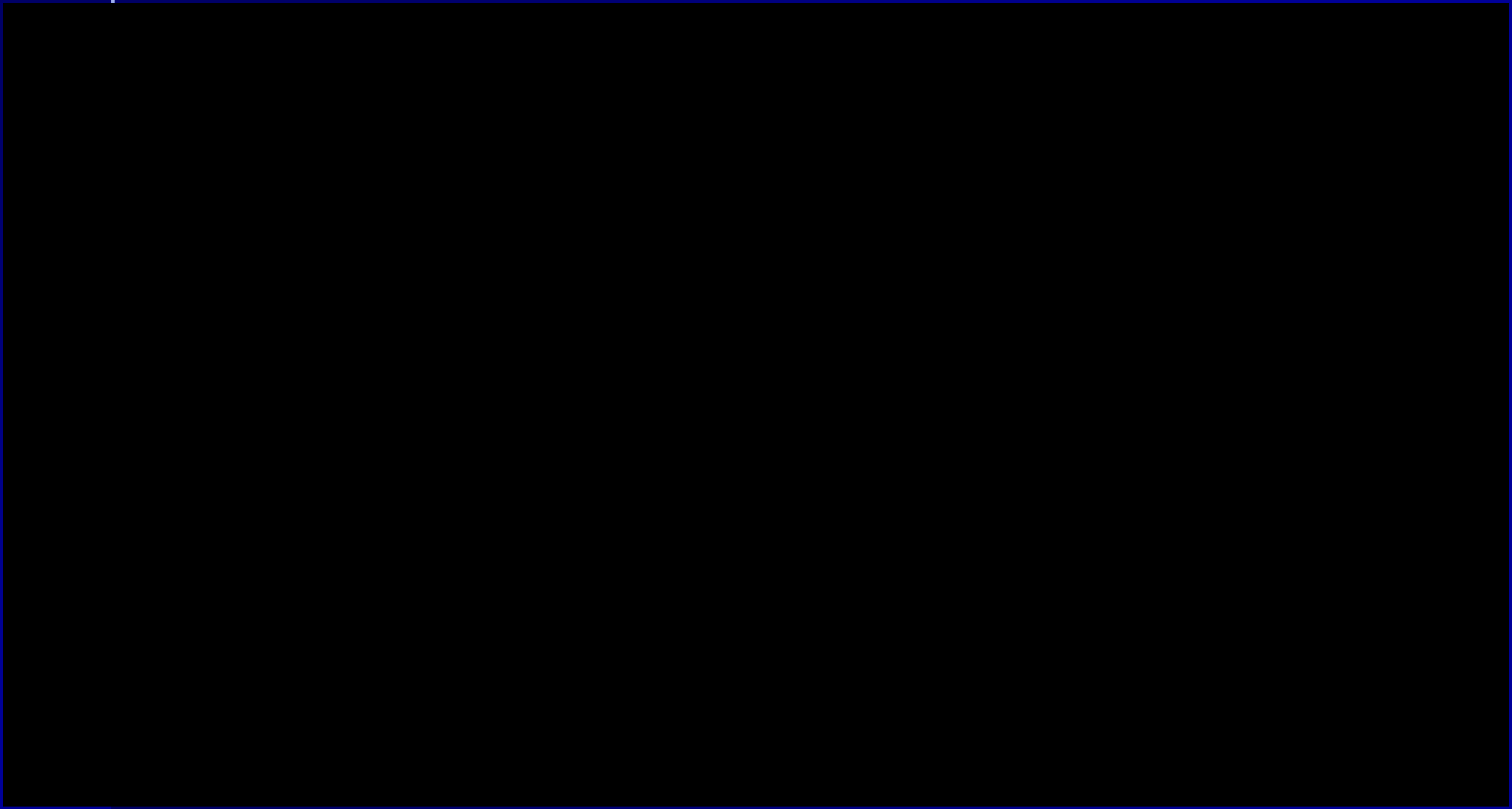
Ionospheric layers.



Signals reflected by the E and F regions


Layer in the ionosphere
Reflection by the earth's surface
Multiple reflections

PROPAGATION OF ELECTROMAGNETIC WAVES



The Ionosphere

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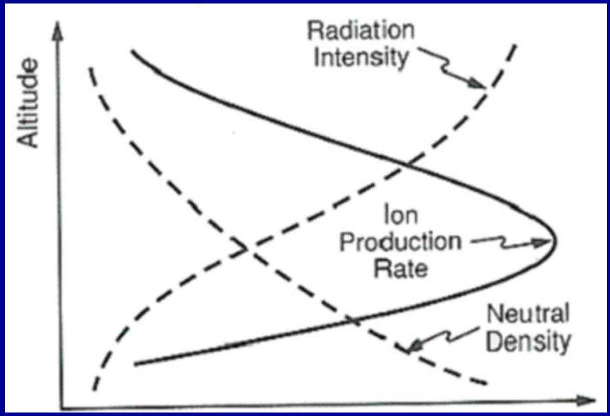
Chapman layer Theory

The Ionization of the atmosphere

The ionization of the atmosphere is produced primarily by the Sun's Ultraviolet and X-ray radiation. **The rate *q* at which ion-electron pairs are produced per unit volume is proportional to the intensity of the ionizing radiation *I* and the number density *Nn* of the neutral atmosphere**, i.e.:

$$q \ \alpha \ I \cdot N_n$$

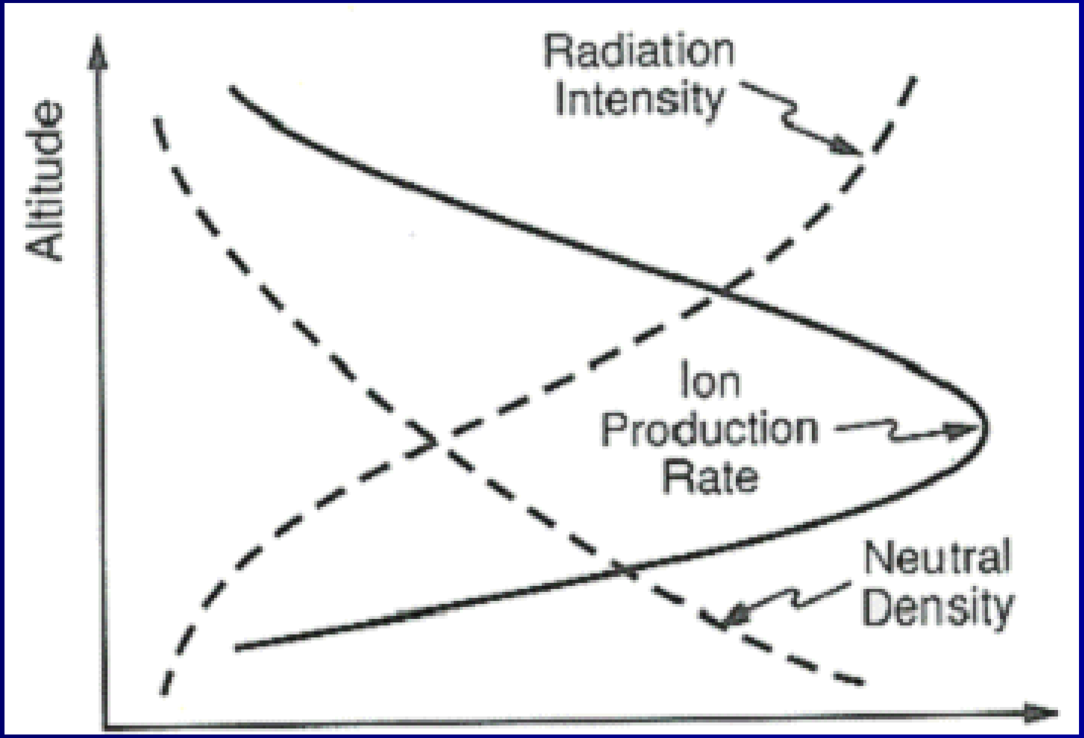
As seen from the following diagram, at high altitudes ***q* is very small because *N_n* is very small.** As the ionizing radiation penetrates deeper into the more dense layers of the atmosphere, *q* reaches a maximum q_m at a height h_m where *I* and *N_n* reach the best possible combination.



Chapman layer Theory

The Ionization of the atmosphere

Below this altitude, the intensity of the ionizing radiation drops rapidly because the energy is spent for the ionization of the atmosphere. As I decreases, q also decreases and finally vanishes near **70 km**.



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.

Chapman layer Theory

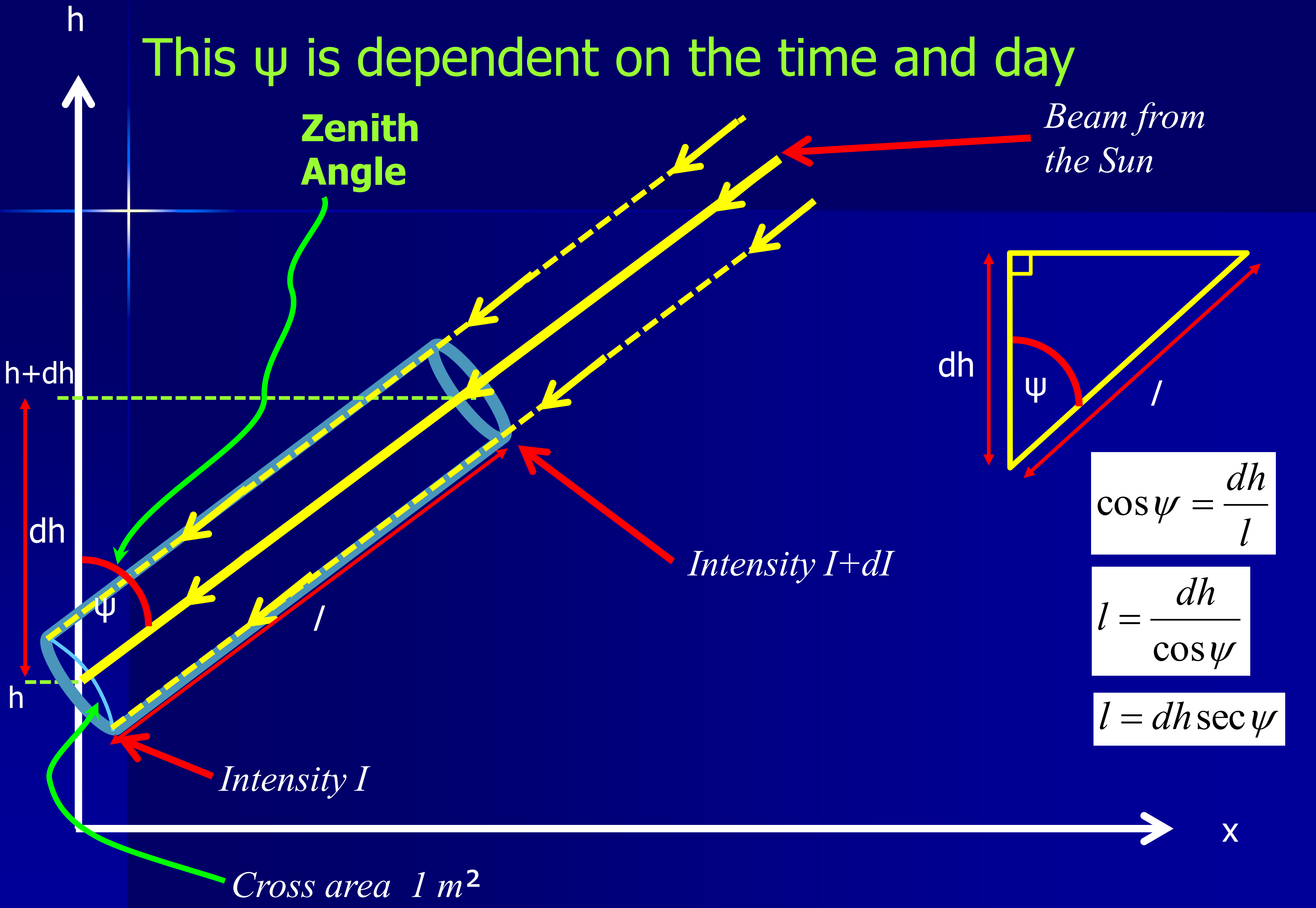
The Chapman Layer Theory in 1931 is a very good example of an **ingenious mathematical formulation** of a very complicated physical problem.

Intensity of Ionizing Radiation :

Let us first compute the absorption sustained by a beam of ionizing radiation at a height *h*. Let the beam have **unit cross-section** and ψ be the angle the beam makes with the vertical (called **Zenith Angle**). The energy of the beam expanded to ionized neutral particles between h and h+dh will be proportional to the intensity of the beam at this height I(h).

P.T.O

This ψ is dependent on the time and day



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

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

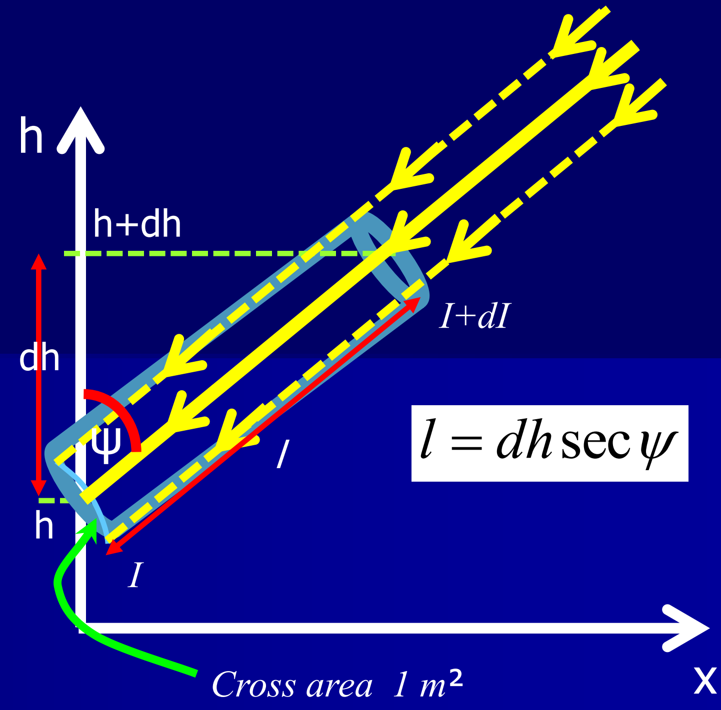
$$l = dh\sec\psi$$

If the molecular number density is N,
Number of molecules in the selected area :

$$= N \times V$$

$$= N \times l \times 1$$

$$= N dh \sec\psi$$



Total cross section :

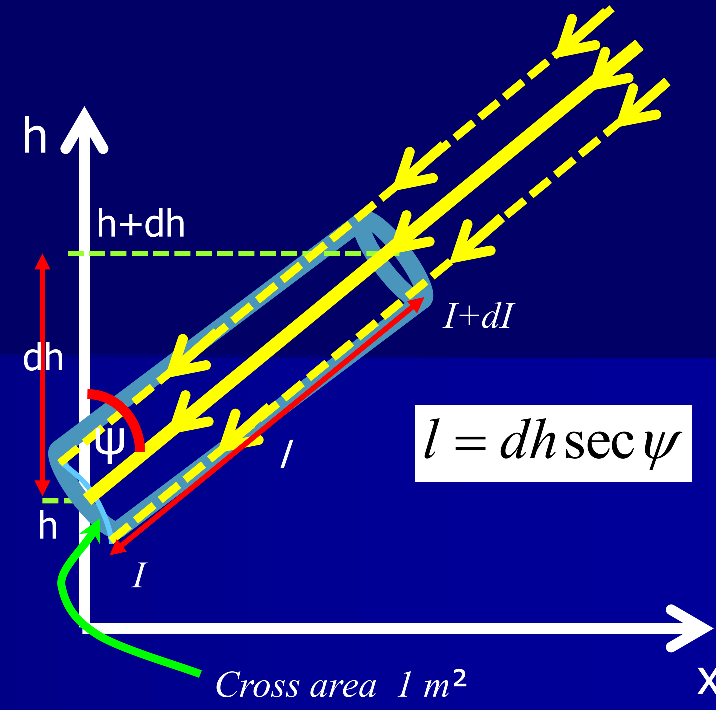
$$= \sigma_a \times N dh \sec\psi$$

Where σa *is Absorption Cross-section*

(Absorption Cross-section is the ability of a molecule to absorb a photon of a particular wavelength and polarization)

The amount of radiation absorbed in this selected layer will be,

$$dI = I \times \sigma_a N dh \sec\psi$$



For the total region : Integrating from the height h to ∞,

$$\int_{I=I}^{I=I_\infty} \frac{dI}{I} = \int_{h=h}^{h=\infty} \sigma_a N \sec\psi \; dh$$

(Assume the intensity of ionizing radiation at infinity is I∞ and intensity of ionizing radiation at h is I)

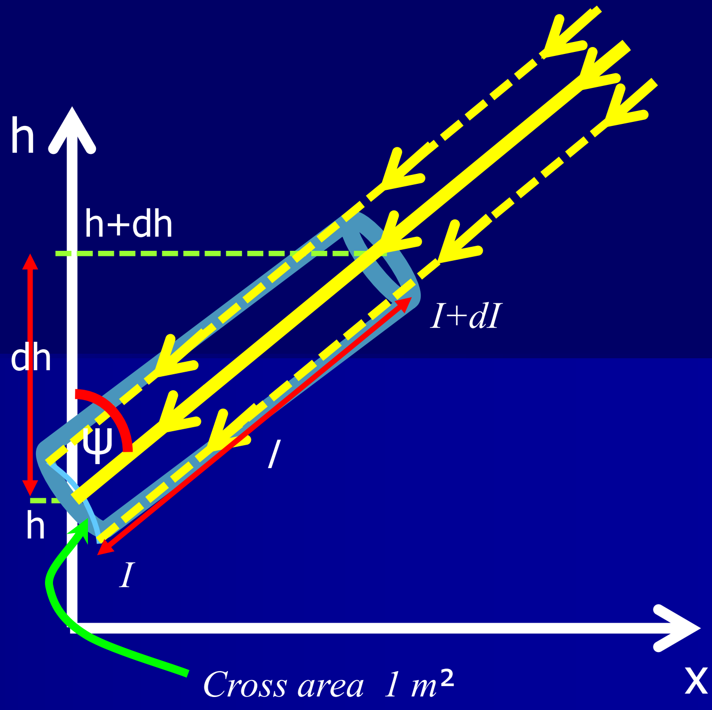
$$\int_{I=I}^{I=I_\infty} \frac{dI}{I} = \int_{h=h}^{h=\infty} \sigma_a N \sec\psi \; dh$$

$$\left[\ln I\right]_{I=I}^{I=I_\infty} = \sigma_a \sec\psi \int_{h=h}^{h=\infty} N dh$$

$$\ln\left(\frac{I_\infty}{I}\right) = \sigma_a \sec\psi \int_{h=h}^{h=\infty} N dh$$

$$\ln\left(\frac{I}{I_\infty}\right) = -\sigma_a \sec\psi \int_{h=h}^{h=\infty} N dh$$

$$I = I_\infty e^{\left(-\sigma_a \sec\psi \int_{h=h}^{h=\infty} N dh\right)}$$



Chapman layer Theory

Intensity of Ionizing Radiation

Intensity of Ionizing Radiation at infinity

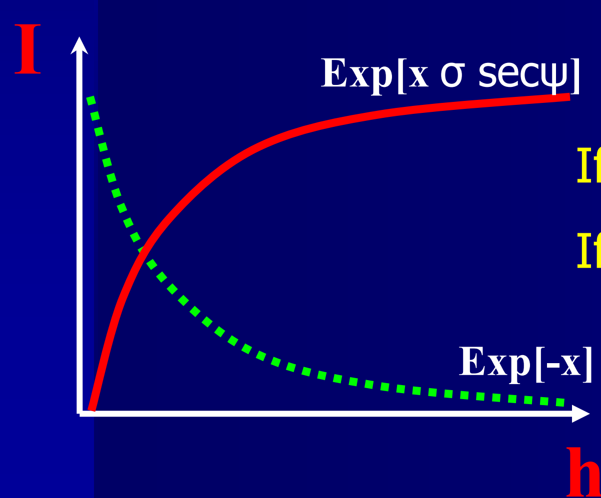
Absorption Cross-section

Zenith Angle

Molecular Number Density

Intensity of Ionizing Radiation at height h

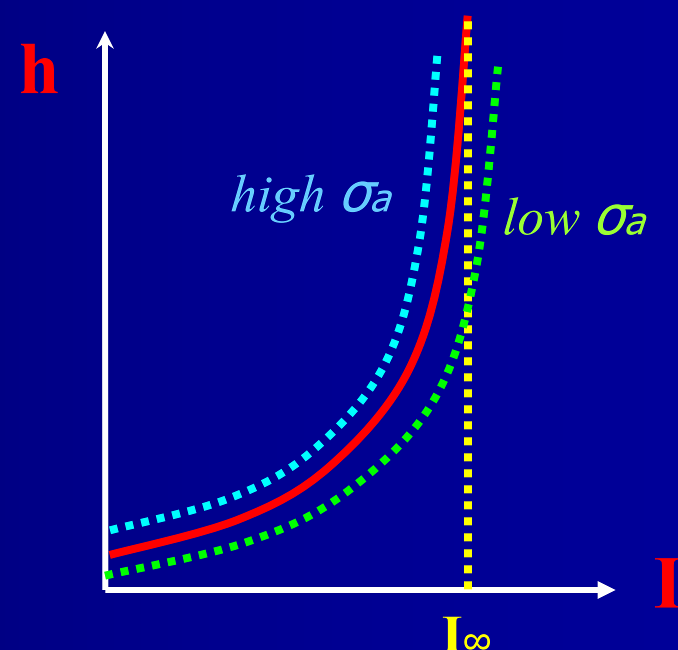
$$I = I_\infty \cdot e^{-\sigma_a \sec\psi \int_{h=0}^{\infty} N \cdot dh}$$



If h ↑ , σ ↓ and

If h ↑ , ψ ↑

Ionization Radiation (I)



Ionization Wavelength (λ) :

Ionization of O, O2 , NO and N2 in the Earth atmosphere due to radiation at a particular wavelength from the Sun. This wavelength is called "Ionization Wavelength".

For Ionization

Given wavelength to ionized → $$\lambda < \lambda_i$$ ← *Wave length that is corresponding maximum energy of ionized of a specific material*

Material	Required wavelength for ionized
N_2	796 Å
O	911 Å
O_2	1118 Å
NO	1340 Å

N2 *is the more difficult material is to be ionized !*

Ionization Efficiency (η) :

The ratio of the number of ions formed to the number of electrons or protons used in an ionization process OR no of ion-paires per unit absorbed energy.

$$\eta = \frac{No\ of\ ion - pairs\left(e^{n}s\right)}{Absorbed\ energy}$$

If $\lambda > \lambda i$ ➡ $\eta = 0$ (Because there are no ionized irons)

If $\lambda < \lambda i$ ➡ $\eta > 0$ (Because there are ionized irons in this case)

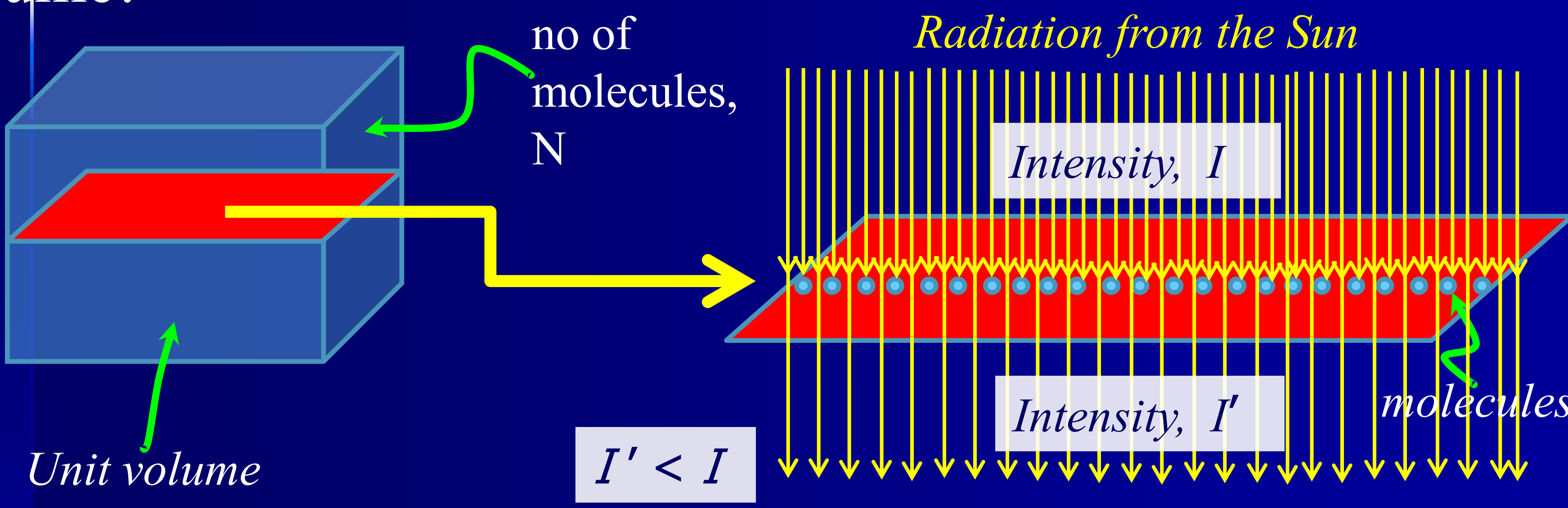
$$\eta = \frac{No\ of\ ion - pairs\left(e^{n}s\right)}{Absorbed\ energy}$$

➡ $No\ of\ ion - pairs\left(e^{n}s\right) \quad \alpha \quad Absorbed\ energy$

Electron Production Rate (Q)

Absorbed Intensity (*dI*)

If we assume there are N no of molecules in an unit volume!

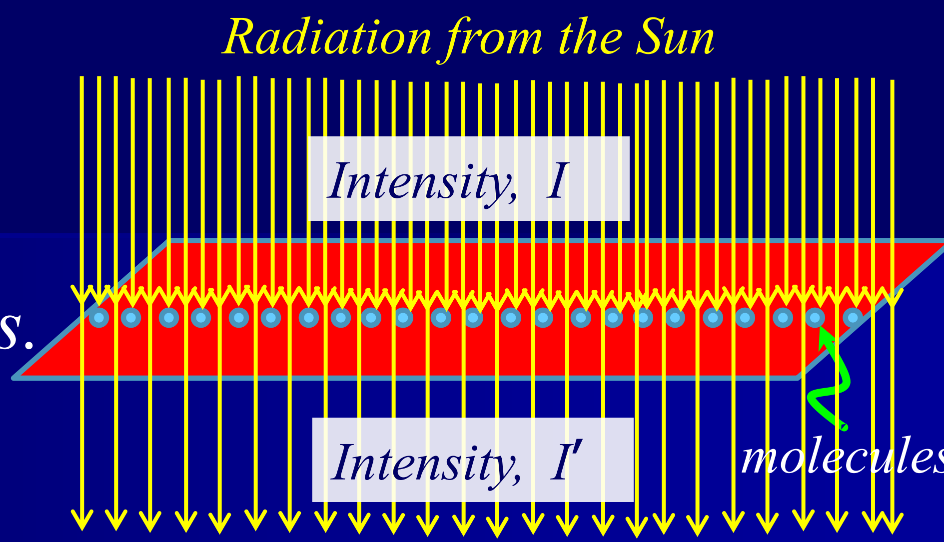


Intensity of the Radiation from the Sun (I) comes from the upside to the selected molecules layer. The intensity I' goes through that layer to the downside. $I > I'$ because the amount of $I - I'$ ($= dI$) radiation intensity stopped by the molecular layer.

Electron Production Rate (Q)

Absorbed Intensity (*dI*)

Assume σa *is the Absorption Cross-section area corresponding to the molecules.*



$I' < I$

Block intensity from the area N σa

Cross Area of the molecules in the Unit Area

$$\frac{dI}{I} = \frac{N\sigma_a}{1}$$

Where, $dI = I - I'$.

Intensity from the Sun

Intensity I comes to the cross area 1m²

Cross Area of the molecules in the Unit Area

Absorbed Intensity

$$dI = N\sigma_a I$$

Intensity of the Radiation from

Electron Production Rate (Q)

No of ion pairs (electrons or positive ions) produce in an unit volume per second is called **Electron Production Rate** (Q)

$$Q = \eta \times dI$$

$$Q = \eta \times N \sigma_a I$$

$\eta \times \sigma_a =$ Ionization Cross Section (σ i)

If the gas is not Ionized; Ionization Cross Section, σ i = 0 because η = 0 .

Electron Production Rate (Q)

Electron Production rate

$$Q = \eta \times N \sigma_a I$$

Intensity of Ionizing Radiation at height h

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

$$\therefore \quad Q = \eta \times N \sigma_a \left(I_\infty \cdot e^{-\sigma_a \sec\psi \int_{h=0}^{\infty} N \cdot dh} \right)$$

But we know;

$$\int_{h=0}^{\infty} N \cdot dh = NH$$

Where H is the "Scale Height"

Electron Production Rate (Q)

$$\int_{h=0}^{\infty} N \cdot dh = NH$$

Total number of molecules from surface of the Earth to infinity !

$$\therefore \quad Q = \eta \sigma_a N \, I_\infty \cdot e^{-\sec\psi . \sigma_a NH}$$

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

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

Substitute ; $\sigma_a NH = e^{-Z}$ *Where Z is (some) height*

Electron Production Rate (Q)

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

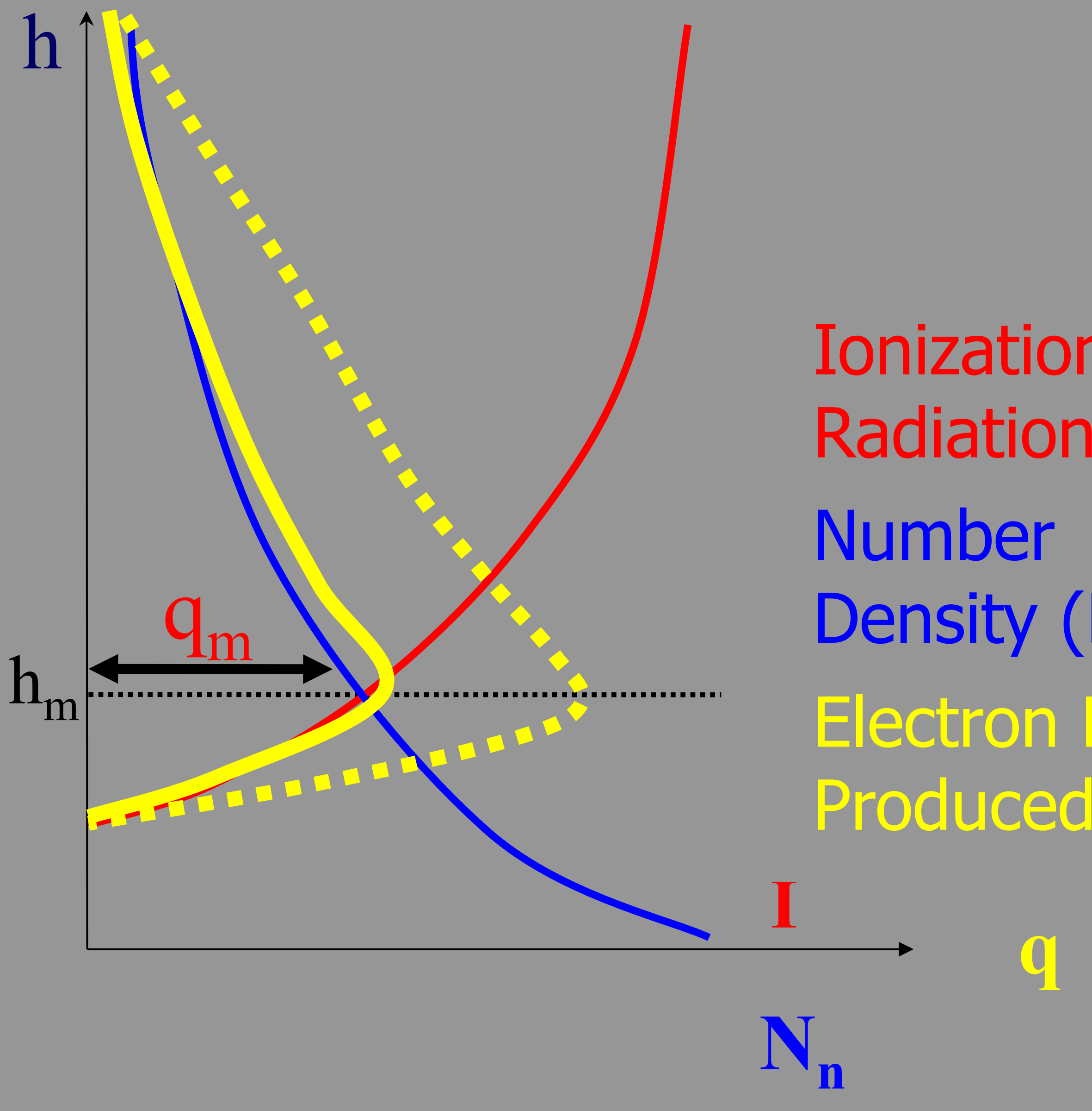
Where N and Z are dependent variables, because

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

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]



Ionization Radiation (I)

Number Density (N)

Electron Pairs Produced Rate [q]

Find the value of Q_m

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

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

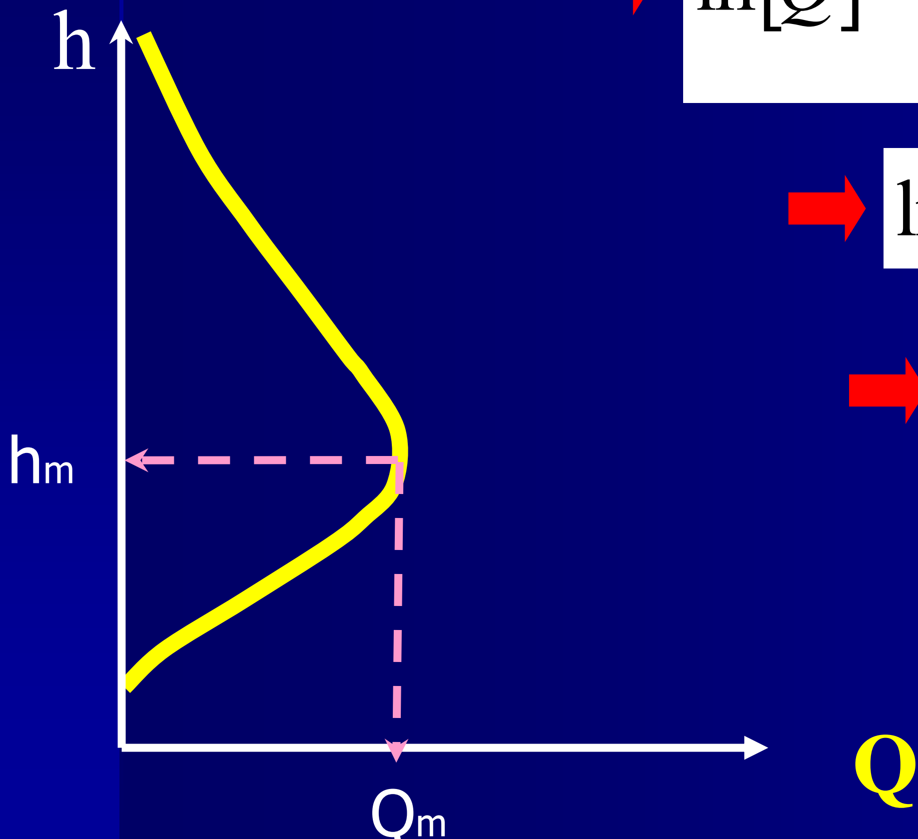
$$\ln[Q] = \ln\left[\frac{\eta \cdot I_\infty}{eH}\right] + \ln\left[e^{\left(1-Z-\sec\psi\cdot e^{-Z}\right)}\right]$$

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 ;

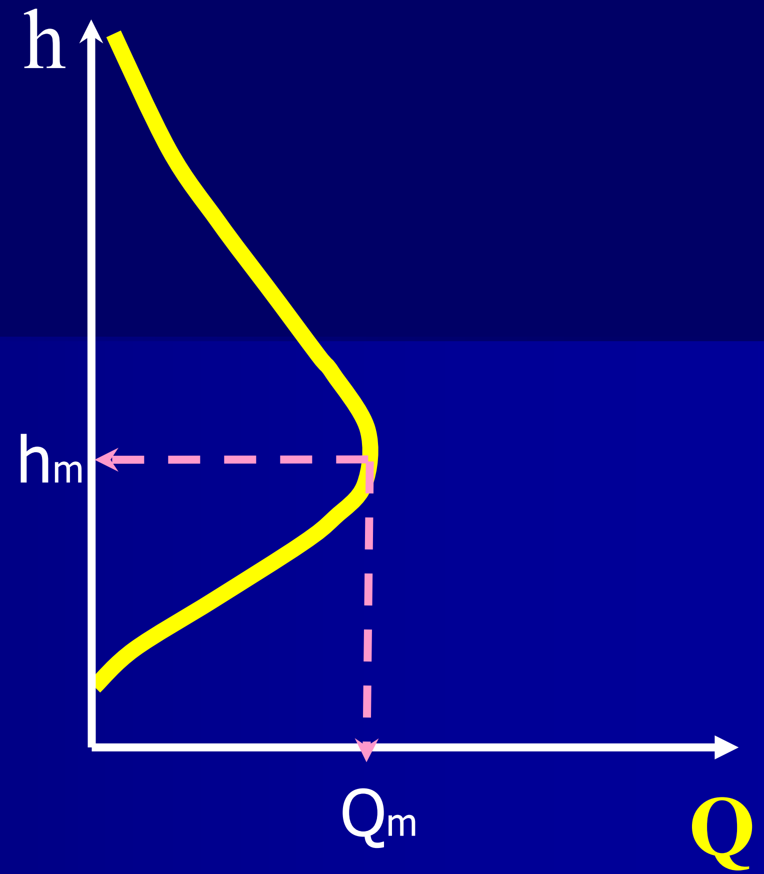
$$\frac{d(\ln[Q])}{dz} = 0$$

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 ;

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

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

We know,

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

Find the value of Q_m

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

For find the maximum ;

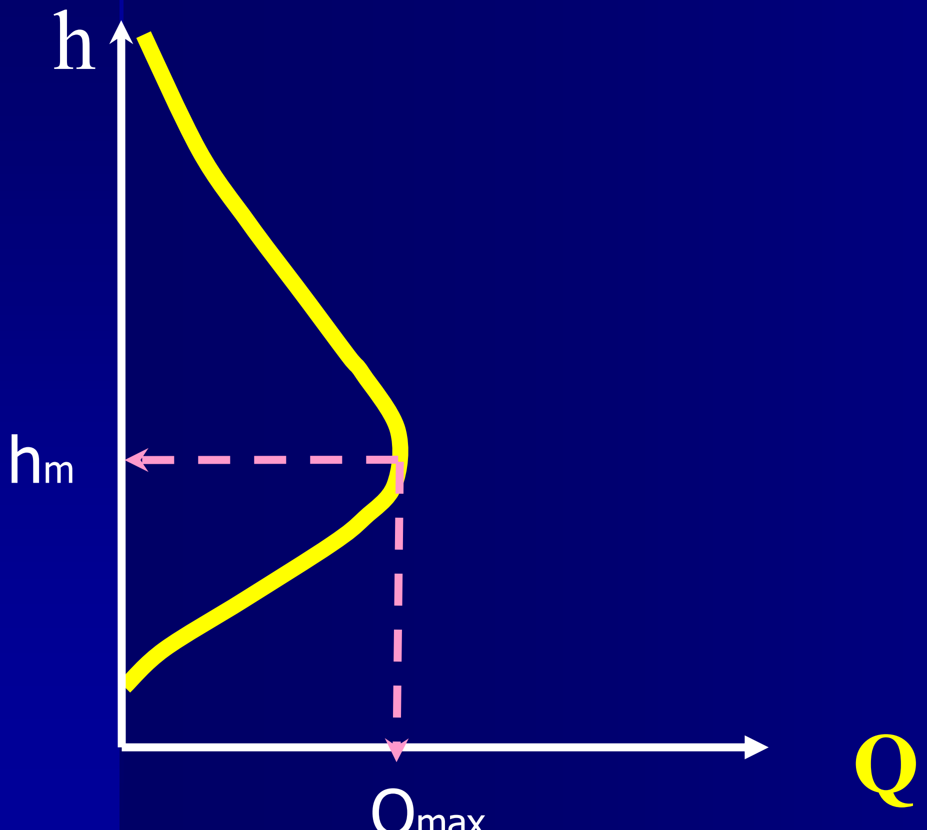
$$\frac{d(\ln[Q])}{dz} = 0$$

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

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

Using equation – 01 :

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



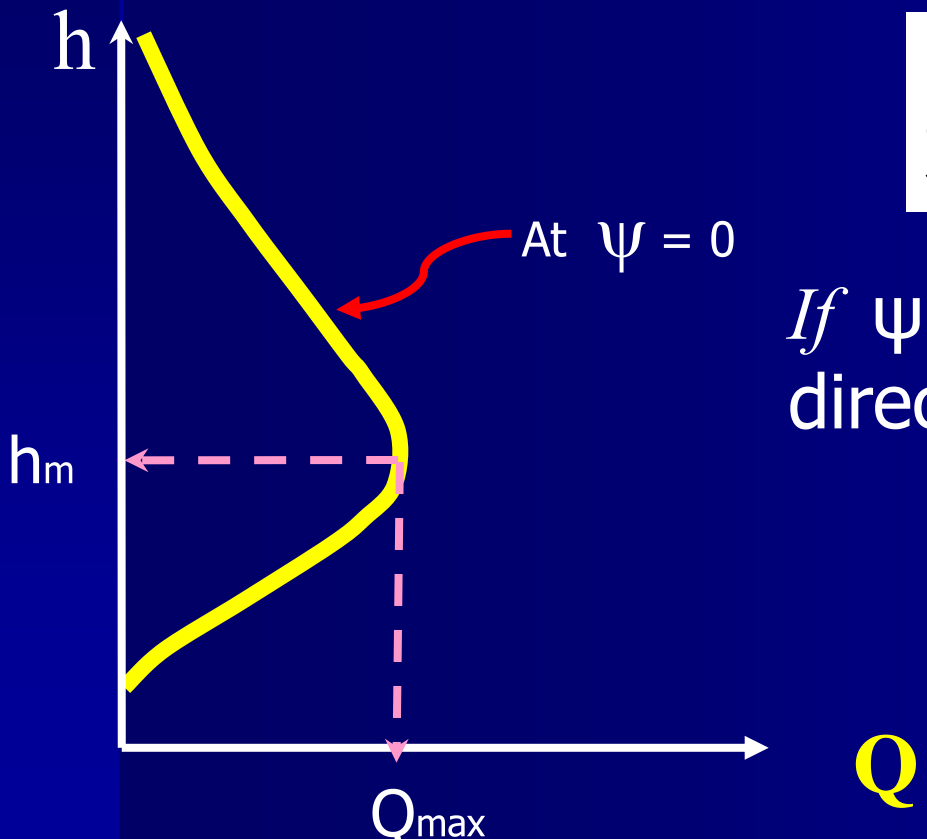
Find the value of Q_m

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

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

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 :

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

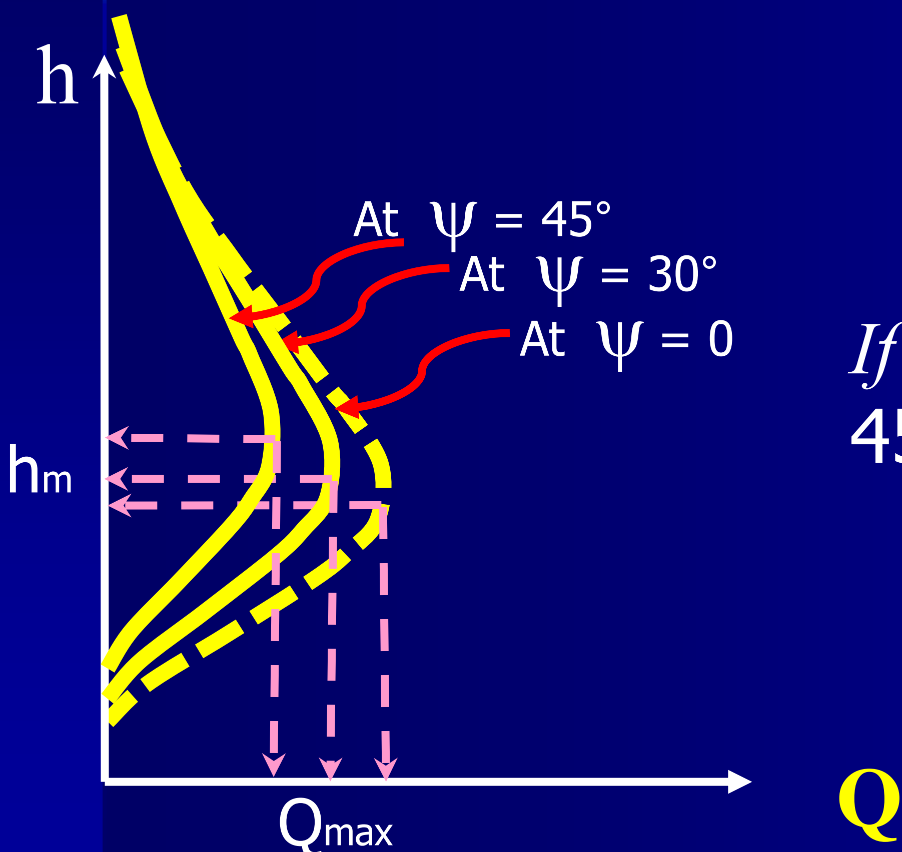
Find the value of Q_m

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

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

$$Q_{max} = \frac{\eta \cdot I_\infty}{eH} (Cos 30)$$

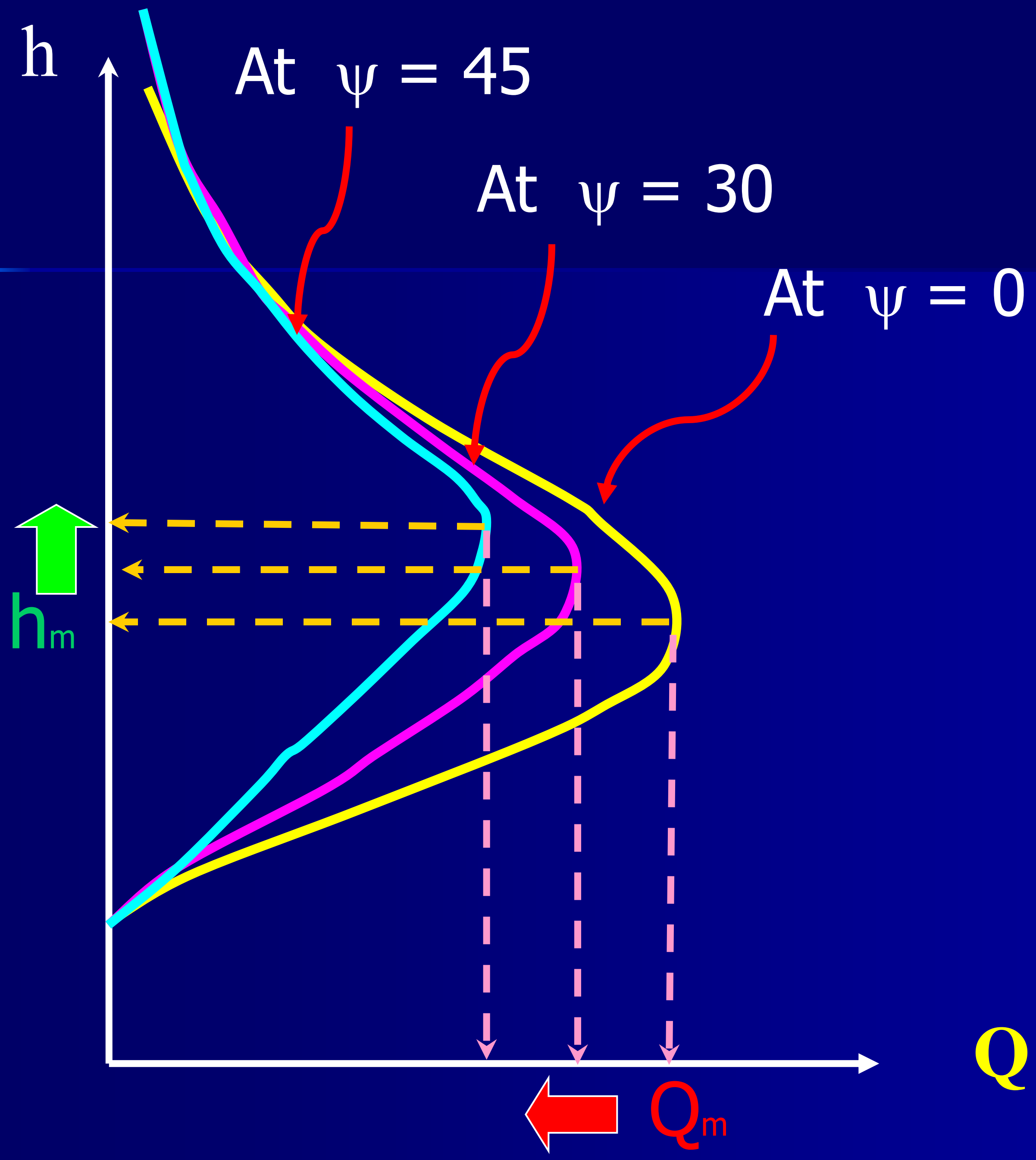
$$Q_{max} = \frac{\eta \cdot I_\infty}{eH} (0.8660)$$



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

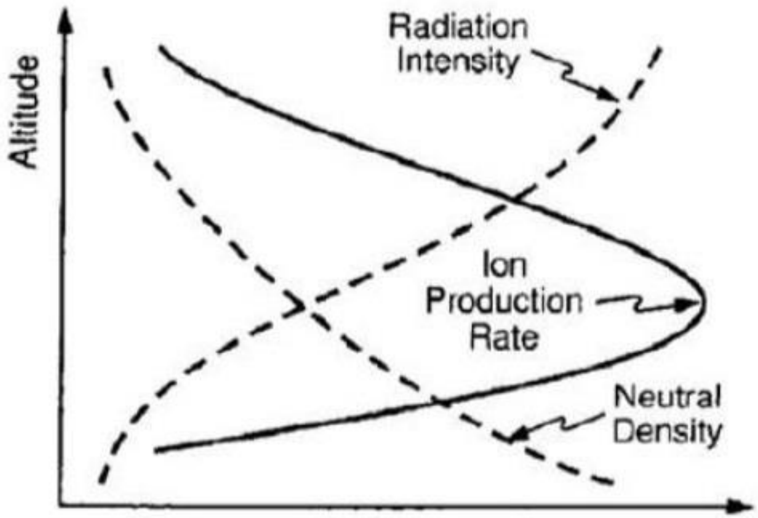
$$Q_{max} = \frac{\eta \cdot I_\infty}{eH} (Cos 45)$$

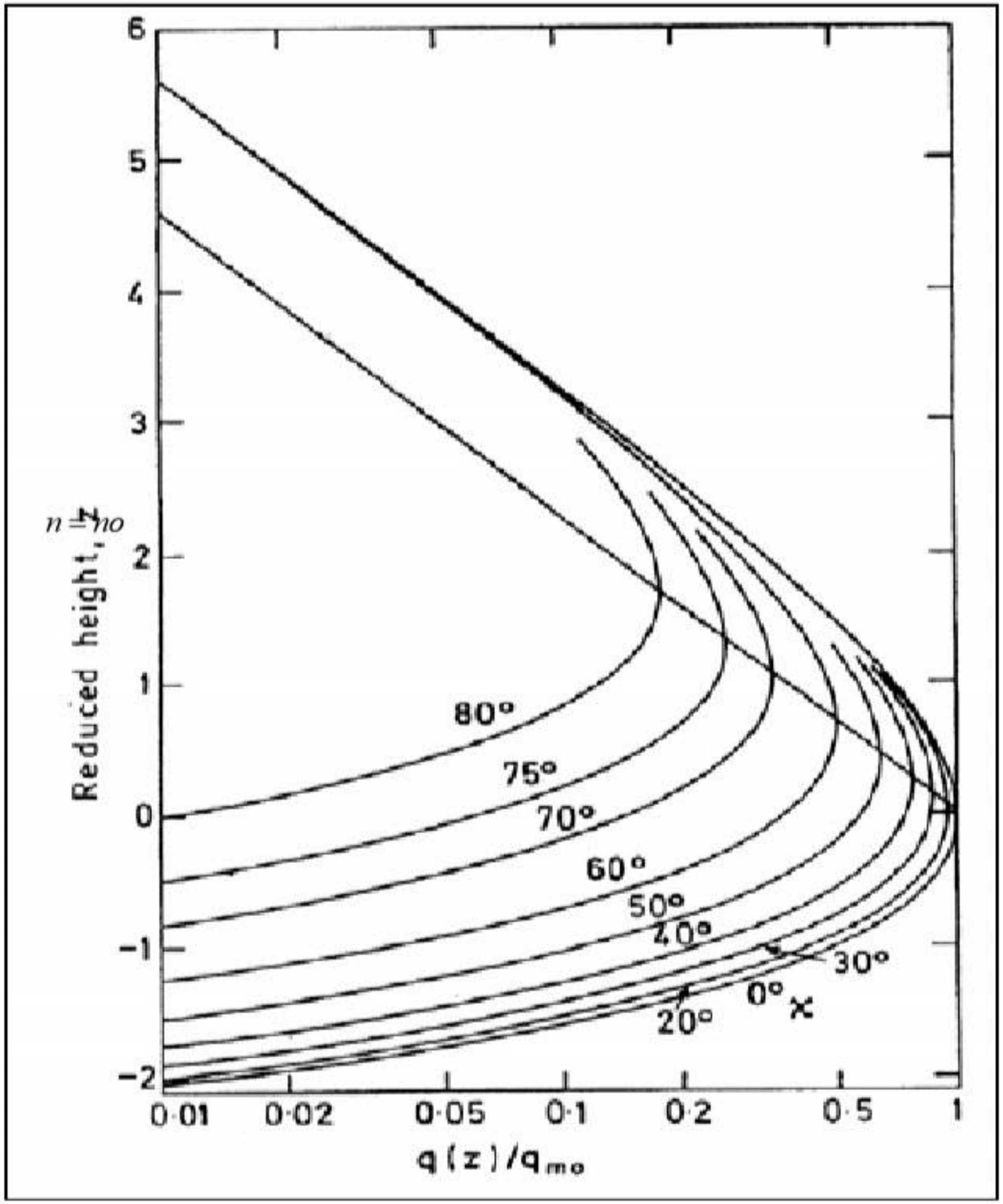
$$Q_{max} = \frac{\eta \cdot I_\infty}{eH} (0.7071)$$



h
At ψ = 45
At ψ = 30
At ψ = 0
hm
Q
Qm

Chapman's Production Profile

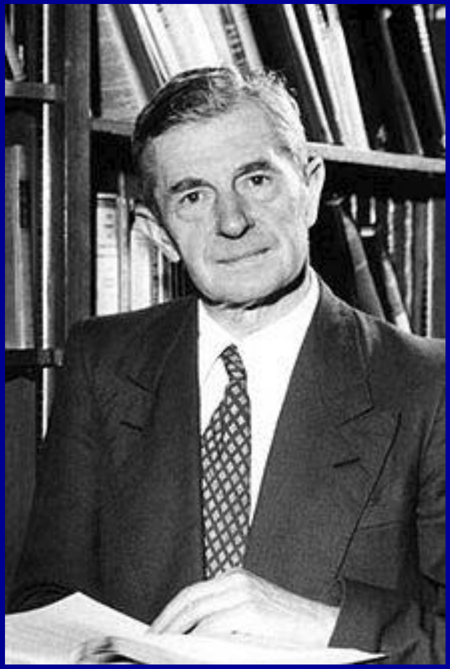


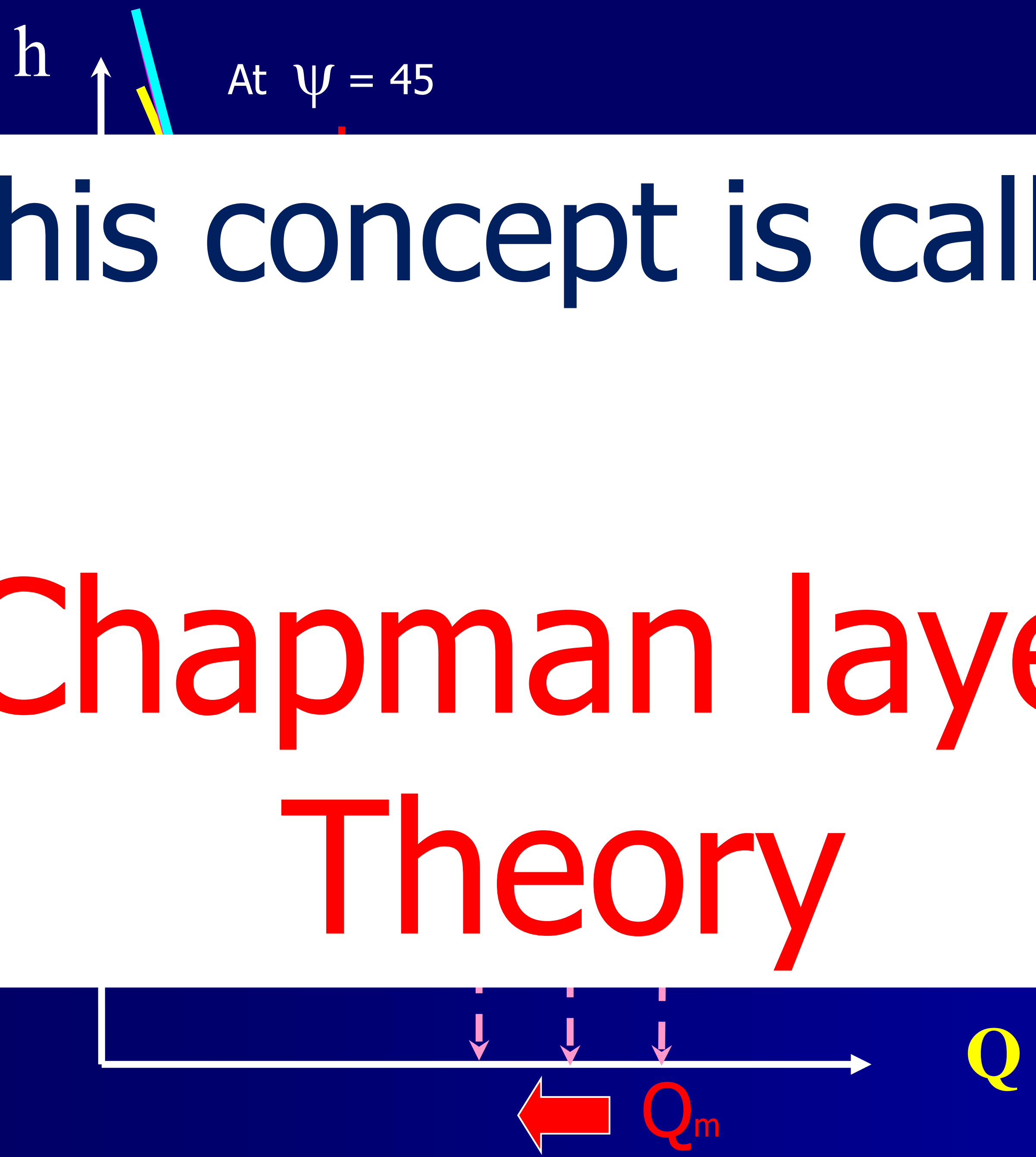


That means ψ is increasing, the maximum value of the Electron Production Rate is decreasing. For that Molecular Number Density of the ionosphere should be decreasing.

.: Region of the Qmax 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


Thank You !
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