Space & Atmospheric Physics

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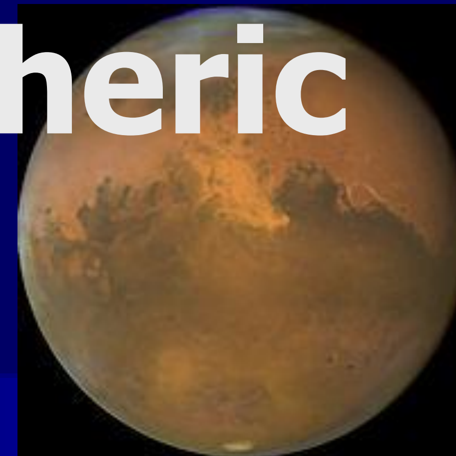
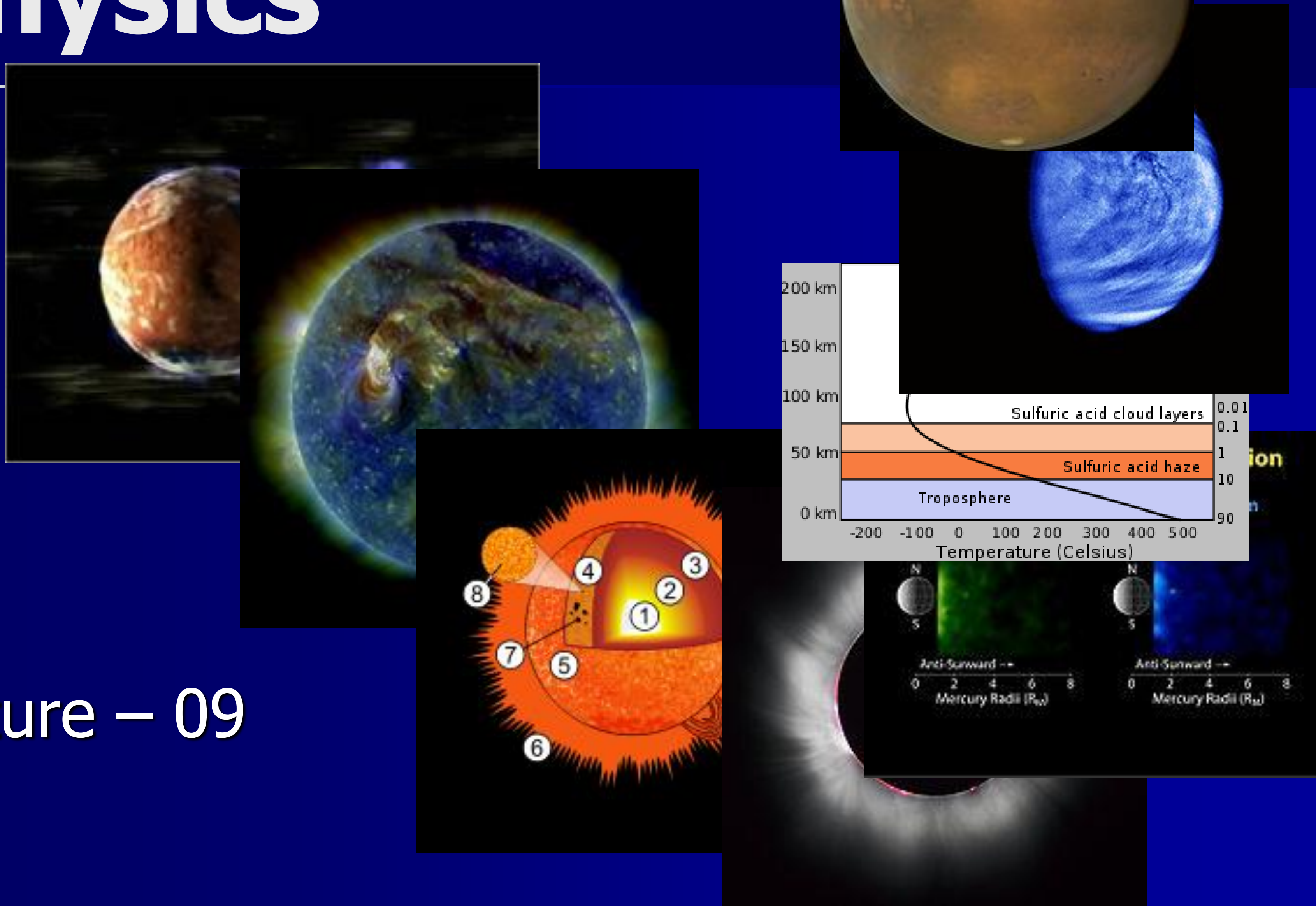
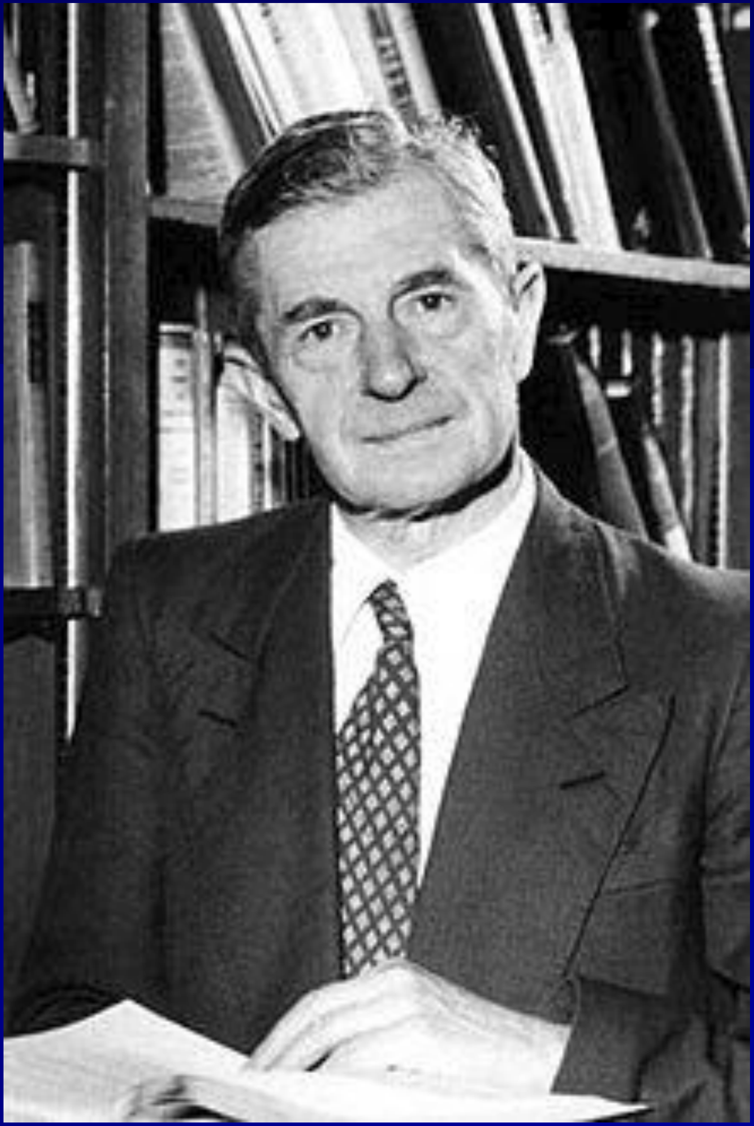




Lecture – 09

Chapman layer Theory

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.

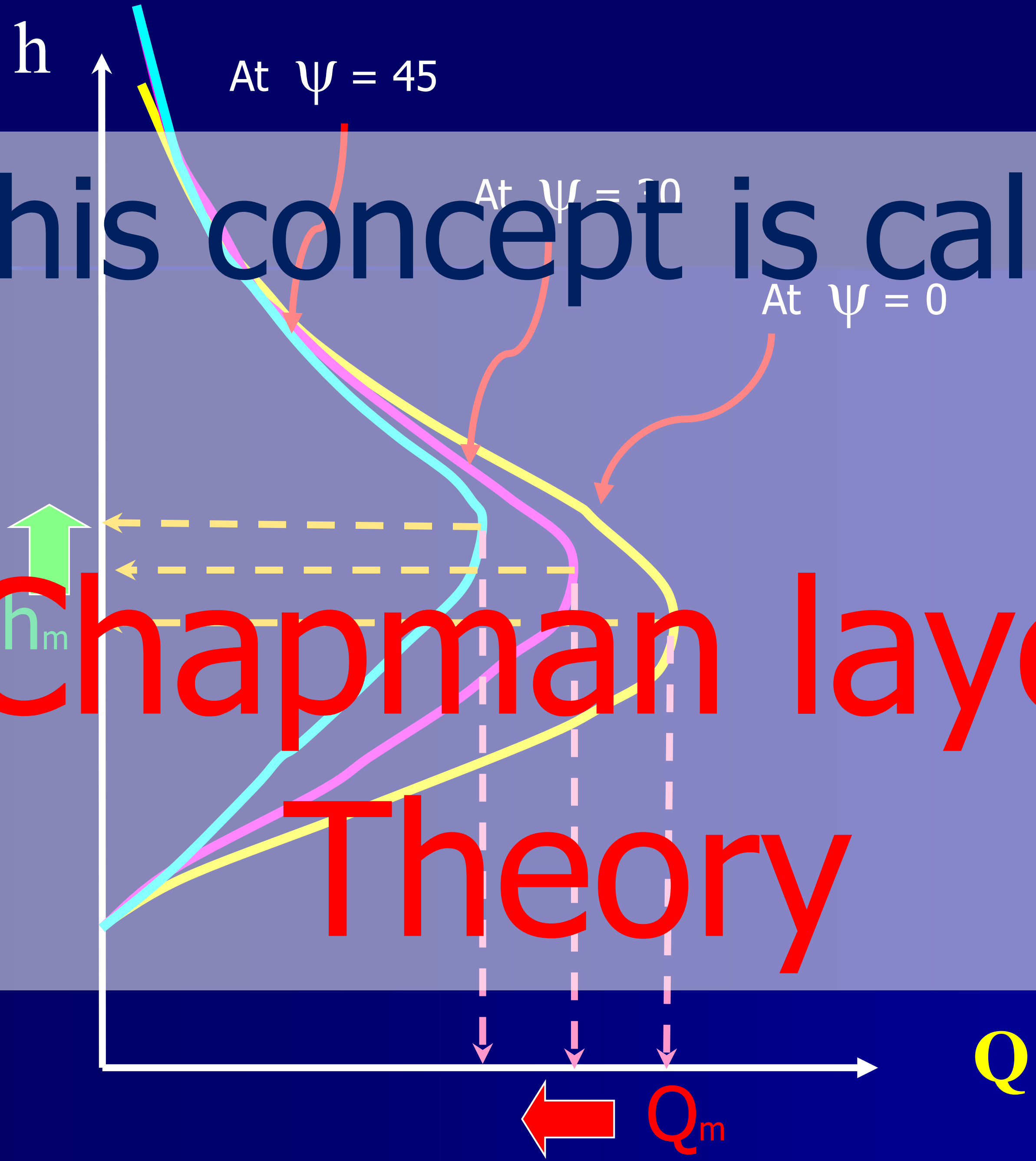


If ψ is increasing, the maximum value of the Electron Production Rate is decreasing. For that Molecular Number Density of the ionosphere should be decreasing.

.: 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.

This concept is called

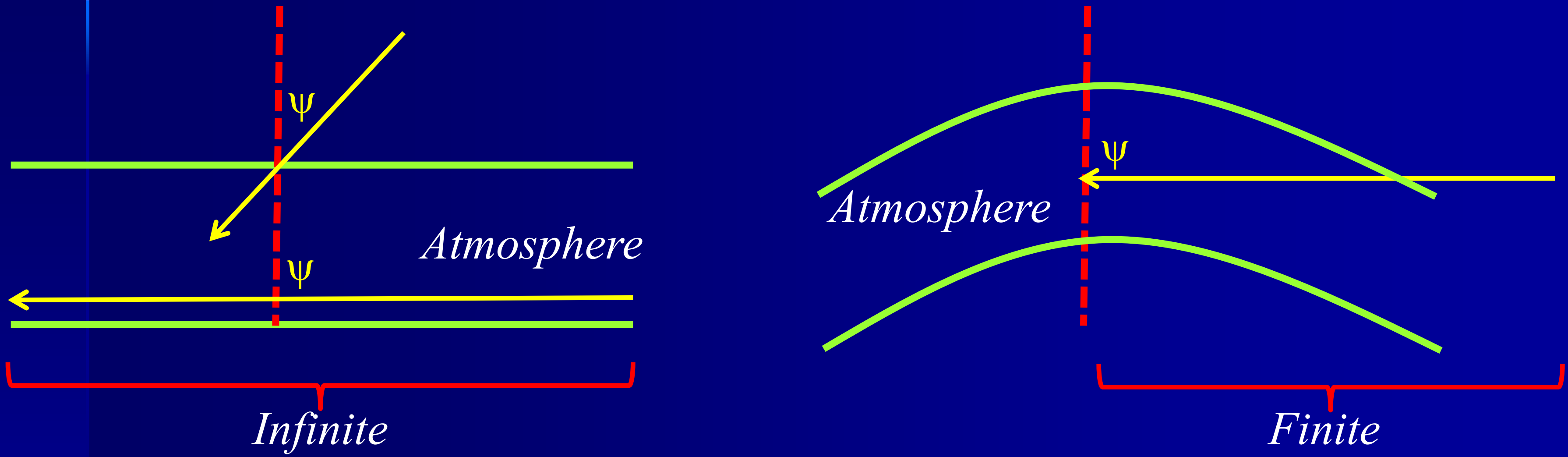
Chapman layer Theory



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.

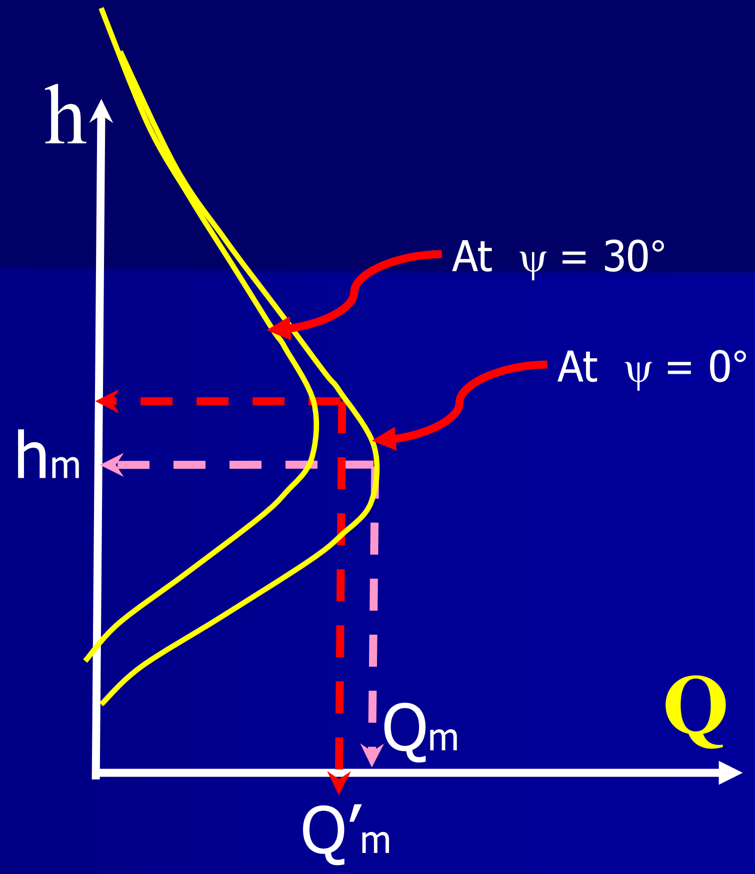


If ψ = 90°, according to our formula and logics, N → 0 ! That means Qmax is going to infinity. This is theoretical. But practically this should be large value; but not infinity.

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 ...

Chapman layer Theory

Electron Production Rate (Q)

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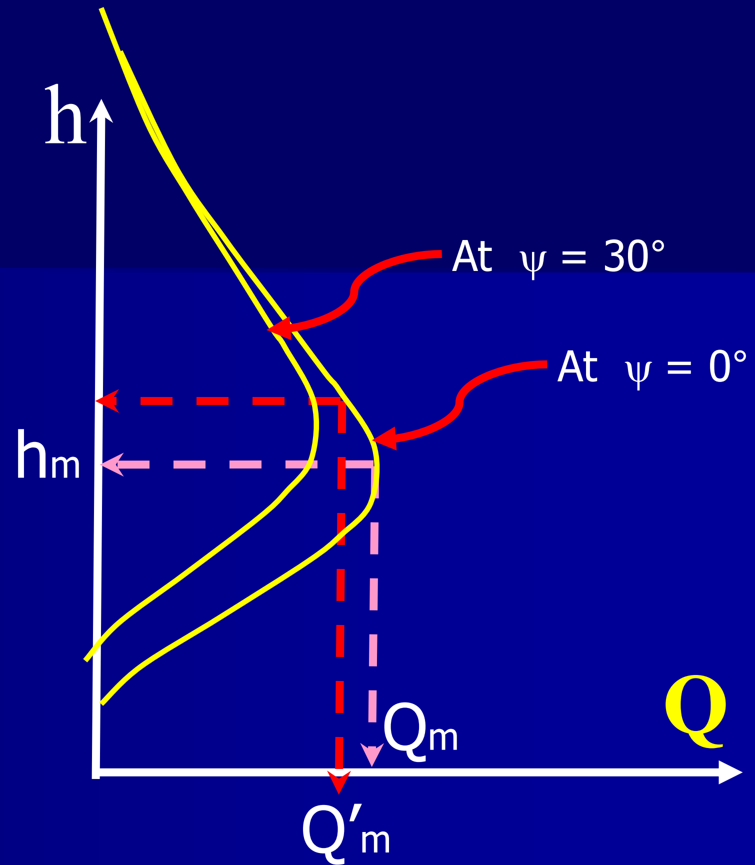
. . .

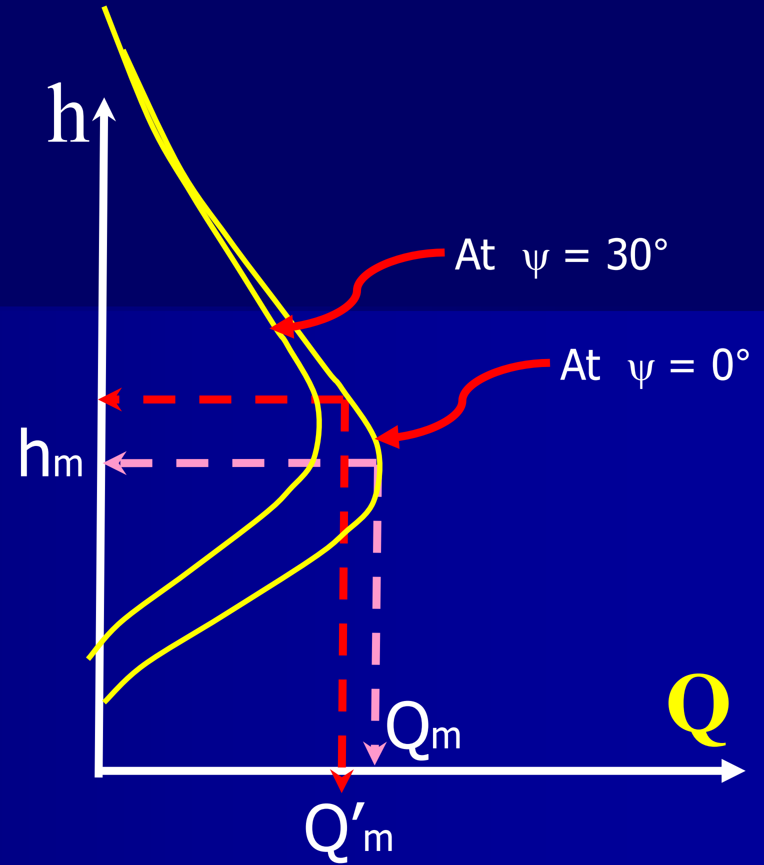


- **At the night** there is **no height to corresponding to our value Q'm** !
  Because our graph [according to Chapman Layer Theory] does not exist at night.

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**.

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**.
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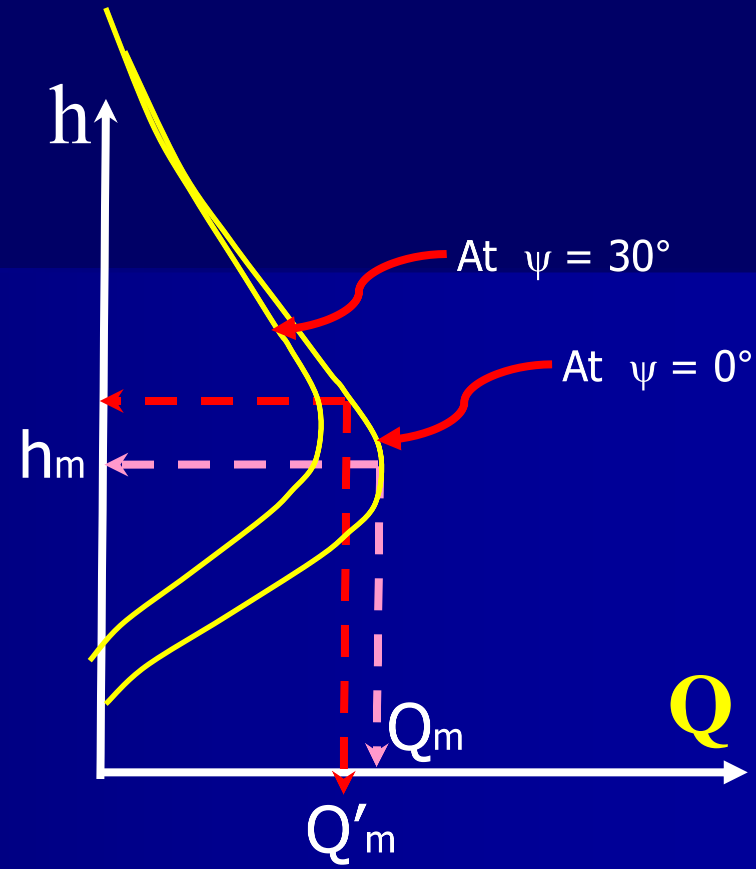
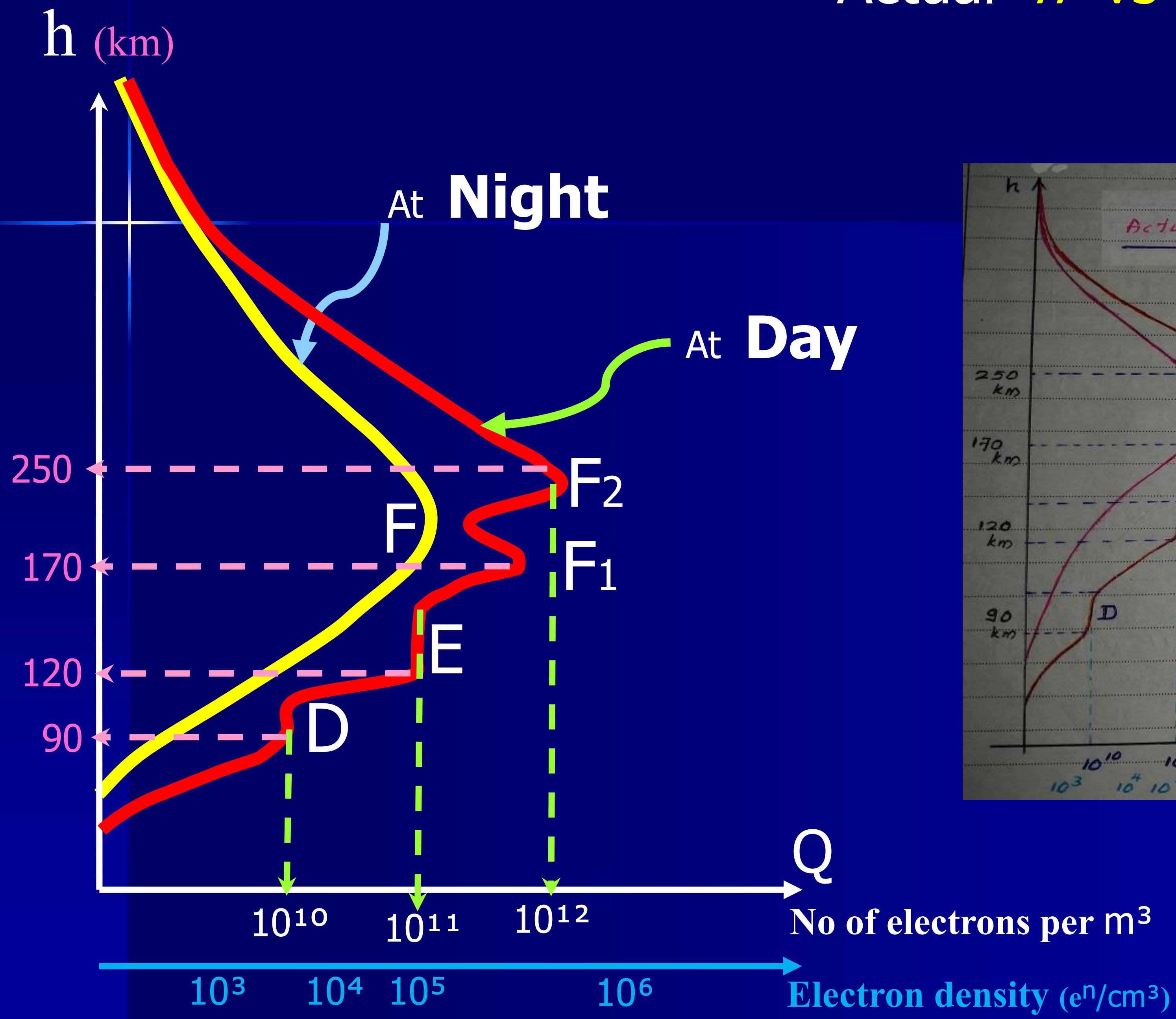
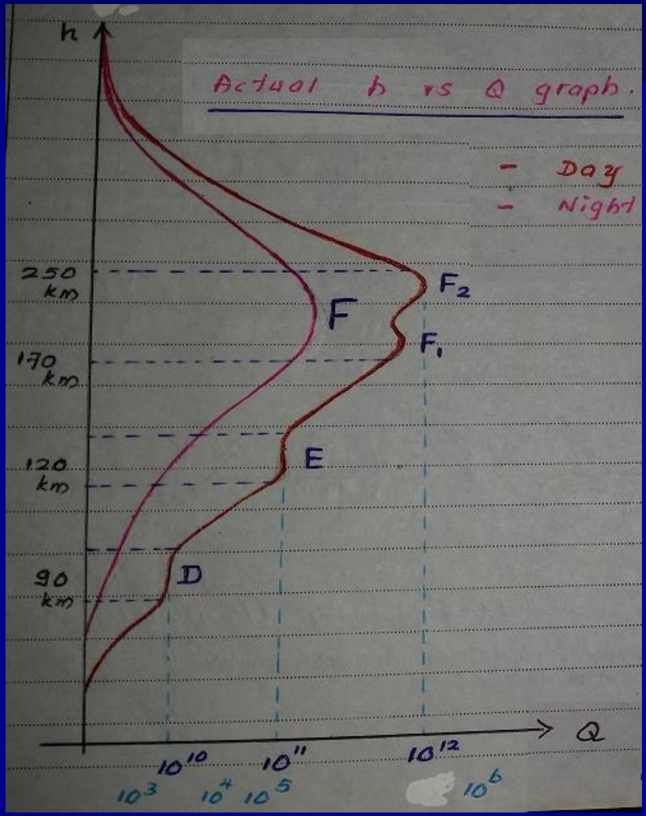
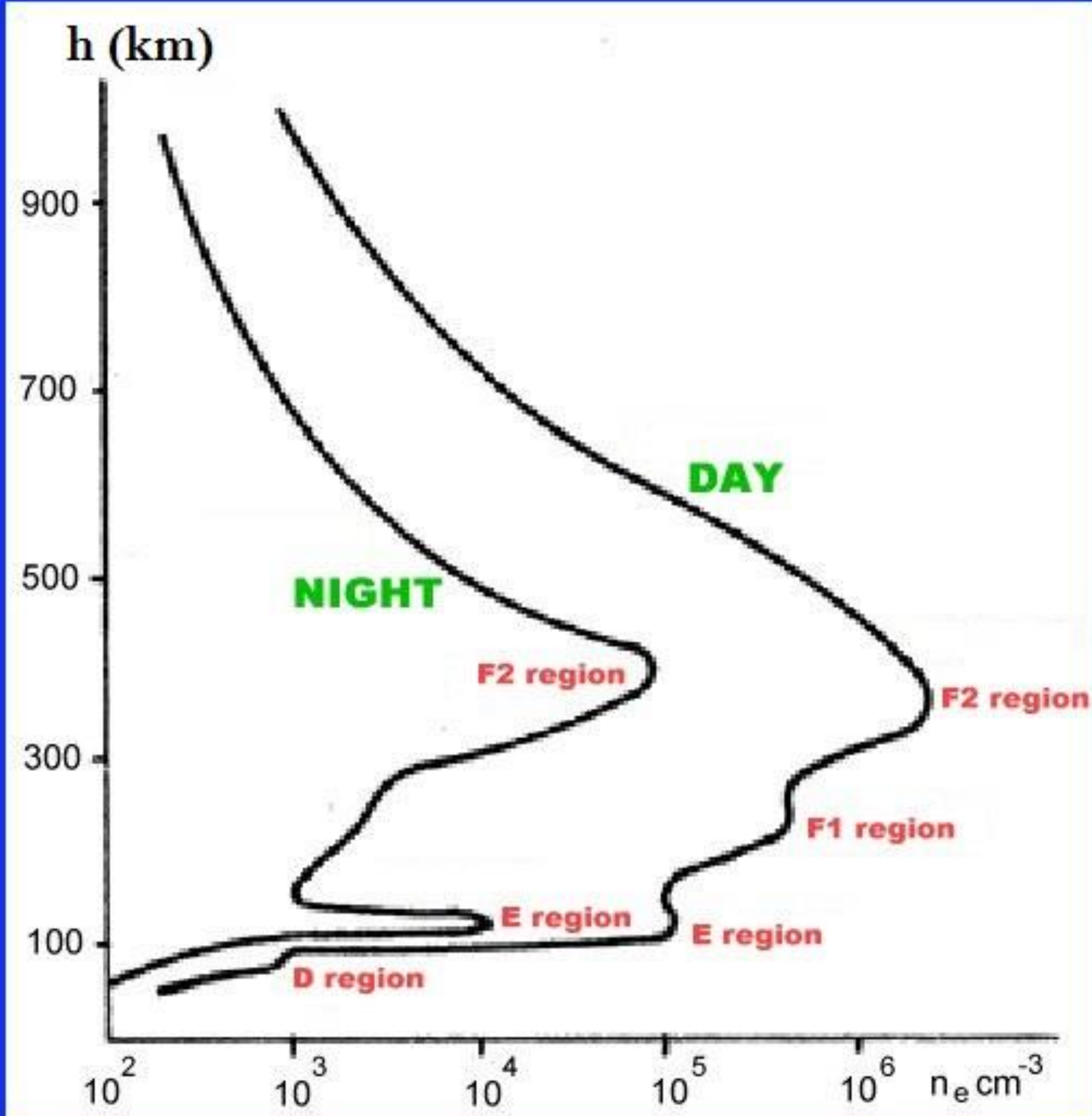


:. We should consider all the effects that we discussed, before plotting the graph of h vs Q.

Actual *h* vs *Q* graph





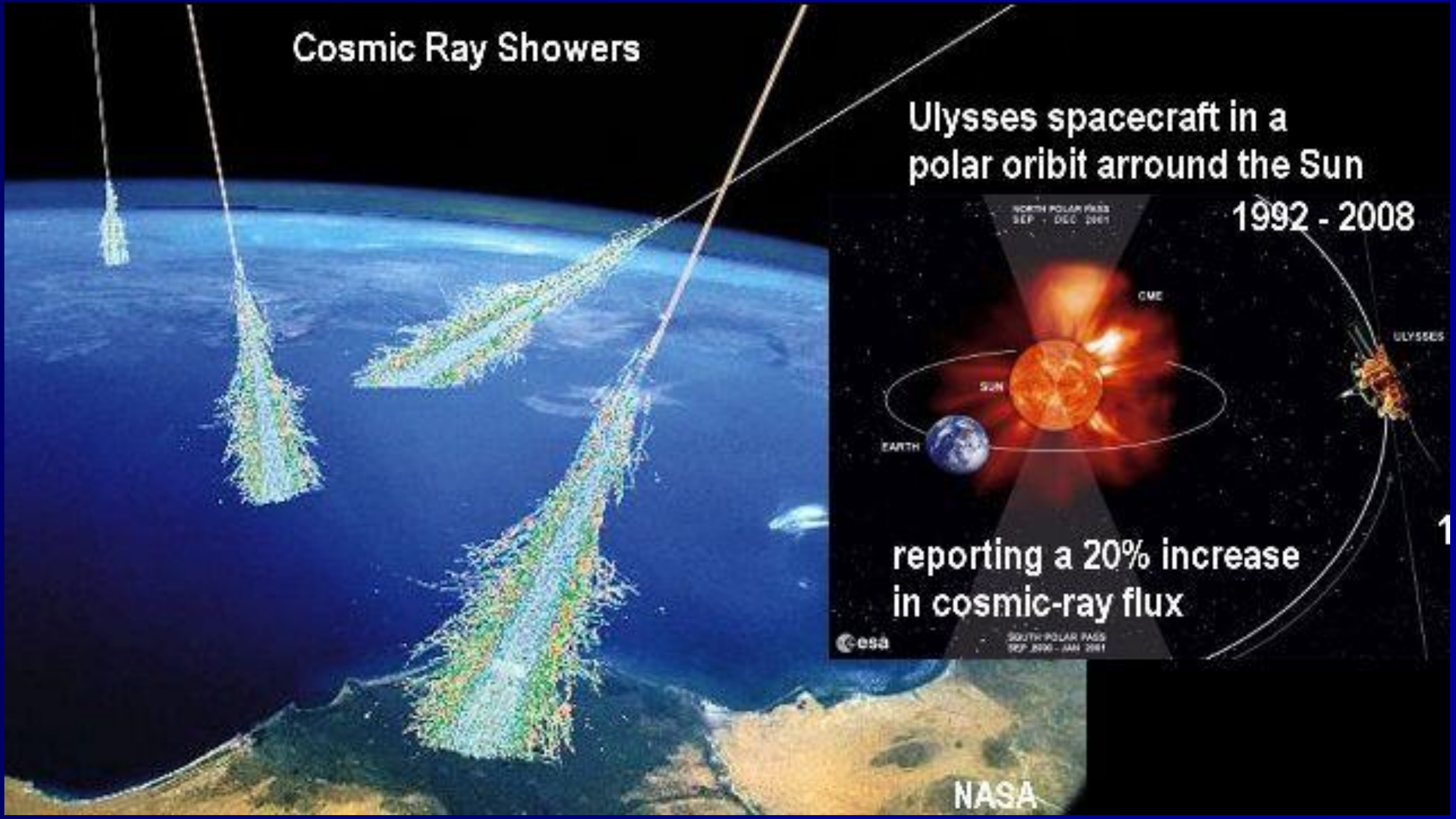


h (km)
900
700
500
300
100
DAY
NIGHT
F2 region
F2 region
F1 region
E region
E region
D region
10^2
10^3
10^4
10^5
10^6
n_e cm^{-3}

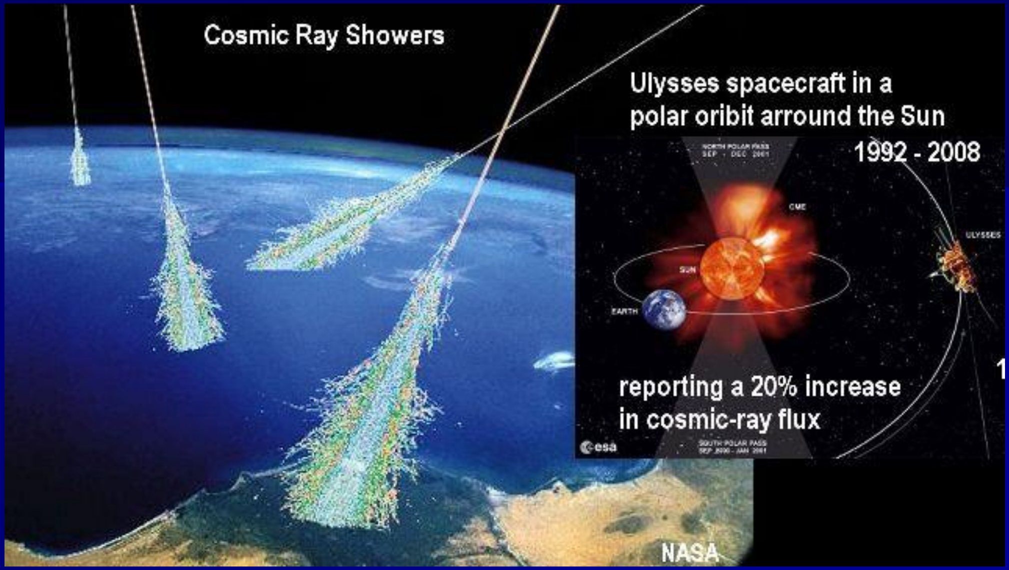
Chapman layer Theory

- 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 !

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



Chapman layer Theory



- 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 !

Plasma Frequency

Practically all of our knowledge about the ionosphere has come through radio sounding. Only in the late fifties and early sixties some measurements of local electron densities were made in the **upper ionosphere** using rockets and satellites, but even these methods have now been abandoned in favor of the more efficient **top-side sounder** satellites which again use radio waves to probe the top side of the ionosphere.

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 fp the waves will pass through the layer, whereas if **f < fp** , the waves will be reflected back. This critical frequency is called the **Plasma Frequency, fp** and is proportional to the square root of the **electron density, N** of the Layer

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

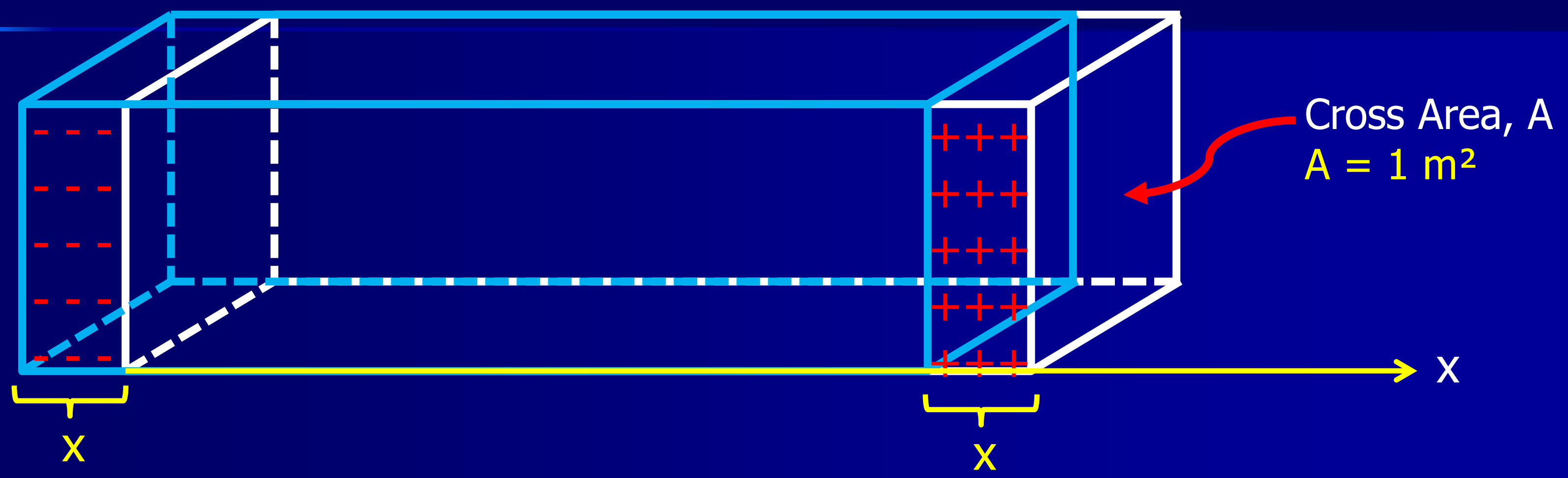
Plasma Frequency

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 $\mathbf{10^4}$ 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 Ni and Ne 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

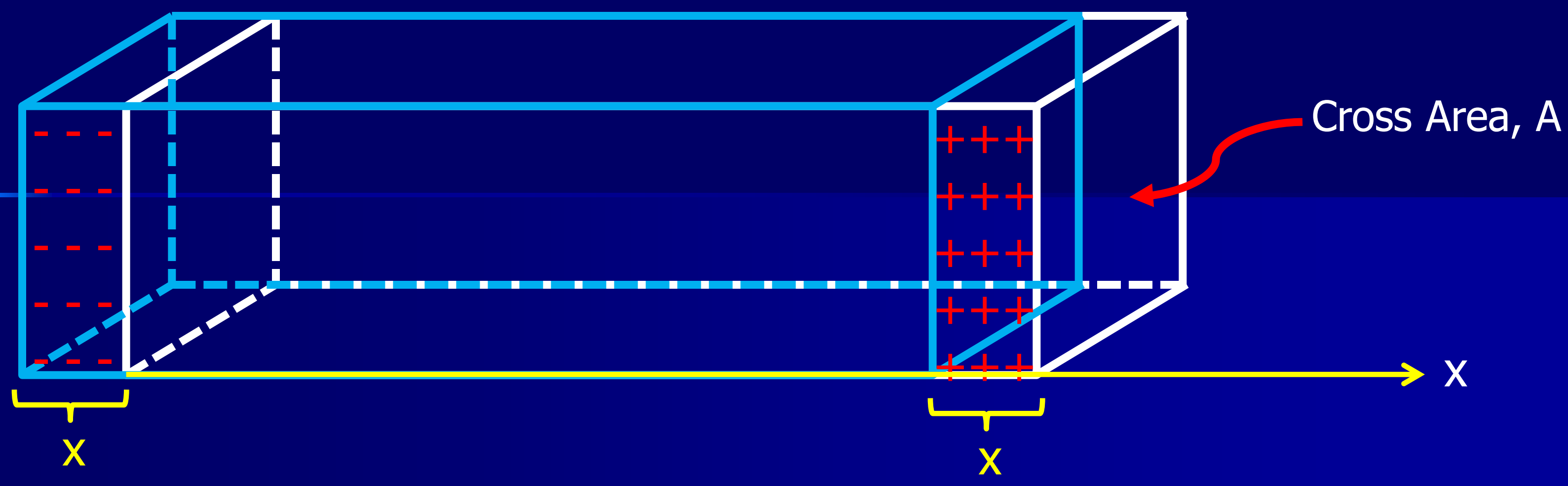
Assuming charge distribution of +ve ions and –ve electrons are separated like the following figure,



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)

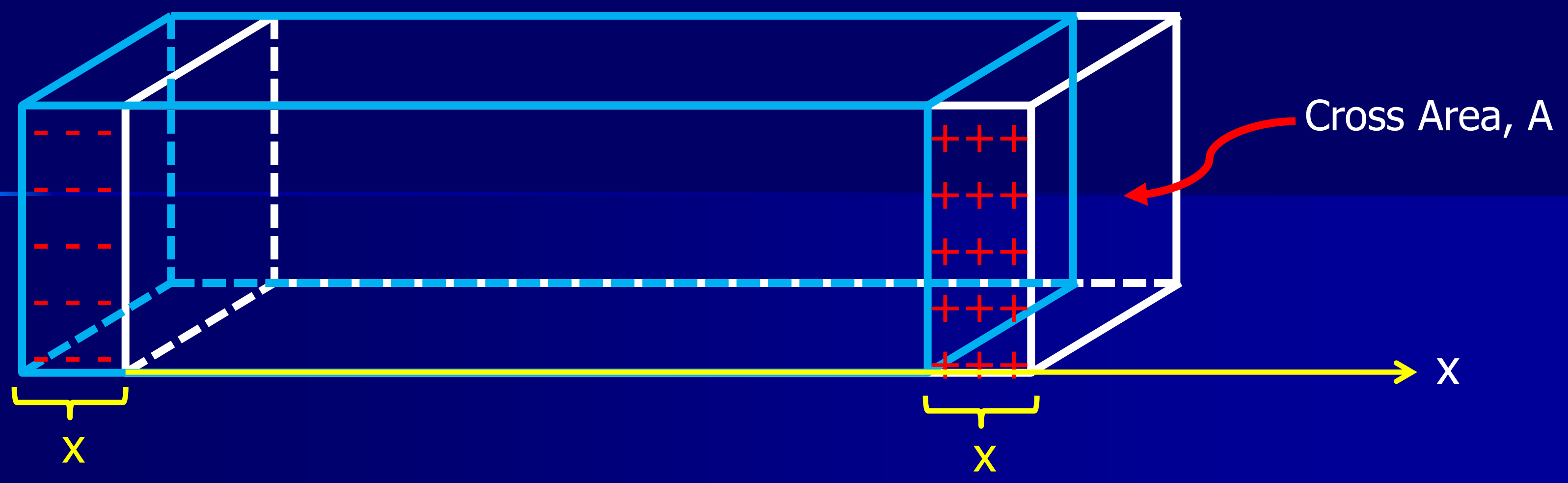
.: Surface charge density = $e \times xN$

(Where e is charge of an electron)

$$\sigma = eNx$$

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

Plasma Frequency



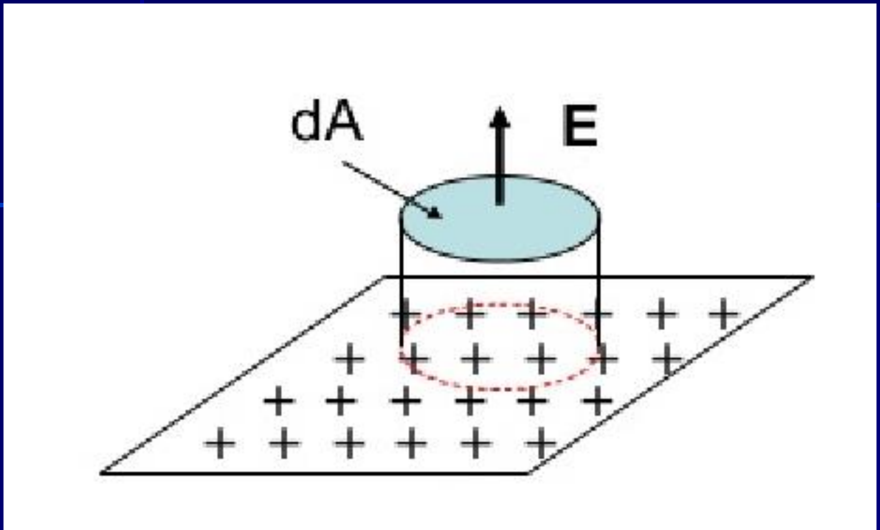
(As equal and opposite charge density develops on the opposite face. The x-direction electric field, generally inside the slab : [Using Gauss law, if we consider this is like a parallel plate situation])

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

(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 :

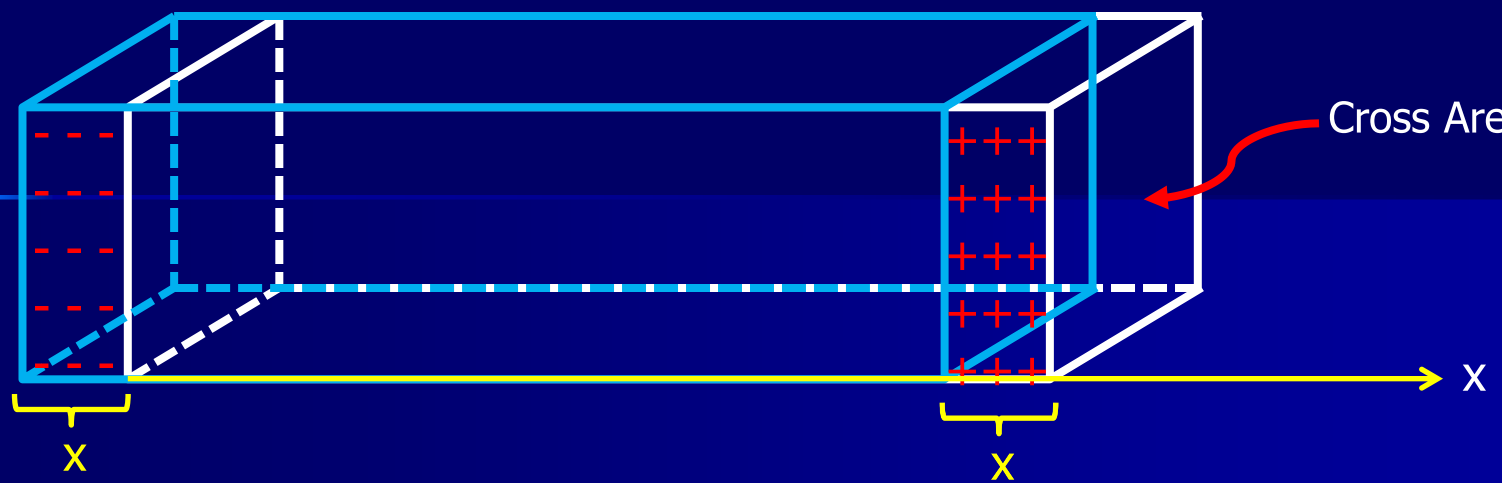
$$E \cdot dA = \frac{\sigma . dA}{\varepsilon_o} \Rightarrow \mathbf{E} = \frac{\sigma}{\varepsilon_o}$$

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



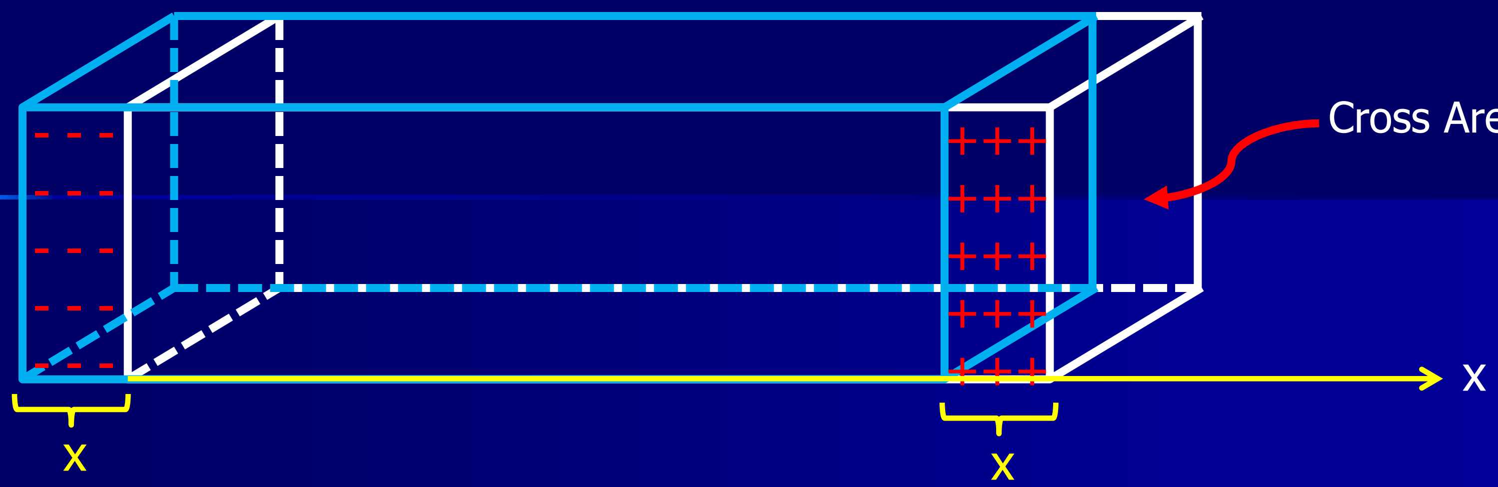
$$F = e \times E \Rightarrow F = e \times \left(-\frac{\sigma}{\varepsilon_o} \right) \Rightarrow F = e \times \left(-\frac{eNx}{\varepsilon_o} \right)$$

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

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

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

Plasma Frequency



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

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

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

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, *fp* 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.

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

$$\rightarrow f_p = 9\times10^6 \rightarrow f_p = 9\ MHz$$

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** (actually **F2** region)

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

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Ionospheric regions

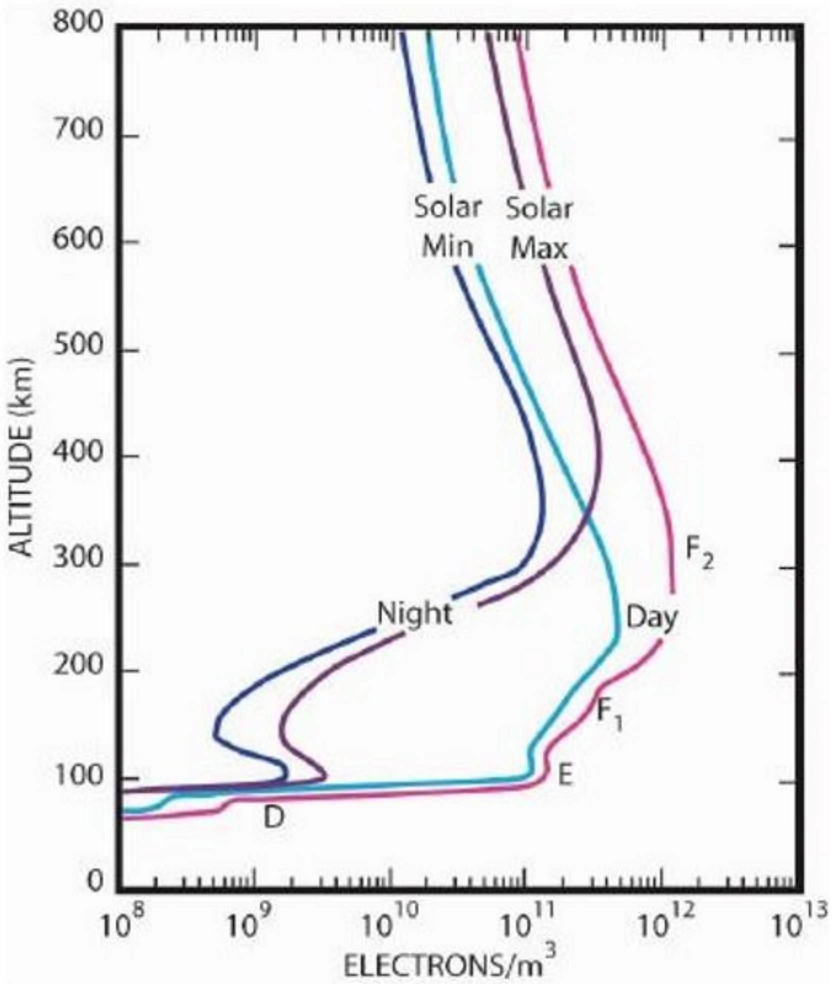


Figure: Typical ionospheric electron density profiles.

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}

$$f_p = 9N^{1/2} \Rightarrow f_p = 9\times(10^8)^{1/2} \Rightarrow f_p = 9\times10^4 \Rightarrow f_p = 90 \ kHz$$

$$\Rightarrow f_p = 9\times(10^{10})^{1/2} \Rightarrow f_p = 9\times10^5 \Rightarrow f_p = 900 \ kHz$$

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}

$$f_p = 9\,N^{1/2} \;\rightarrow\; f_p = 9\times\left(10^{10}\right)^{1/2} \;\rightarrow\; f_p = 9\times 10^{5}$$

$$\rightarrow\; f_p = 900\ kHz$$

$$\rightarrow\; f_p = 9\times\left(10^{11}\right)^{1/2} \;\rightarrow\; f_p = 9\times 10^{5}\times\sqrt{10}$$

$$\rightarrow\; f_p = 2.85\ MHz$$

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} .

$$f_p = 9N^{1/2} \Rightarrow f_p = 9\times\left(10^{11}\right)^{1/2} \Rightarrow f_p = 9\times10^5\times\sqrt{10}$$

$$\Rightarrow f_p = 2.85\ MHz$$

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

$$\Rightarrow f_p = 9\ MHz$$

That means, if we send a Radio Wave of frequency 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.

In conclusion, the plasma frequency of an ionized region is the natural frequency at which the electrons of the region would oscillate about their position of equilibrium if their original condition was disturbed.

The disturbance in this case is caused by the **electric field** of the wave which also varies in a harmonic fashion with the frequency *f* of the **Radio Wave**. i.e.;

$$E_x = E_o \cos \omega t \quad \Rightarrow \quad E_x = E_o \cos 2\pi f t$$

As a result, the electrons become forced harmonic oscillators because they are forced to oscillate in the frequency of the radio wave rather than in their own natural plasma frequency.

The equation of the forced harmonic oscillator with an external force F is;

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

$$F_o \cos\omega t - \frac{e^2 N x}{\varepsilon_o} = m\frac{d^2x}{dt^2}$$

$$m\frac{d^2x}{dt^2} = -m\frac{e^2 N}{\varepsilon_o m}x + F_o \cos\omega t$$

$$m\frac{d^2x}{dt^2} = -m\omega_p{}^2 x + F_o \cos\omega t$$

And its solution is : $x = x_o \cos\omega t$

Where, $x_o = \frac{F_o}{m\left(\omega^2 - \omega_p^2\right)}$

$$x = x_o \cos \omega t$$ Where, $$x_o = \frac{F_o}{m\left(\omega^2 - \omega_p^2\right)}$$

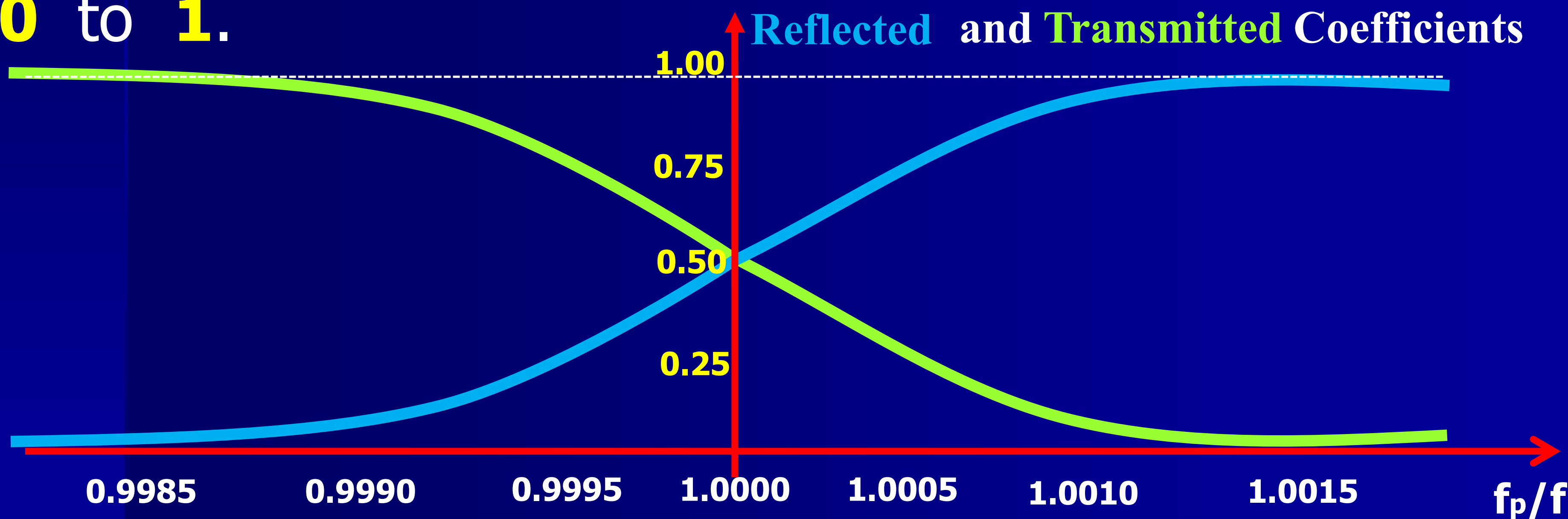
When the two frequencies are far apart, the **amplitude xo is small** and **tends to zero** for **large values of ω**.

When on the other hand **ω approaches ωp**, the **amplitude of the oscillation becomes very large**. It is very much like pushing a child on a swing. One gets the best results when the periodic pushes are coordinated with the natural period of the swing.

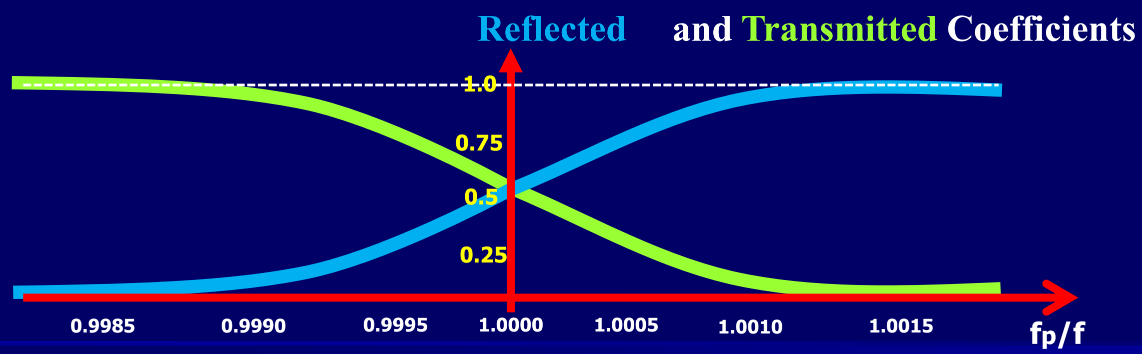
At **ω = ωp**, the **amplitude appears to become infinite**, but **this not actually happen** because frictional and other forces that are normally negligible become important near the resonance frequency.

At frequencies below the plasma frequency of the medium the **transmitted** (forward) **wave tends to zero**, while the **reflected** (backward) **wave tends to reach the full intensity** of the incoming wave !

In the full wave solution of the problem, liked in quantum mechanics the **transmission** and **reflection coefficients** very smoothly with frequency **0** to **1**.



The change of the reflection |R| and the transmission |T| coefficients with frequency, for a parabolic electron density profile.



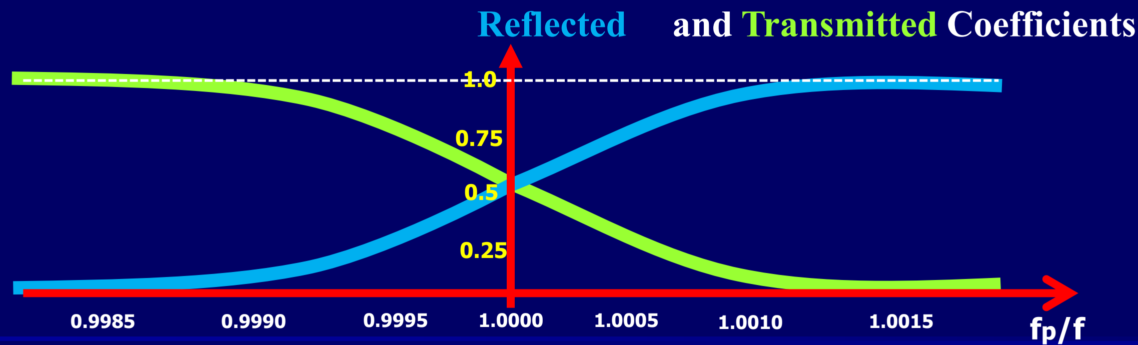
As seen from the above diagram, which describes the passage of radio waves through a parabolic layer of maximum plasma frequency f_p, most of this variation takes place very near f_p and for this reason we can adopt the classical step function formulation and simply state that radio waves with $f > f_p$ will be able to pass through this medium, whereas radio waves with $f < f_p$ will be reflected from this medium.

The group velocity of radio waves, i.e.: the velocity with which a group of radio waves (a radio signal) propagates through a plasma, is given by the following relation :

$$V_{gr} = \frac{c}{\mu_{gr}} \qquad (01)$$

Where μ_{gr} is the group index of reflection, which is related to the index of reflection μ of the plasma through the expression,

(P.T.O)



$$\frac{1}{\mu_{gr}} = \mu = \left(1 - \frac{f_p}{f^2}\right)^{1/2} \quad \rightarrow 02$$

From 01 and 02 it follows that, $V_{gr} = \mu\, c$

which says that the group velocity becomes zero when , $\mu = 0$

$$\Rightarrow \quad f = f_p = \left(\frac{e^2}{\varepsilon_o m} N\right)^{1/2} \quad \rightarrow 03$$

Which occurs, as we have seen, when the waves are about to be reflected. It should be made clear that this is the case only for **normal incidence**.

When the radio waves approach a plasma layer at an angle θ to the normal, then the **critical frequency** (the heights frequency reflected by the layer) **fc** is;

$$f_c = f_p \sec\theta$$

In accordance with that we have discussed up now, radio waves transmitted vertically from the ground will be reflected in the ionosphere at a height where the plasma frequency of the ionosphere becomes equal to the frequency of the wave.

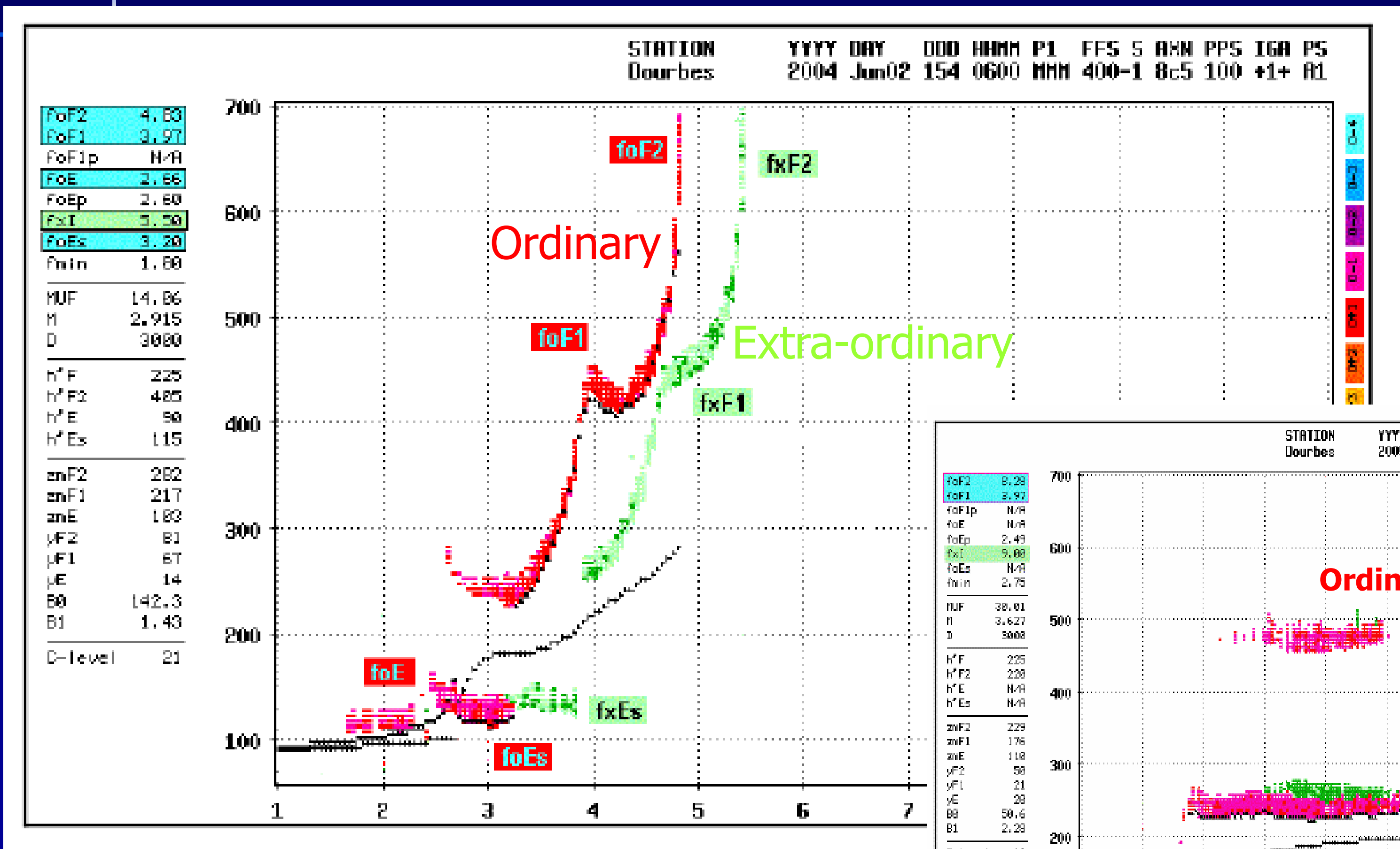
As seen from the above equation, for oblique transmission the same layer will be able to reflect considerably higher frequencies.

The presence of the **Earth Magnetic Field** makes the ionosphere a magneto-active plasma. (i.e.; A plasma with an embedded magnetic field) Radio waves in magneto-active plasma split into two modes of propagation called the **Ordinary** and the **Extra-ordinary**.

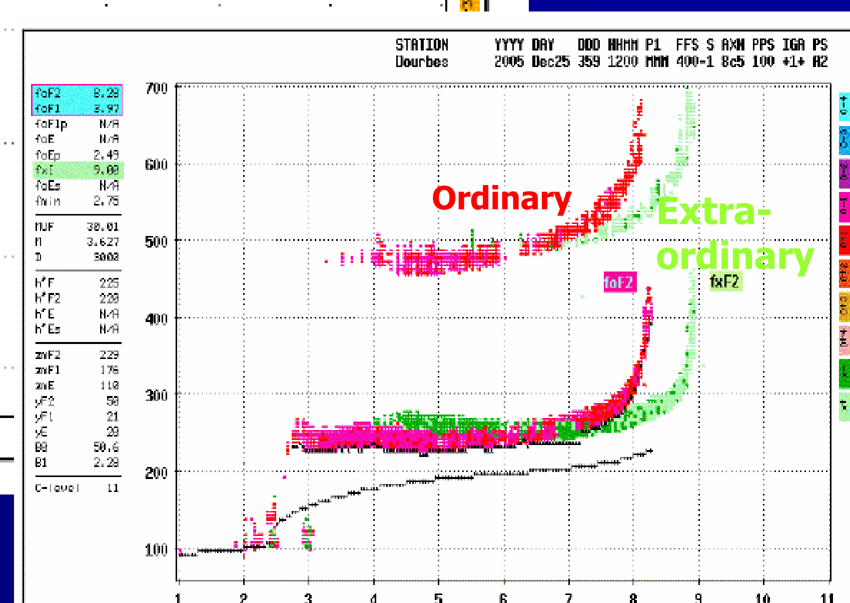
Each mode has its own index of reflection which is much more completed than equation 03.

$$f = f_p = \left(\frac{e^2}{\varepsilon_o m} N \right)^{1/2} \quad \rightarrow \quad 03$$

As a result the two modes propagate with different group velocities and are reflected at different heights in the ionosphere. Thus for each transmitted radio pulse we receive back to separate echoes. This is clearly seen in the **ionogram** of the following figure.



A typical ionogram showing the ordinary and extra-ordinary traces from the different ionospheric layers



A typical wintertime ionogram from the same ionosonde.

The horizontal axis of the ionogram gives the **Transmission Frequency of the ionospheric sounder,** and the vertical axis is the **equivalent height**. To a first approximation, the ordinary *fo* and the extra-ordinary *fx* frequencies reflected from the same ionospheric layer are related through the expression.

$$f_x - f_o = \frac{1}{2} f_H \quad \rightarrow 04$$

Where *fH* is the **cyclotron frequency** of the **Earth's Magnetic Field H**.

$$f_H = \frac{1}{2\pi} \times \frac{eH}{mc}$$

If H is expressed in Gauss and fH in MHz, then,

$$f_H = 2.8H$$.

$$f_x - f_o = \frac{1}{2} f_H$$

$$f_H = \frac{1}{2\pi} \times \frac{eH}{mc}$$

$$f_H = 2.8H$$

In the terrestrial ionosphere fH ≈ 1.0 – 1.5 MHz. As seen from the equation 04 the highest frequency that will be reflected by the ionosphere will be the frequency of the extra-ordinary mode reflected at Nmax. This is called the **Maximum Usable Frequency** (MUF) and its values and variations around the globe are of great importance to all radio telecommunications.

The Ionosphere

Collision Frequency & Absorption

The rate at which electrons collide with neutral particles and ions is called **Collision Frequency**.

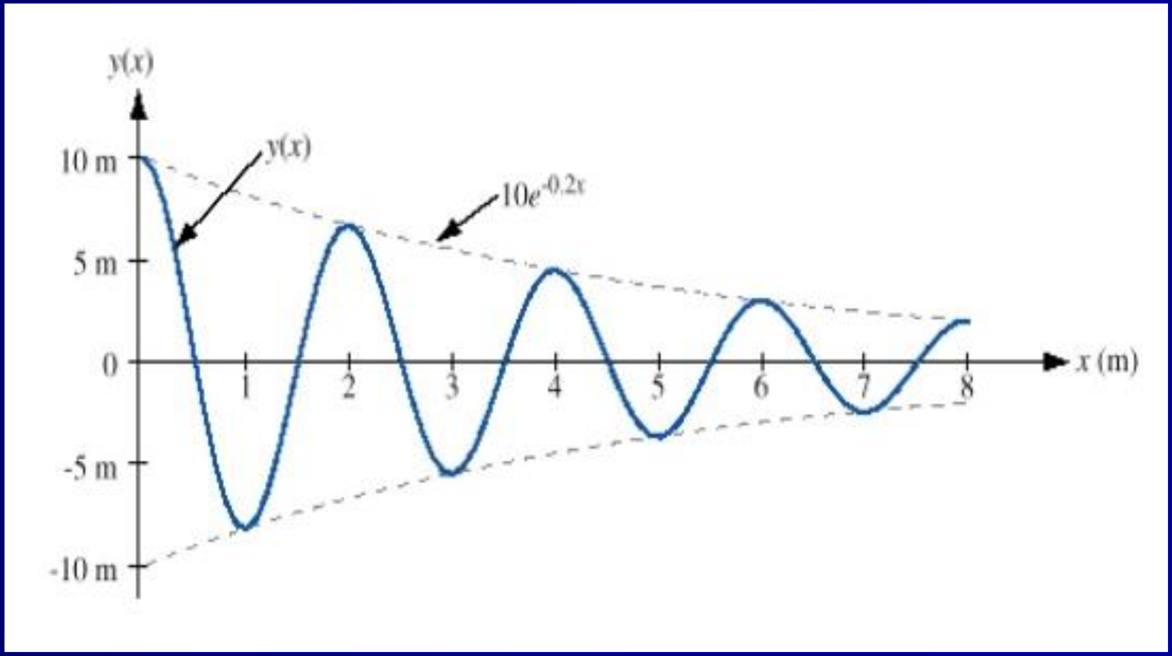
If a passing radio wave had set the electrons in harmonic motion, these collisions would disrupt it and the ordered (harmonic) **energy of the electrons** will be converted into **random (thermal) kinetic energy**.

As a result, the radio wave will have to spent some more of its energy to start again the harmonic motion of the electrons and in this manner collisions cause the **attenuation of radio waves**.

The Ionosphere

Collision Frequency & Absorption

Collisions of electrons with electrons, because both particles have the same mass, **contribute much less to the thermalization** of their energy than do collisions with the much heavier ions and neutral particles.



Collision Frequency & Absorption

For this reason **electron-electron collisions can be neglected** in most cases in computing the collision frequency which cause the attenuation of the passing radio waves.

The collision frequency of electrons with the neutral particles fn is proportional to **the physical cross section** of the neutral particles σn ≈ 10^{-15} cm^2, **their concentration** (particle number density) Nn and the **thermal velocity of the electrons** Ve.

$$f_n \; \alpha \; f_n(\sigma_n, N_n, V_e)$$

Thus we have,

$$f_n = \sigma_n . N_n . V_e$$

σ_n cross area,

$$\sigma_n = \pi \, r_n^2$$

The Ionosphere

Collision Frequency & Absorption

Thermal velocity of the electrons, Ve

$$K.E \; \alpha \; T$$

$$K.E = \frac{3}{2}kT$$

$$T.E = K.E$$

$$\Rightarrow \frac{1}{2}mV_e^2 = \frac{3}{2}kT \Rightarrow V_e = \left(\frac{3kT}{m}\right)^{1/2}$$

The collision frequency of electrons with the neutral particles,

$$f_n = \sigma_n . N_n . V_e \Rightarrow f_n = \left(\pi r_n^2\right) . N_n . \left(\frac{3kT}{m}\right)^{1/2}$$

$$\Rightarrow f_n = \frac{\pi r_n^2 \sqrt{3k}}{\sqrt{m}} . N_n . T^{1/2}$$

C_n

The Ionosphere

Collision Frequency & Absorption

Numerical const $\sim 10^{-10}$ *in CGS sys*

Collision frequency of electrons with the neutral particles

$$f_n = C_n \cdot N_n \cdot T^{1/2}$$

Temperature in K

The collision frequency of electrons with the ions

The collision of electrons with ions are actually **Coulomb Collisions** in which the **electrons are scattered by the ions through the interaction of their electric fields** rather than through physical contact. The collision cross-section, therefore, is much larger than the physical cross-section of the ions.

The Ionosphere

Collision Frequency & Absorption

As a first approximation one can say that the **maximum distance for an effective interaction is the distance r** at which the kinetic energy of the electrons is equal to the Coulomb Potential of the two particles.

$$C.P.E \;\alpha\; F \times d$$

$$K.E = \left(\frac{1}{4\pi\varepsilon}\frac{q_1 q_2}{r^2}\right)\times r$$

$$K.E = \left(k\frac{e^2}{r^2}\right)\times r$$

For CGS units k=1

$$\therefore \; K.E = \frac{e^2}{r}$$

The collision frequency of electrons with the ions f_i is proportional to **the physical cross section** of the ions σ_i, **their concentration** (particle number density) N_i and the **thermal velocity of the electrons** V_e.

$$f_i \;\alpha\; f_i(\sigma_i, N_i, V_e)$$

Thus we have,

$$f_i = \sigma_i . N_i . V_e$$

σ_n cross area,

$$\sigma_i = \pi r^2$$

The Ionosphere **Collision Frequency & Absorption**

As a first approximation one can say that the **maximum distance for an effective interaction is the distance r** at which the kinetic energy of the electrons is equal to the Coulomb Potential of the two particles.

$$C.P.E \;\alpha\; F \times d$$

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For CGS units k=1

$$\therefore \quad K.E = \frac{e^2}{r}$$

The Ionosphere

Collision Frequency & Absorption

Thermal velocity of the electrons, Ve

Coulomb Potential Energy, $C.P.E = T.E$

$$\Rightarrow \frac{e^2}{r} = \frac{1}{2} m V_e^2 \quad \rightarrow 01$$

K.E. of the e^n = Thermal E. of the e^n $T.E = K.E$

$$\Rightarrow \frac{1}{2} m V_e^2 = \frac{3}{2} kT \quad \rightarrow 02$$

Using 01 and 02 ;

$$\therefore \quad r = \frac{2e^2}{3kT}$$

and,

$$V_e = \left(\frac{3kT}{m} \right)^{1/2}$$

The Ionosphere

Collision Frequency & Absorption

$$f_i = \sigma_i . N_i . V_e \;\Rightarrow\; f_i = \left(\pi r^2\right) . N_i . V_e$$

$$\Rightarrow\; f_i = \pi \left(\frac{2e^2}{3kT}\right)^2 . N_i . \left(\frac{3kT}{m}\right)^{1/2}$$

$$\Rightarrow\; f_i = \frac{4\sqrt{3}\ \pi\ e^4 k^{-3/2}}{9\sqrt{m}} . N_i . T^{-3/2}$$

C_i

Numerical const ~10

Collision frequency of electrons with irons

$$f_i = C_i \cdot N_i \cdot T^{-3/2}$$

Temperature in K

The Ionosphere

Collision Frequency & Absorption

Numerical const $\sim 10^{-10}$ *in CGS sys*

Collision frequency of electrons with the neutral particles

$$f_n = C_n \cdot N_n \cdot T^{1/2}$$

Temperature in K

Numerical const ~10

Collision frequency of electrons with irons

$$f_i = C_i \cdot N_i \cdot T^{-3/2}$$

Temperature in K

Electrons Number Density

Ions Number Density

$$N_i = N_e = N$$

Total Collision frequency

$$f = f_n + f_i$$

The Ionosphere

Collision Frequency & Absorption

Total Collision frequency

$$f = f_n + f_i$$

$$f = C_n \cdot N_n \cdot T^{1/2} + C_i \cdot N_i \cdot T^{-3/2}$$

$$f = C_n \cdot N_n \cdot T^{1/2} + C_i \cdot N \cdot T^{-3/2}$$

$$\because \; N_i = N_e = N$$

From the collision frequency we can now compute the absorption coefficient. It can be shown that the damping force due to the collision is to a first approximation proportional to the velocity $V=\dot{r}$ of the electrons. Also that the constant of proportionality is equal to mf, where m is the mass of the electrons and f is the collision frequency.

Hence, the equation of motion of an electron under the oscillating force of a field E and in the presence of collision is,

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

$$-e\,E = m\,\ddot{r} + m\,f\,\dot{r} \quad \rightarrow 03$$

Since, $E = E_o e^{i\omega t}$ and, $r = r_o e^{i\omega t}$, we can write the above equation in the following form

$$-e\,E = -m\,\omega^2 r + i\,m\,f\,\omega\,r$$

Because, $r = r_o e^{i\omega t}$ $\Rightarrow$ $\dot{r} = \frac{dr}{dt} = \frac{d\left(r_o e^{i\omega t}\right)}{dt}$ $\Rightarrow$ $\dot{r} = i\omega r$

$\Rightarrow$ $\ddot{r} = \frac{d\dot{r}}{dt} = \frac{d\left(i\omega r\right)}{dt} = \frac{d\left(i\omega r_o e^{i\omega t}\right)}{dt}$ $\Rightarrow$ $\ddot{r} = -\omega^2 r$

The Ionosphere **Collision Frequency & Absorption**

Now, since the **dipole moment** between an electron and an ion separated by a distance r is equal to -er, and since we have N electron ion pairs per unit volume, the polarizibility P, i.e.; The induced dipole moment per unit volume is **P = - N e r .**

By introducing P in the equation 03 we obtain :

$$-e\,E = m\,\omega^2 \frac{P}{eN} - i\,m\,f\,\omega\,\frac{P}{eN}$$

because, $r = -\frac{P}{eN}$

$$P = -\left[\frac{e^2 N}{m\omega^2\left(1 - i\frac{f}{\omega}\right)}\right]E$$

But we know, Plasma frequency

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

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

$\left\{ \frac{1}{4\pi\varepsilon_o} = k = 1 \quad \text{For CGS units k=1} \quad \therefore \frac{1}{4\pi} = \varepsilon_o \right\}$

The Ionosphere

Collision Frequency & Absorption

$$P = -\left[\frac{e^2 N}{m\omega^2\left(1 - i\dfrac{f}{\omega}\right)}\right]E$$

and

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

also

$$\frac{1}{4\pi} = \varepsilon_o$$

$$\Rightarrow \quad P = -\left[\frac{\varepsilon_o \omega_p^2}{\omega^2\left(1 - i\dfrac{f}{\omega}\right)}\right]E$$

$$\Rightarrow \quad P = -\left[\frac{\omega_p^2}{4\pi\ \omega^2\left(1 - i\dfrac{f}{\omega}\right)}\right]E$$

$$\Rightarrow \quad P = -\left[\frac{\omega_p^2 / \omega^2}{4\pi\ \left(1 - i\dfrac{f}{\omega}\right)}\right]E$$

The Ionosphere

Collision Frequency & Absorption

From the Electro-Magnetic Theory on the other hand we have : $D = \varepsilon E$

$$D = E + \frac{P}{\varepsilon_o}$$

OR

$$D = E + 4\pi P$$

$$D = E + 4\pi\left(-\left[\frac{\omega_p^2 / \omega^2}{4\pi\left(1 - i\frac{f}{\omega}\right)}\right]E\right)$$

$$D = \left(1 - \frac{\omega_p^2 / \omega^2}{\left(1 - i\frac{f}{\omega}\right)}\right)E$$

The Ionosphere

Collision Frequency & Absorption

Then, $D = \varepsilon E$ and,

$$D = \left(1 - \frac{\omega_p^2 / \omega^2}{\left(1 - i\frac{f}{\omega} \right)} \right) E$$

➡ $$\varepsilon = \left(1 - \frac{\omega_p^2 / \omega^2}{\left(1 - i\frac{f}{\omega} \right)} \right)$$

From which we conclude that the square of the **complex index of reflection n^2**, which is equal to the **complex di-electric constant ε**, is given by the expression,

$$n^2 = \varepsilon = 1 - \frac{\omega_p^2 / \omega^2}{\left(1 - i\frac{f}{\omega} \right)}$$

The Ionosphere

Collision Frequency & Absorption

From which we conclude that the square of the **complex index of reflection** **n^2**, which is equal to the **complex di-electric constant** **ε**, is given by the expression,

$$n^2 = \varepsilon = 1 - \frac{\omega_p^2 / \omega^2}{\left(1 - i\frac{f}{\omega}\right)} \quad \cdots\cdot \;\Rightarrow\; n^2 = \left[1 - \frac{\left(\omega_p^2/\omega^2\right)}{\left(1+\left(\frac{f}{\omega}\right)^2\right)}\right] - i\left[\left(\frac{f}{\omega}\right)\frac{\left(\omega_p^2/\omega^2\right)}{\left(1+\left(\frac{f}{\omega}\right)^2\right)}\right]$$

Let **μ** then be the **Real Part** and **$\varkappa$** the **Imaginary Part** of the complex index of reflection, so that,

$$\mathbf{n = \mu - i\,\varkappa}$$

$$\mathbf{n^2 = (\mu - i\,\varkappa)^2} = 1 - \frac{\left(\omega_p^2/\omega^2\right)}{1+\left(\frac{f}{\omega}\right)^2} - i\left(\frac{f}{\omega}\right)\frac{\left(\omega_p^2/\omega^2\right)}{1+\left(\frac{f}{\omega}\right)^2}$$

The Ionosphere

Collision Frequency & Absorption

When the collision frequency f, is much smaller than the operating frequency ω; i.e.:

When f « ω then **ϰ** « 1 and equations of **μ** & **ϰ** become,

$$\mu^2 \approx 1 - \frac{\omega_p^2}{\omega^2}$$

and

$$\chi \approx \frac{f\,\omega_p^2}{2\mu\omega^3}$$

The electric field of a wave in a medium with a complex index of refraction n is given by the expression,

$$E = A\ e^{-i(kr-\omega t)}$$

$$\Rightarrow\quad E = A\ e^{-i(nk_o r-\omega t)}$$

$$\Rightarrow\quad E = A\ e^{-i((\mu-i\chi)k_o r-\omega t)}$$

$$\Rightarrow\quad E = A\ e^{-i(\mu k_o r-\omega t)}e^{-k_o\chi r}$$

$$\Rightarrow\quad E = E_o e^{-k_o\chi r}$$

The Ionosphere

Collision Frequency & Absorption

And since the intensity of the radiation I is proportional to the square of the electric field E; we have,

$$I \ \alpha \ E^2$$

$$\Rightarrow I = a E^2$$

$$\Rightarrow I = a \left(E_o e^{-k_o \chi r}\right)^2$$

$$\Rightarrow I = a E_o^2 e^{-2k_o \chi r}$$

$$\Rightarrow I = I_o e^{-\kappa r}$$ and $$\kappa = 2k_o \chi$$

$$\Rightarrow I = I_o e^{-\tau}$$

The Ionosphere

Collision Frequency & Absorption

$I = I_o e^{-\tau}$ where $\tau = \kappa r$ and $\kappa = 2k_o\chi$

Where κ is the **absorption coefficient** of the medium

Absorption coefficient of the medium : $\kappa = 2k_o\chi$

$$\kappa = 2\left(\frac{\omega}{c}\right)\chi$$

$$\kappa = 2\left(\frac{\omega}{c}\right)\left(\frac{f\,\omega_p^2}{2\mu\omega^3}\right)$$

$$\kappa = \left(\frac{f}{\mu c}\right)\left(\frac{\omega_p^2}{\omega^2}\right)$$

$\omega = 2\pi f_o$

$$\kappa = \left(\frac{f}{\mu c}\right)\left(\frac{f_p^2}{f_o^2}\right)$$

And τ is the **Optical Thickness** or **Opacity** of the medium, $\tau = \int \kappa\, dr$

$$\tau = \kappa r$$

The Ionosphere

Collision Frequency & Absorption

From equations of κ and Ʈ we see that the absorption coefficient κ and the opacity Ʈ of the medium are directly proportional to the collision frequency f.

For a very weakly ionized plasma, like the lower ionosphere (D-Region) where N_n » N_i, we can set $f=f_n$ and we get,

$$\kappa_n \alpha \frac{N.N_n.T^{1/2}}{f_o^2}$$

The electron density N in the D-Region is usually low and therefore the κ_n of the D-Region is usually low !

The absorption of the D-layer is usually measured with radio receivers which monitor continuously the radio noise from our galaxy. These receivers are called **Riometers**, where the prefix **rio** stands for the initials of the words **relative ionospheric opacity**.

The Ionosphere

Collision Frequency & Absorption

During the span of a day both the **ionospheric absorption** and the **galactic radio background change**.
The first because the **electron density of the D-layer varies with the Zenith Angle of the Sun**, and
The second because the galactic radio noise is concentrated in the plane of the galaxy and especially towards the galactic center and as the earth rotates our antenna focuses an different regions of the galaxy.

Through long observations, we can take into account these variations, which have also a seasonal component and we can establish the normal levels of ionospheric absorption and the expected, under normal conditions, intensity I of the galactic radio emission. Any decreases of the signal strength to a new level I' represents an increase in the D-region absorption and is usually expressed in dB units.

$$dB = 10 Log_{10}\left(\frac{I'}{I}\right)$$

The Ionosphere

Collision Frequency & Absorption

$$dB = 10 \log_{10}\left(\frac{I'}{I}\right)$$ and $$\log_{10} x = 2.3 \ln x$$

$$dB = 23 \ln\left(\frac{I'}{I}\right)$$

$$dB = 23 \ln\left(\frac{I_o e^{-\tau'}}{I_o e^{-\tau}}\right)$$

$$dB = 23 \ln\left(e^{\tau-\tau'}\right)$$

$$dB = 23 (\tau - \tau')$$

$$dB = 23\, \tau'\left(\frac{\tau}{\tau'} - 1\right)$$

$$dB = -23\, \tau'\left(1 - \frac{\tau}{\tau'}\right)$$

$$dB \approx -23\, \tau'$$

Because, $\tau \ll \tau'$.

Where τ and τ' are the normal and the enhanced opacity of the ionosphere, which are essentially proportional to the normal and enhanced electron density of the D-Region.

The Ionosphere

Collision Frequency & Absorption

Riometer observations are usually conducted in the frequency range between 15 MHz and 60 MHz. **The reason is that lower frequencies can hardly penetrate through the ionosphere** while higher frequencies as seen from,

$$\chi \approx \frac{f}{2\mu}\left(\frac{\omega_p^2}{\omega^3}\right),$$

suffer very little attenuation which is difficult to measure.

For a fully ionized plasma, like the solar corona, we can set $f = f_i$ and we get,

$$\tau_i = \kappa_i \; r \; \alpha \left(\frac{N^2}{f_o^2 \; T^{3/2}}\right) r$$

Here it is important to note that in certain cases through κ_i might be very small, the total attenuation represented by the opacity τ_i might be quite large simply because the radio waves have travelled a very long distance r in the medium. This is quite often the case in **astronomical observations**.

The Structure of the Ionosphere and Plasmasphere

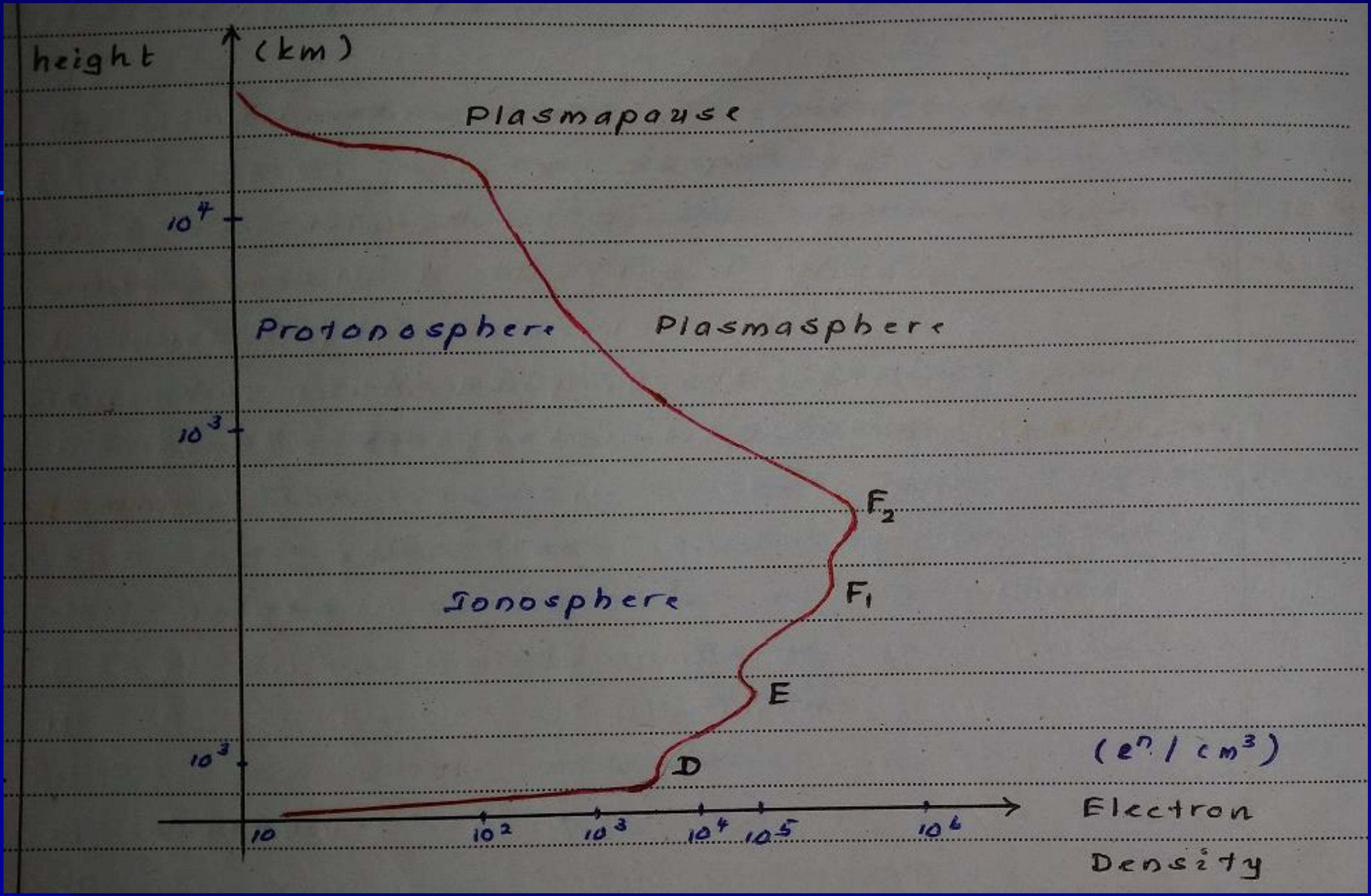
The Structure of the Ionosphere and Plasmasphere

The most obvious difference from the simple **Chapmon Layer Theory** is that the **ionosphere has several peaks of the electron density**. These peaks are called layers and have the names **D-layer**, **E-layer**, **F1-layer** and **F2-layer**.

We also have the **plasma pause**, a rather sharp change in electron density, at **a distance of 4 to 5 Earth radii**.

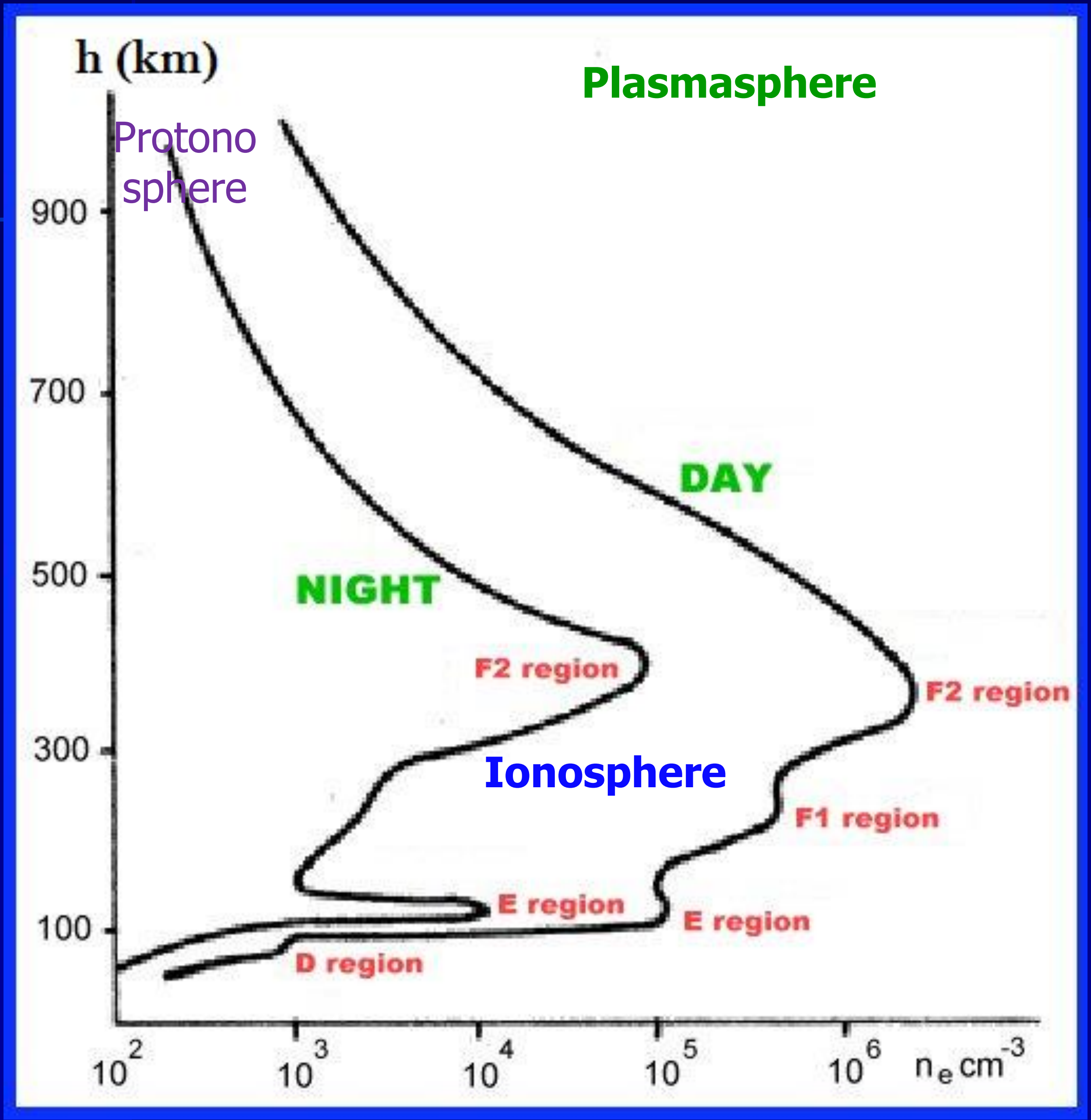
The D, E, F1 and F2 layers are formed because the ionizing radiation from the sun is **not monochromatic** and because the atmosphere consists of **several different constituents** which are ionized at different wavelengths of the solar spectrum.

The Structure of the Ionosphere and Plasmasphere



A typical daytime profile of the ionosphere and the plasma sphere.

The Structure of the Ionosphere and Plasmasphere



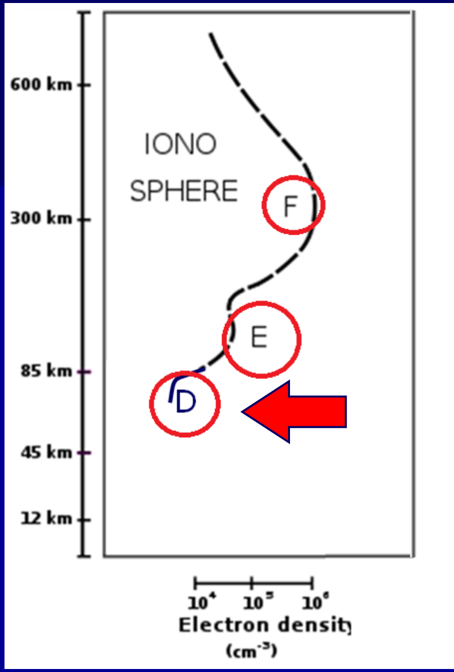
Each one of these ionizing processes reaches its peak at a different attitude which becomes an individual peak of the ionospheric electron density profile. The height dependence of the different loss-mechanisms is also a factor in the formation of the ionosphere layers.

A typical daytime and nighttime profiles of the ionosphere and the plasma sphere.

The Structure of the Ionosphere and Plasmasphere

The D – region

It is present only during the day and covers the range between **60 and 85 km**. Quite often the valley between the D-layer and the E-layer is not very obvious, and as a result the D-layer is not always well defined.

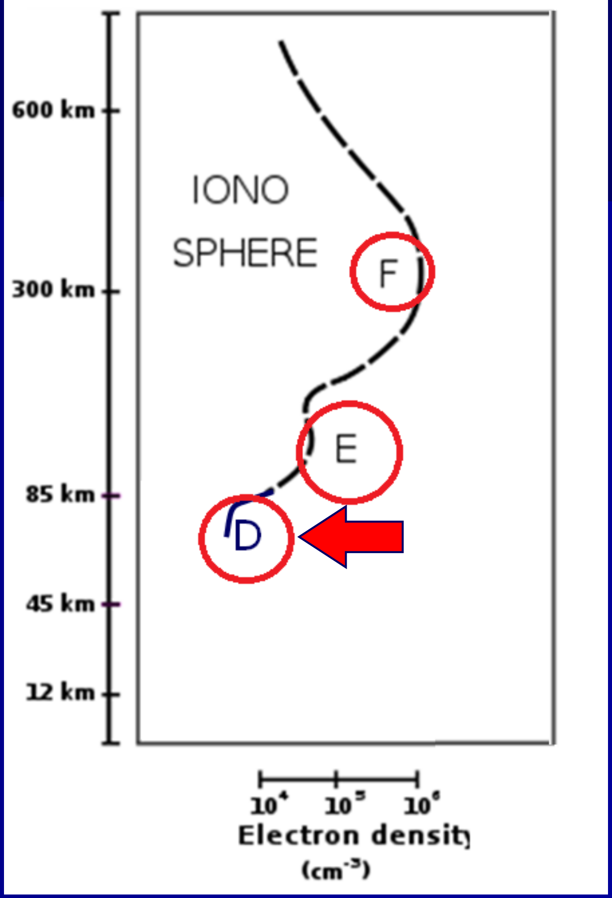


In the **70 to 85 km** range electrons are produced mainly from the ionization of the traces of NO that exit in the upper atmosphere by the Lyman - Alpha radiation (1216 Å) of the Sun. The peak electron density of the D-layer occurs near 80 km and is of the order of 3×10^3 e^n/cm^3.

The Structure of the Ionosphere and Plasmasphere

The D – region

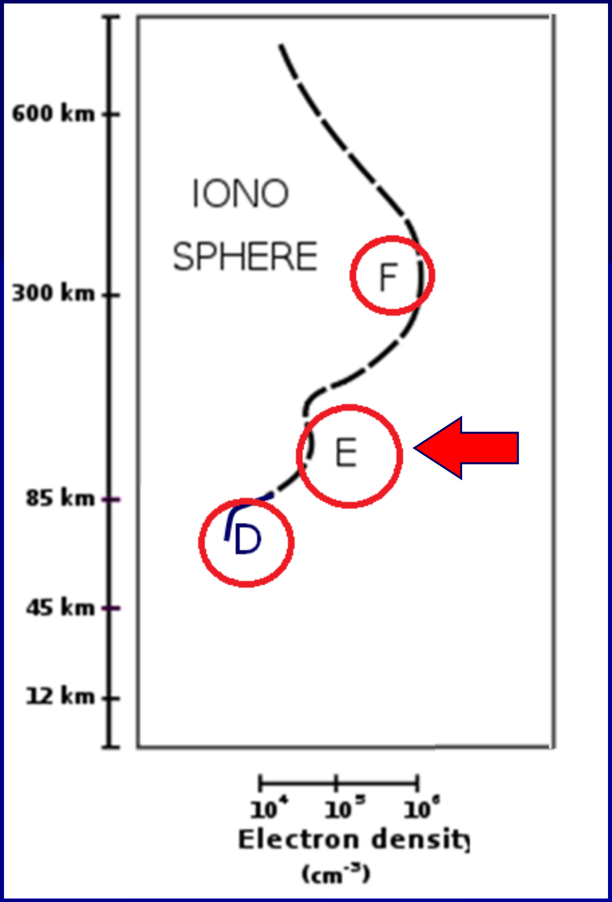
Solar X - rays acting on molecular oxygen and molecular nitrogen contribute also to the ionization of the D -layer. This becomes especially apparent during periods of intense solar activity (solar flares,... etc.) when the electron content of the D- region can increase by more than an order of magnitude.



The Structure of the Ionosphere and Plasmasphere

The E – region

It extends from 85 km to about 150 km and has a daytime maximum of ~$3x10^5$ e^n/cm^3 around 115 km. During the night the electron density decreases by at least two orders of magnitude and the E-layer disappears.



The Structure of the Ionosphere and Plasmasphere

The lower part of the E-region (85-100 km) is ionized mainly by solar x-rays in the 30-100 Å range. Above 100km the ionization is produced mainly by soft x-rays and by UV radiation in the range between 800 Å and the Lymon-β at 1026 Å.

The main ions in the E-region are NO^+ and O_2^+. Though N_2^+ is produced in large numbers it is virtually absent in the ionosphere because of its extremely high recombination rate. The recombination coefficient of E-layer is, $\alpha \approx 2\times10^{-8}$ cm^3/s and the relaxation time is of the order of ~10 min, which explains the rapid disappearance of the E-layer after Sunset.

The Structure of the Ionosphere and Plasmasphere

The E – region

The small amount of ionization which persists in the E-region during the night could be due to micrometeorite bombardment.

The relaxation time t_r is the time in which the **electron density would reduce to one half**, if there was no more production of electrons.

.: Diffusion rate,

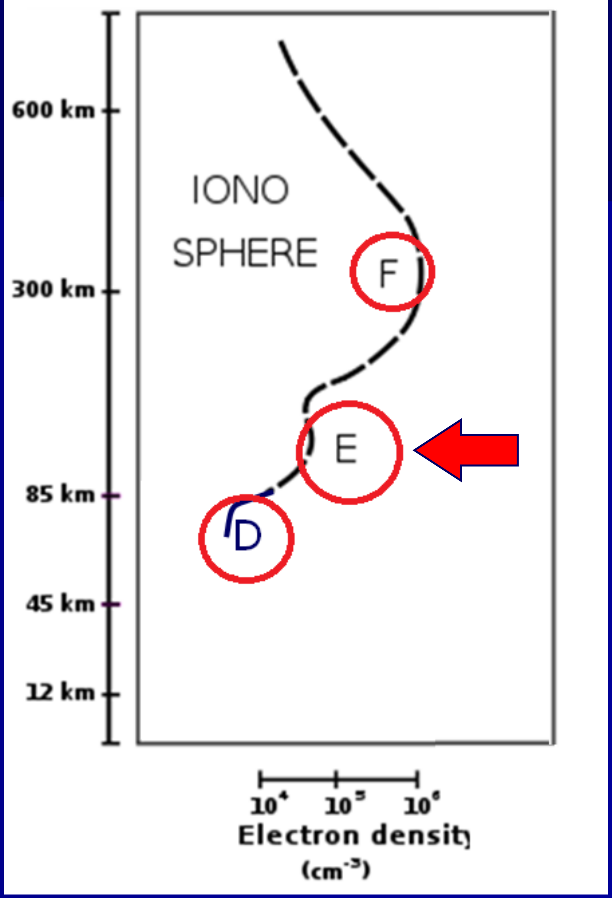
$$\frac{dN}{dt} \alpha \; -N^2$$

If t↑ then, N↓

$$-\frac{dN}{N^2} = \alpha \; dt$$

Where alpha is the proportional constant (**Recombination Coefficient**)

$$-\int_{N(0)}^{N(t_r)} N^{-2} dN = \alpha \int_{t=0}^{t_r} dt$$



The Structure of the Ionosphere and Plasmasphere

The E – region

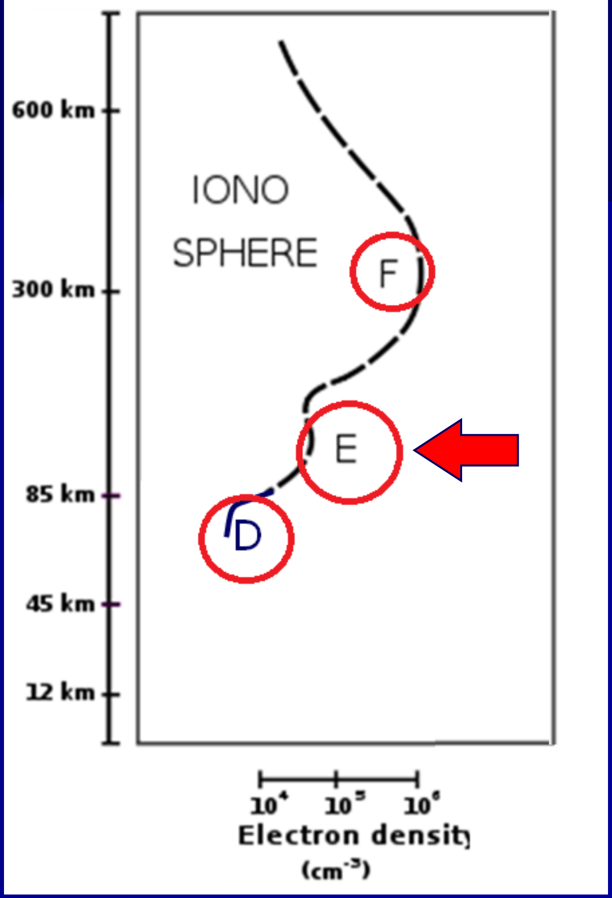
.: Diffusion rate,

$$-\left(\frac{1}{N(0)}-\frac{1}{N(t_r)}\right)=\alpha\ t_r$$

We know, $N(t_r)=\dfrac{N(0)}{2}$

$$\therefore\quad t_r=\frac{1}{\alpha\ N(0)}$$

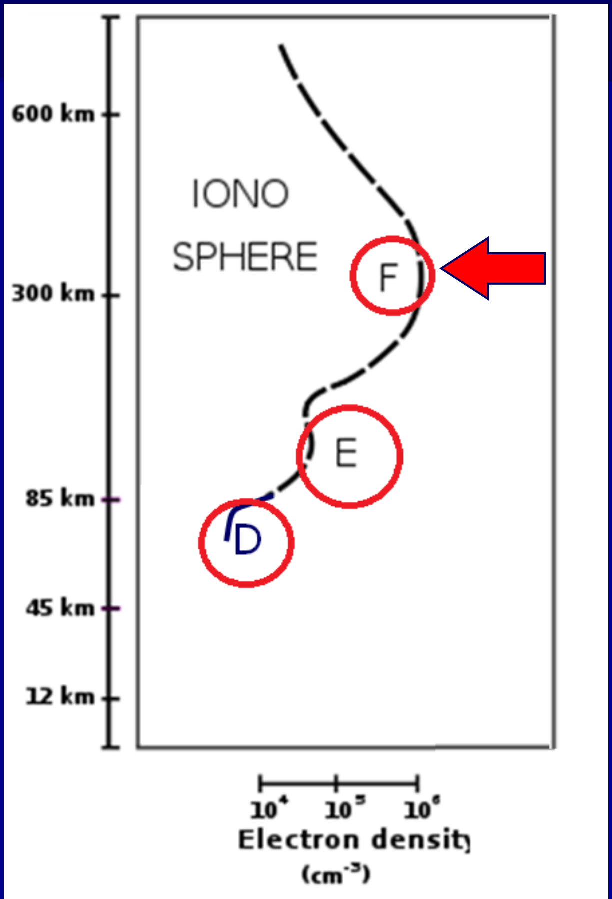
Studies for the experimental determination of t_r can best be made during Solar Eclipses !



The Structure of the Ionosphere and Plasmasphere

The F1 – region

It is present like the D and E-layers only during the day. It extends from 150 to 200 km with a typical maximum of ~$2x10^5$ e^n/cm^3 around 180 km.



The Structure of the Ionosphere and Plasmasphere

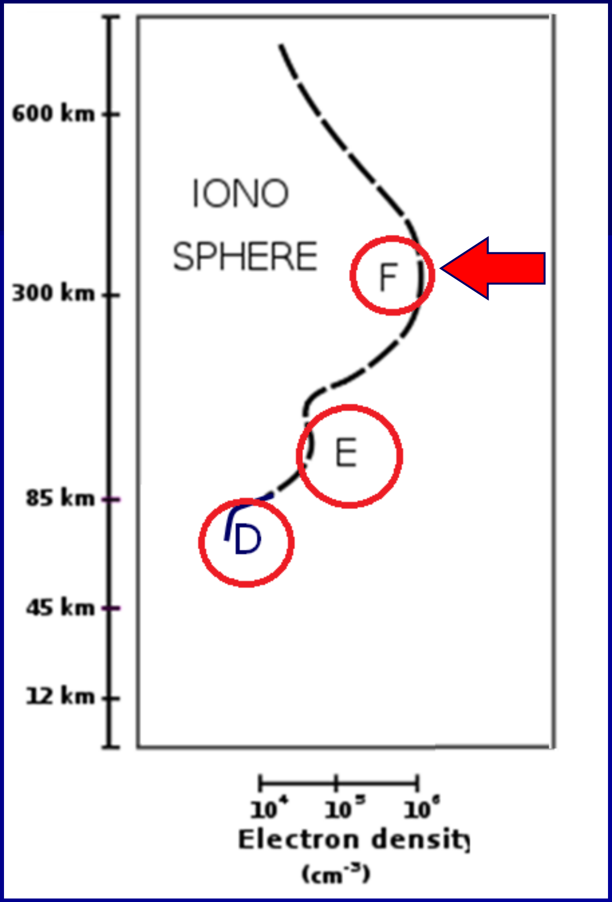
The principle ionizing agent is the Sun's ultra-violet radiation in the 200 Å to 900 Å range. The main atmospheric constituent which is ionized in the F1-region is **atomic oxygen** which diffuses from the lower layers where it is produced from the dissociation of O2.

The recombination coefficient of the F1 layer is $\alpha \approx 5 \times 10^{-9}\ cm^3/s$ and the corresponding relaxation time is similar to the relaxation time of the E-layer.

The Structure of the Ionosphere and Plasmasphere

The F2 – region

It extends from 200 km to roughly 1000 km and has a **daytime maximum** near 250 km of about ~$5x10^5$ e^n/cm^3. **During the night the D, E and F1 peaks disappear and the ionosphere takes the form of a single layer, called the F-layer, with a maximum of about ~$5x10^5$ e^n/cm^3 around 350 km.**



The Structure of the Ionosphere and Plasmasphere

As we move to higher attitudes the rate at which electrons and irons recombine decreases rapidly with height and the relaxation time at higher attitudes is much longer (~several days)

Electrons can be lost by recombining directly with the positive ions, which are present in approximately equal numbers. It should be mentioned that the neutral atoms are occasionally produced in excited states and they return their ground state they emit **photons** which are responsible for a faint glowing of the sky, a phenomenon which is called **airglow**.

Ion composition

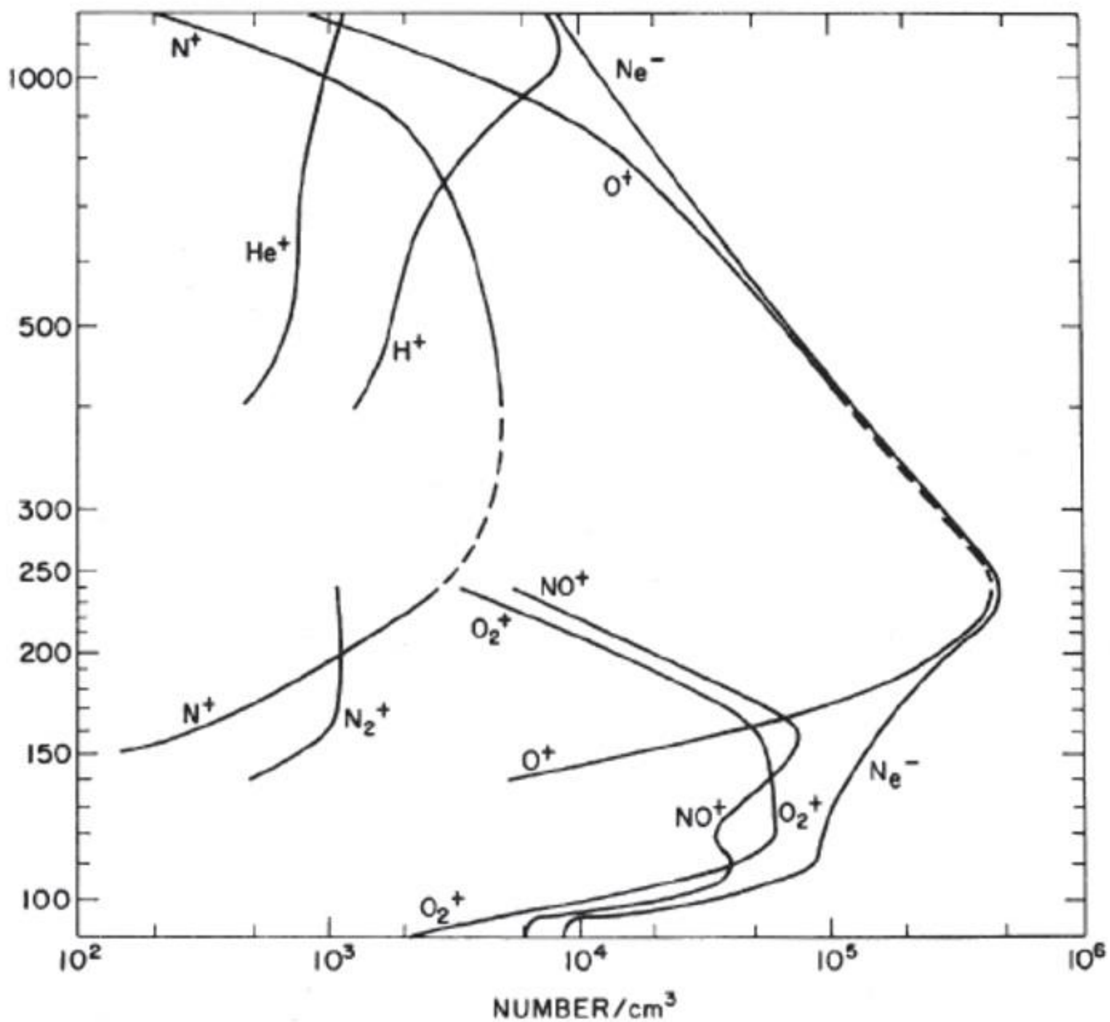
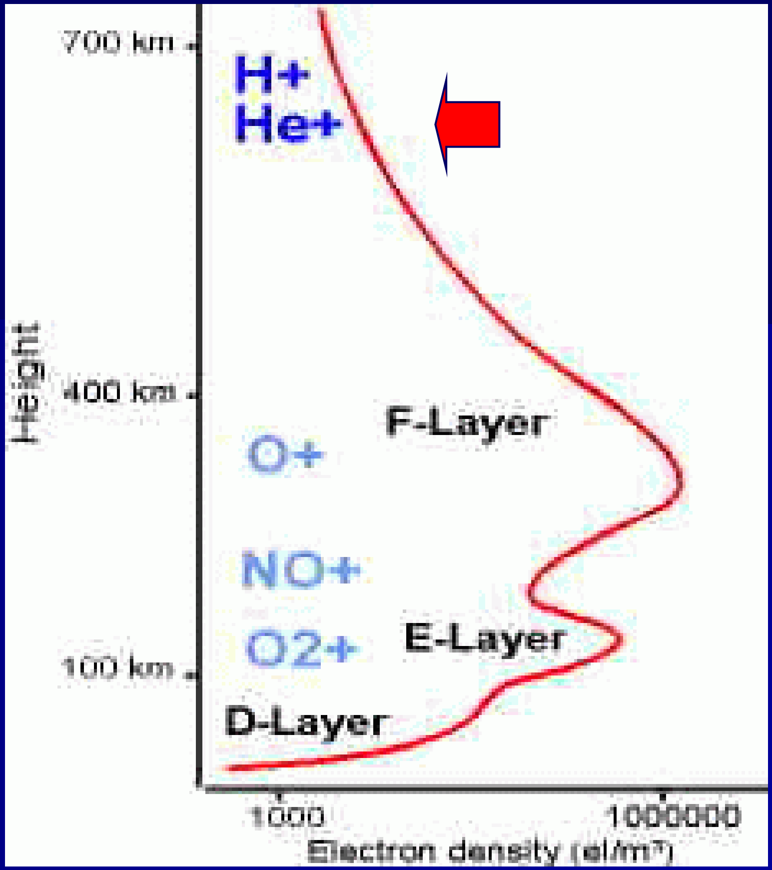


Figure: Daytime solar minimum ion profiles.

- O^+ dominates around F region peak and H^+ starts to increase rapidly above 300 km.
- NO^+ and O_2^+ are the dominant ions in E and upper D regions (Ion chemistry: e.g. $N_2^+ + O \longrightarrow NO^+ + N$).
- D-region (not shown) contains positive and negative ions (e.g. O_2^-) and ion clusters (e.g. $H^+(H_2O)_n$, $(NO)^+(H_2O)_n$).

The Upper Ionosphere

At attitudes above the F2 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.



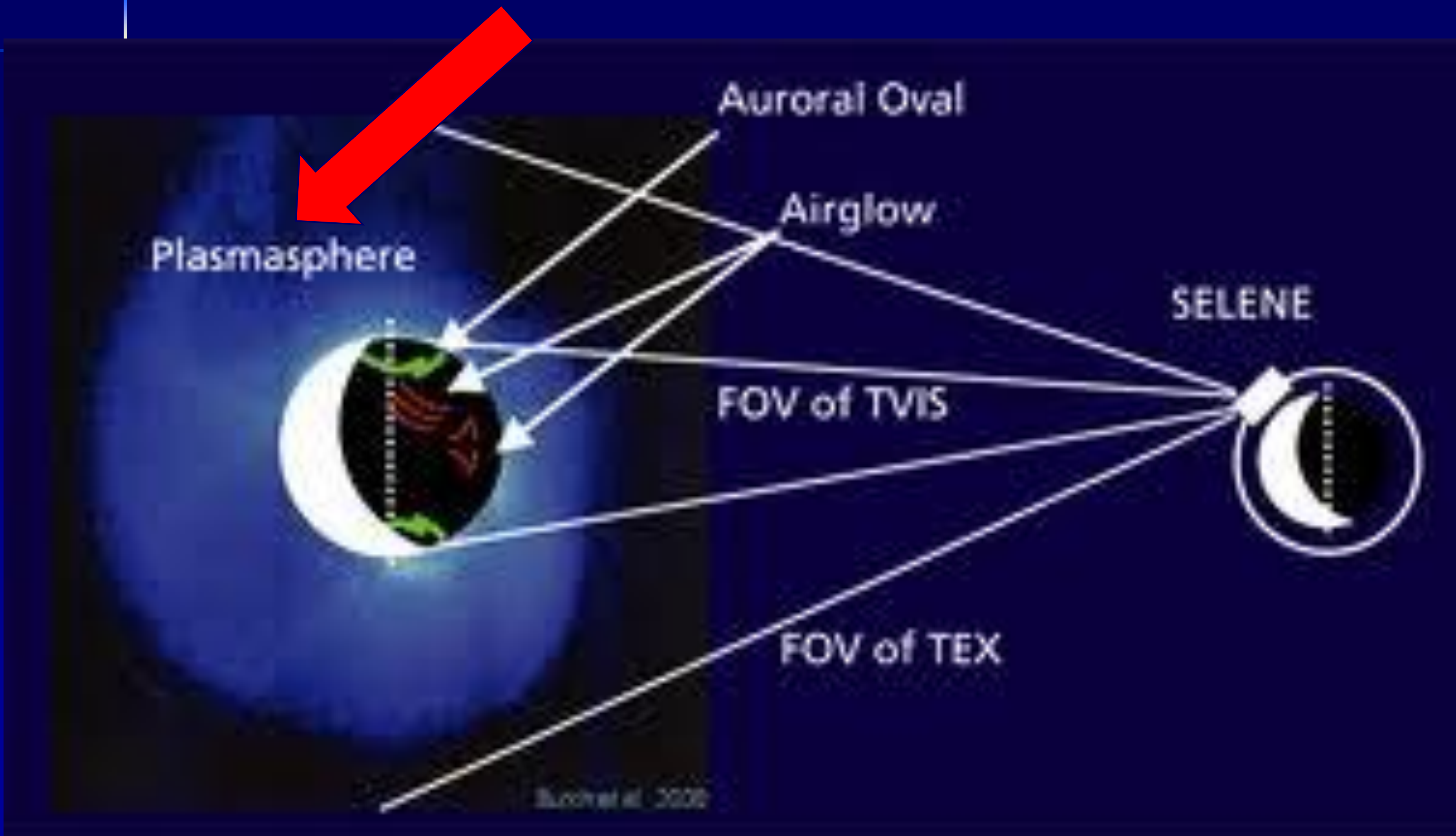
In the presence of the **Earth's Magnetic Field**, which tends to guide the diffusion of the charged particles along the field lines, this becomes a very complicated phenomenon to study.

The Upper Ionosphere

Contrary to the diffusion of neutral particles, where different species diffuse independently, electrons and ions tend to diffuse as a body because there separation builds up an electric field which brings them back together. This phenomenon is called **ambi-polar diffusion**.

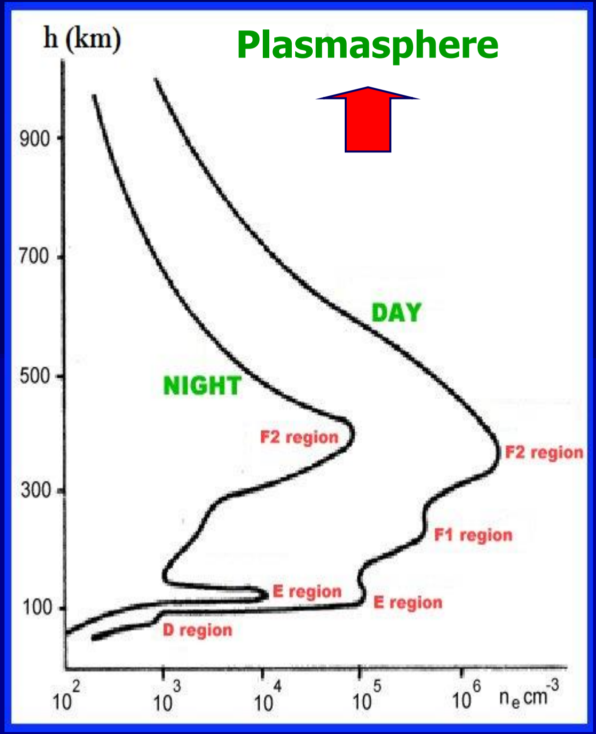
Around 1000 km O^+ is replaced by He^+ as the predominant ion, and at even higher attitudes (~2500 km) He^+ is replaced by H^+, i.e.; by free protons. The layer where helium ions dominate is often called **heliosphere** and the region above it is called the **protonosphere**.

The Plasmasphere

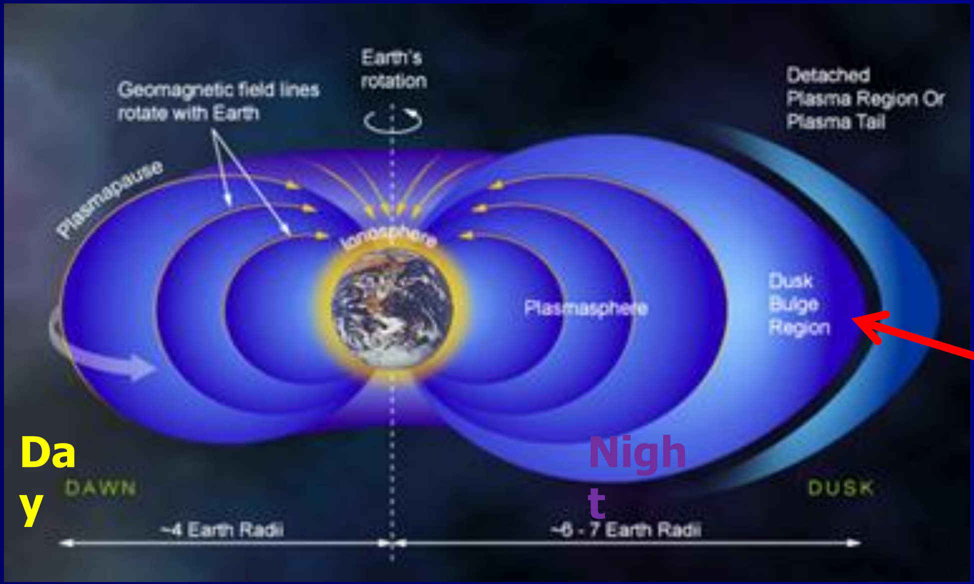


The Plasmasphere

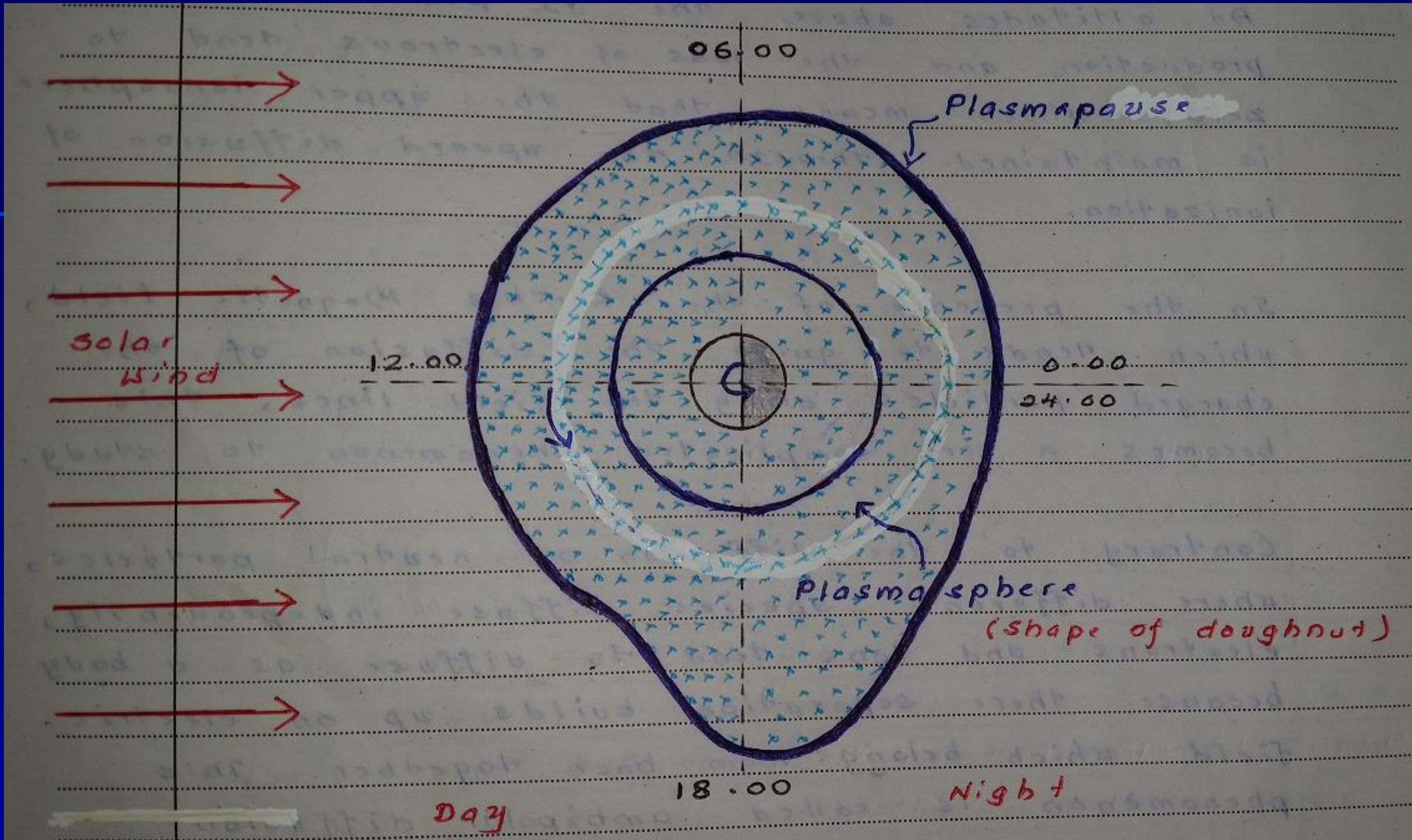
This is the region of the Earth's ionized atmosphere which basically follows the rotation of the Earth. The plasmasphere has the shape of a doughut, very much like the volume formed by the lines of the Earths dipole magnetic field which provides the link that keeps the plasmasphere rotating with Earth.



Solar Wind

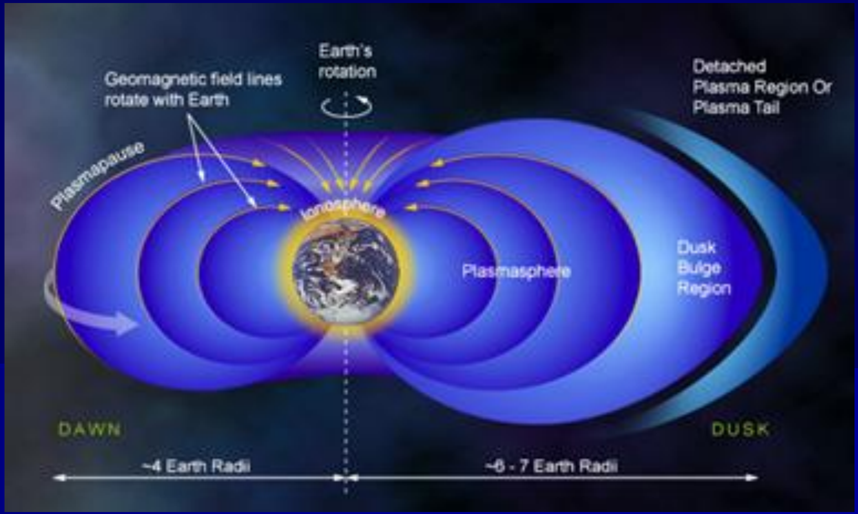


Shape of a doughnut



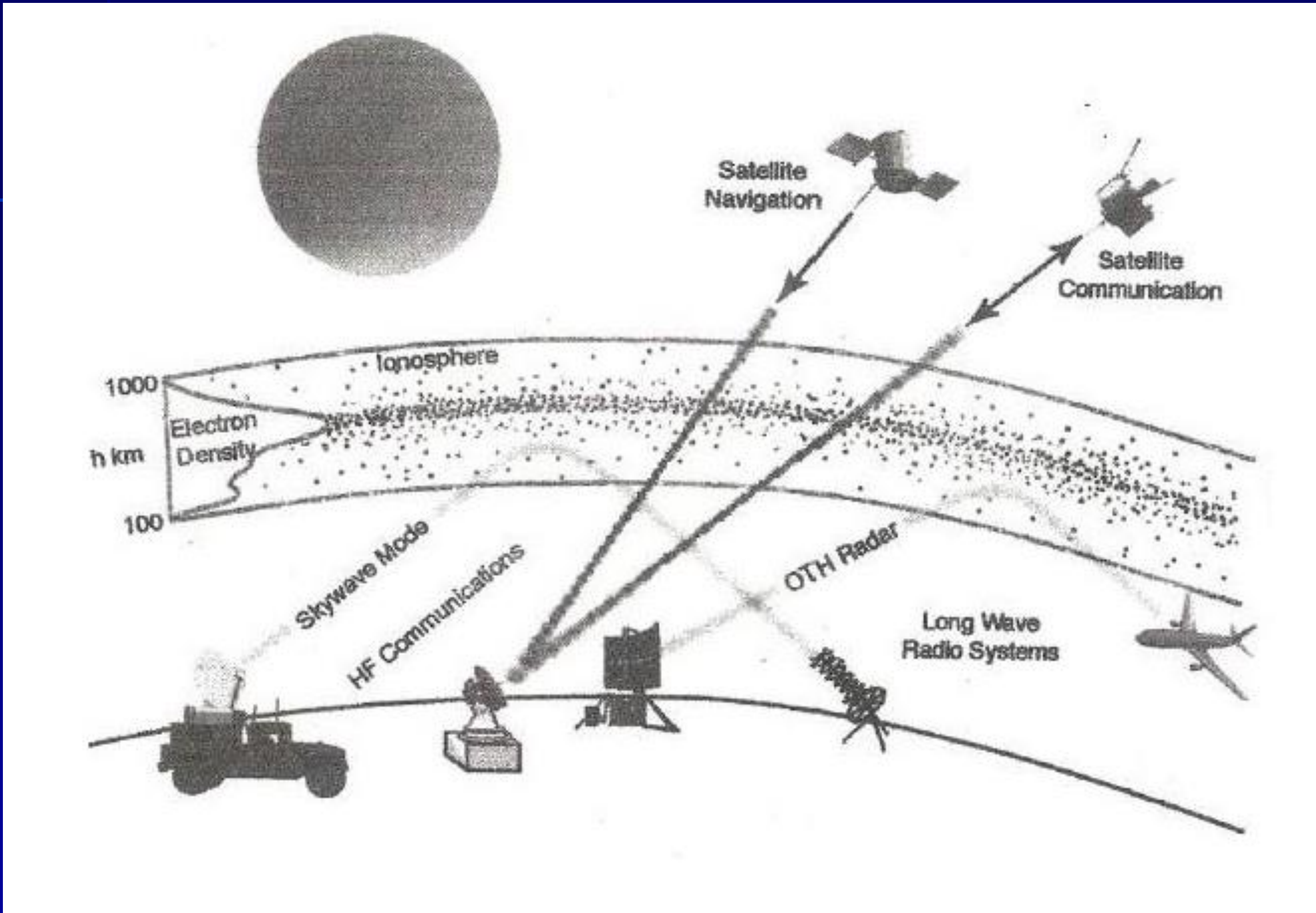
06.00
Plasmapause
Solar wind
12.00
0.00
24.00
Plasmasphere
(shape of doughnut)
18.00
Day
Night

The Plasmasphere & Plasmapause



The boundary of the plasmasphere, which at the equatorial plane occurs at a geocentric distance of 4 or 5 Earth radii, is called the **plasmapouse**. At the plasma pause the **electron density drops** sharply from a few hundred e^n/cm^3 to only a few e^n/cm^3.

The **plasmasphere** is filled with thermal plasma [a plasma with a Maxwellian Distribution of velocities and a temperature of a few thousand degrees kelvin] with diffuses upwards from the upper ionosphere.



Satellite
Navigation
Satellite
Communication
Ionosphere
1000
Electron
Density
h km
100
Skywave Mode
HF Communications
OTH Radar
Long Wave
Radio Systems

Penetration Depth

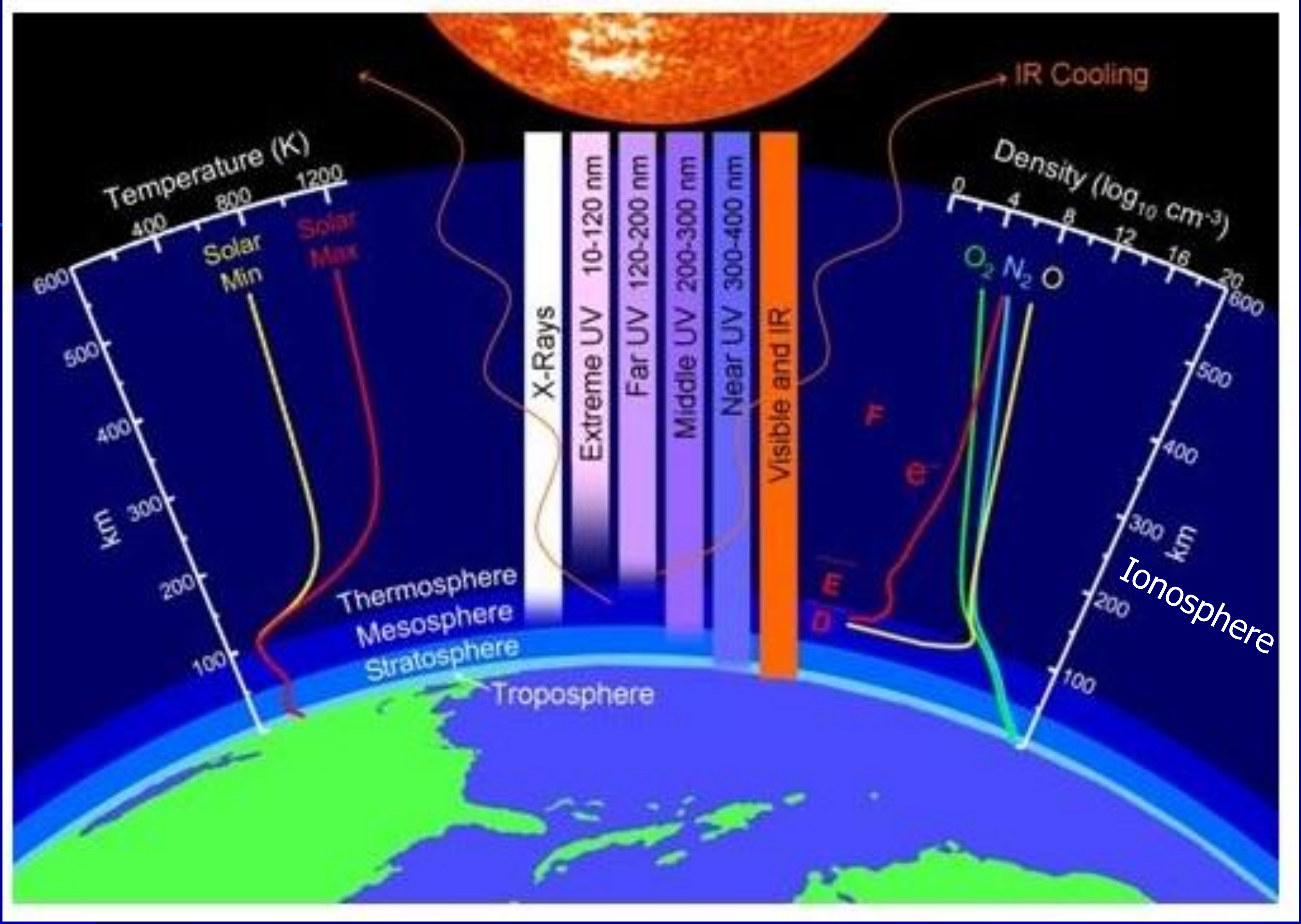
Penetration Depth is defined as the depth at which the intensity of the radiation in the atmosphere falls to 1/e (~37%) of its original value of the surface.

The equation of the intensity;

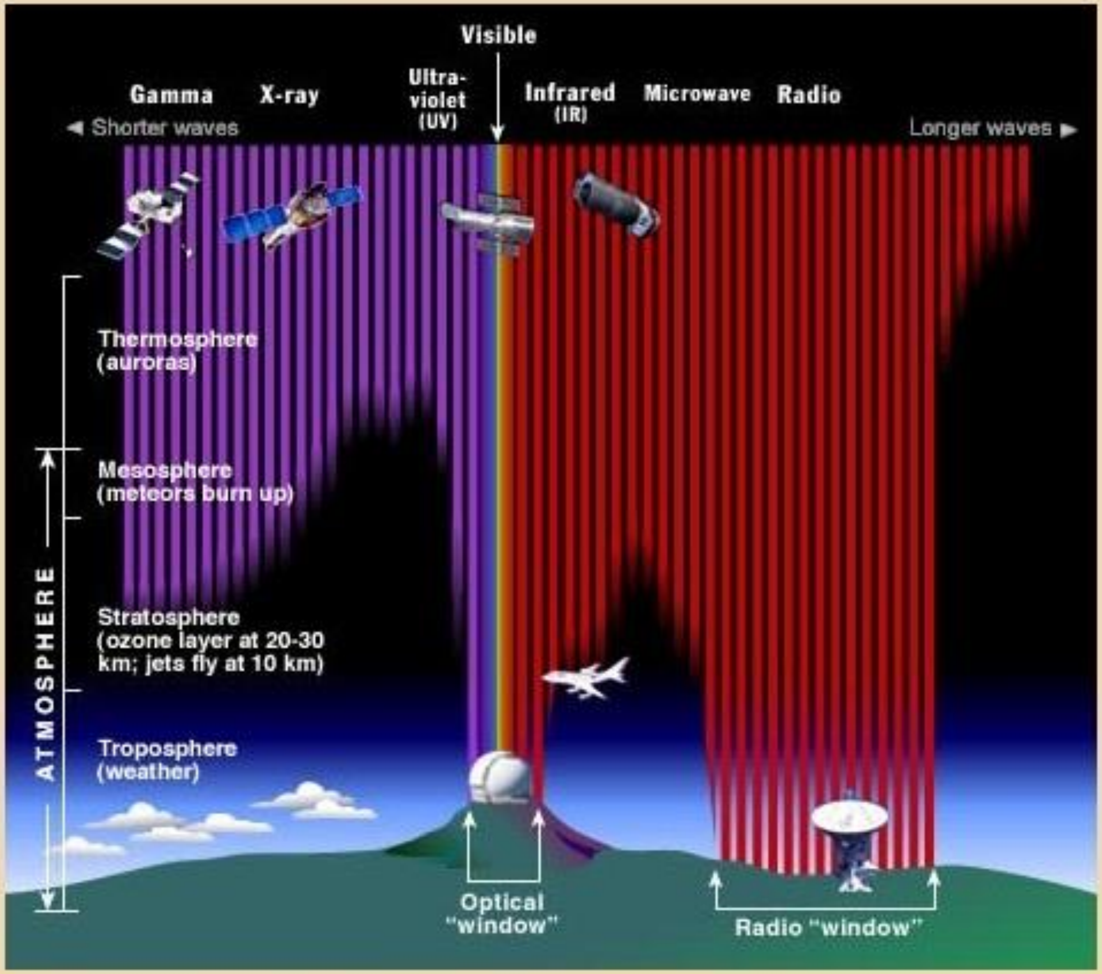
$$I(h) = I(0)\ e^{-\alpha\ h}$$

Where ***alpha*** is some constant.

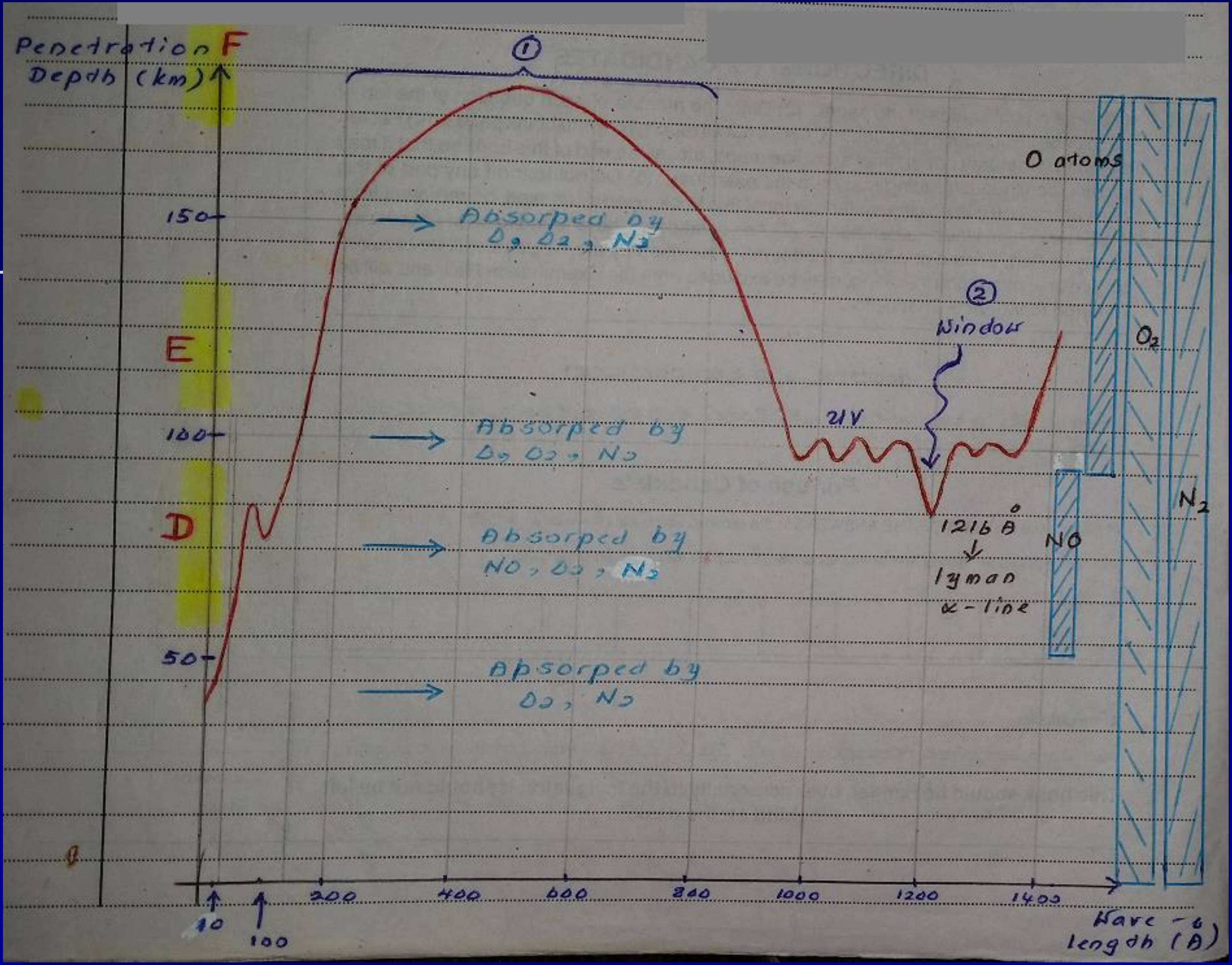
Penetration Depth = $^1/_\alpha$


IR Cooling
Temperature (K)
400
800
1200
600
500
400
300
200
100
km
Solar Min
Solar Max
X-Rays
Extreme UV 10-120 nm
Far UV 120-200 nm
Middle UV 200-300 nm
Near UV 300-400 nm
Visible and IR
Density (log10 cm-3)
0
4
8
12
16
20
O2 N2 O
F
e-
E
D
Thermosphere
Mesosphere
Stratosphere
Troposphere
Ionosphere

Solar EM Radiation Penetration into Earth's Atmosphere



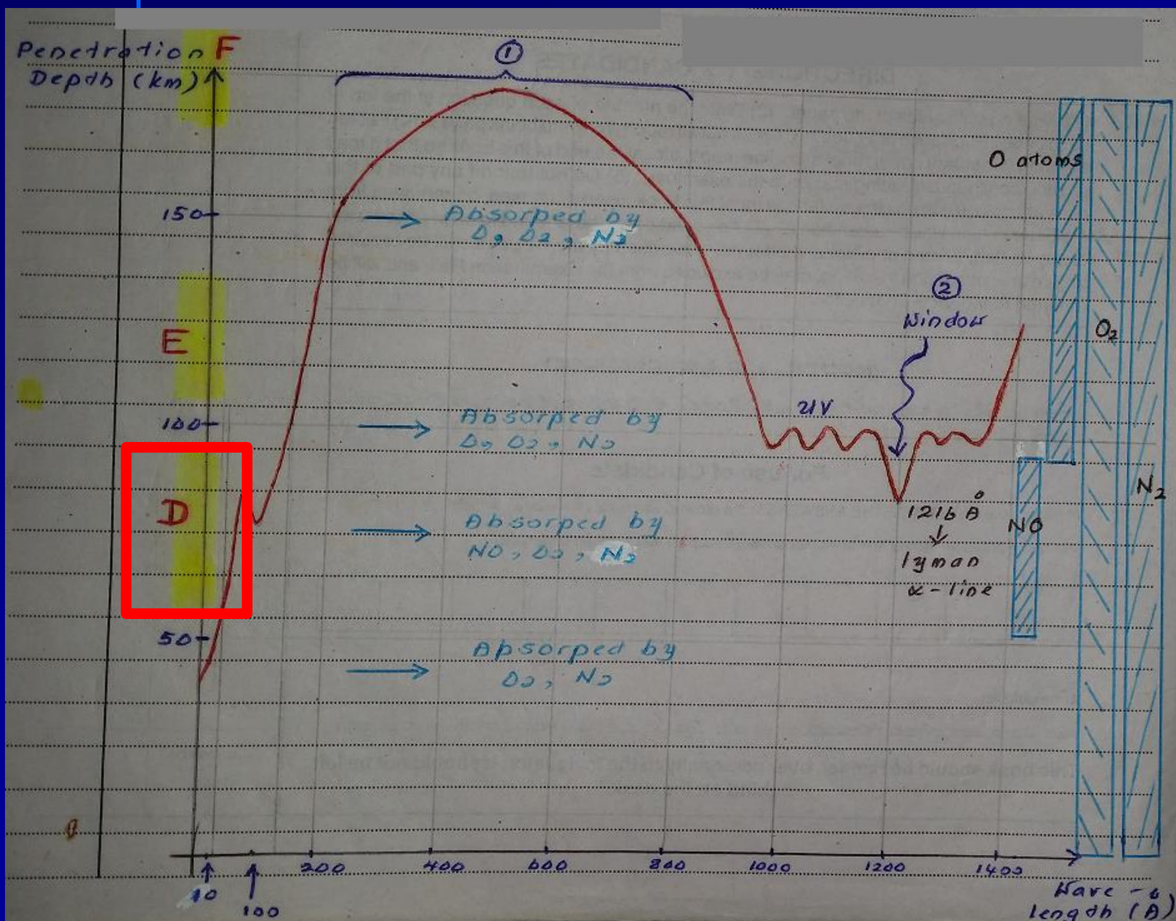
Various wavelengths of solar EM radiation penetrate Earth's atmosphere to various depths. Fortunately for us, all of the high energy X-rays and most UV is filtered out long before it reaches the ground. Much of the infrared radiation is also absorbed by our atmosphere far above our heads. Most radio waves do make it to the ground, along with a narrow "window" of IR, UV, and visible light frequencies. **Credit:** Image courtesy STCI/JHU/NASA.



The graph of Penetration Depth vs wave-length of the Radiation comes from the Sun

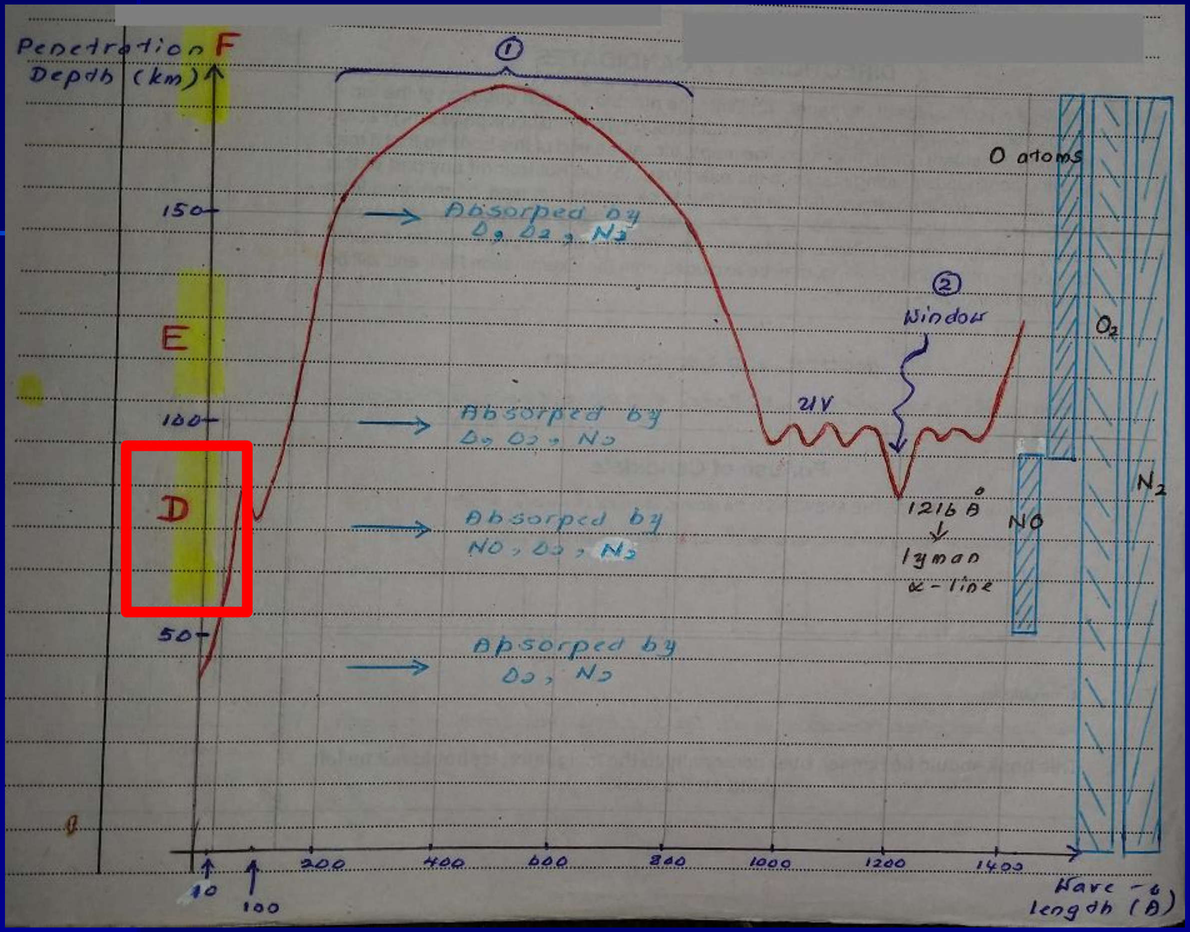
Penetration Depth

This diagram indicates penetration depth of the radiation comes from the Sun. Also that radiation comes from the upper side of the atmosphere to the surface of the Earth.



- Cause of the D-Region of the the ionosphere, wavelength of the radiation 10 Å comes from the Sun.

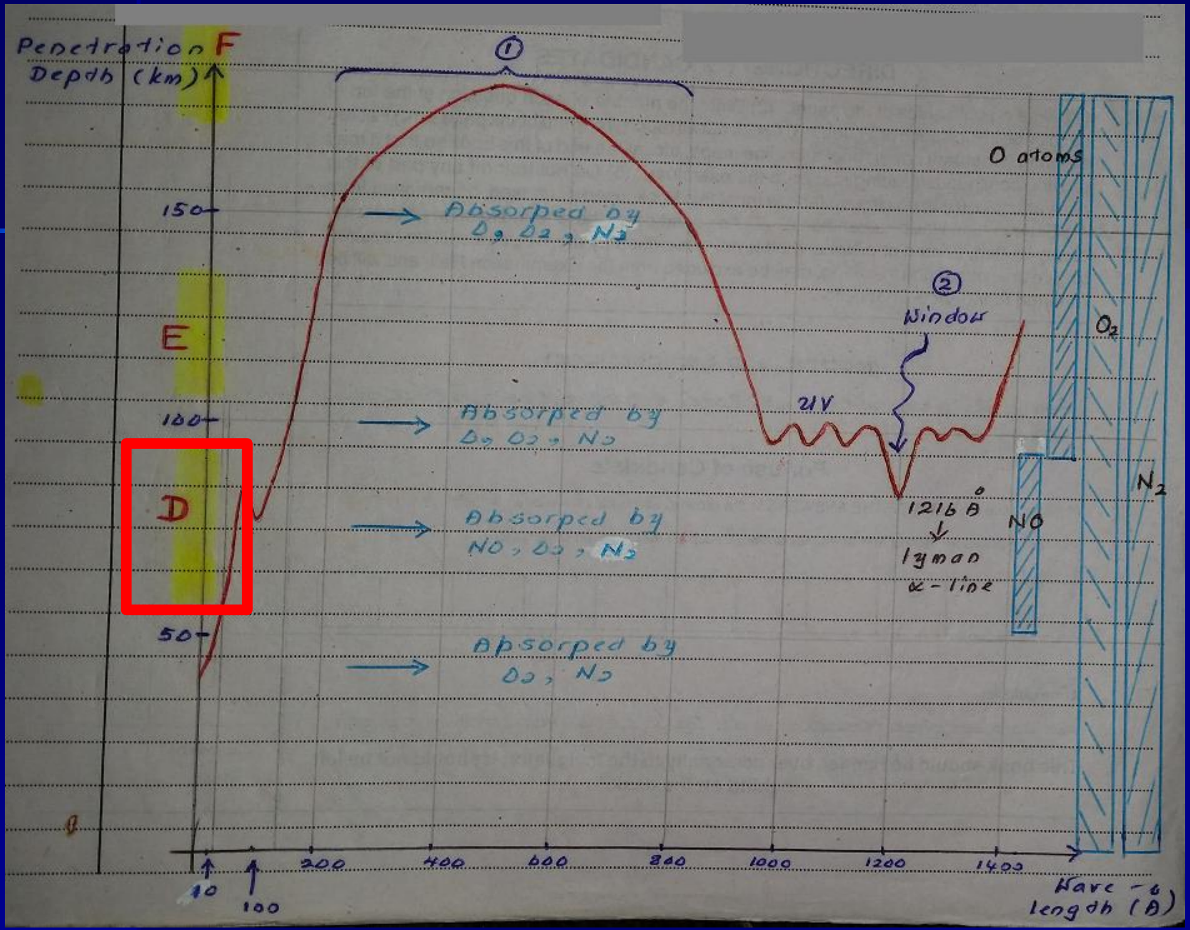
Penetration Depth



- The size of the D-Region is **increasing** when the season of the **increase of the Solar Activity**.

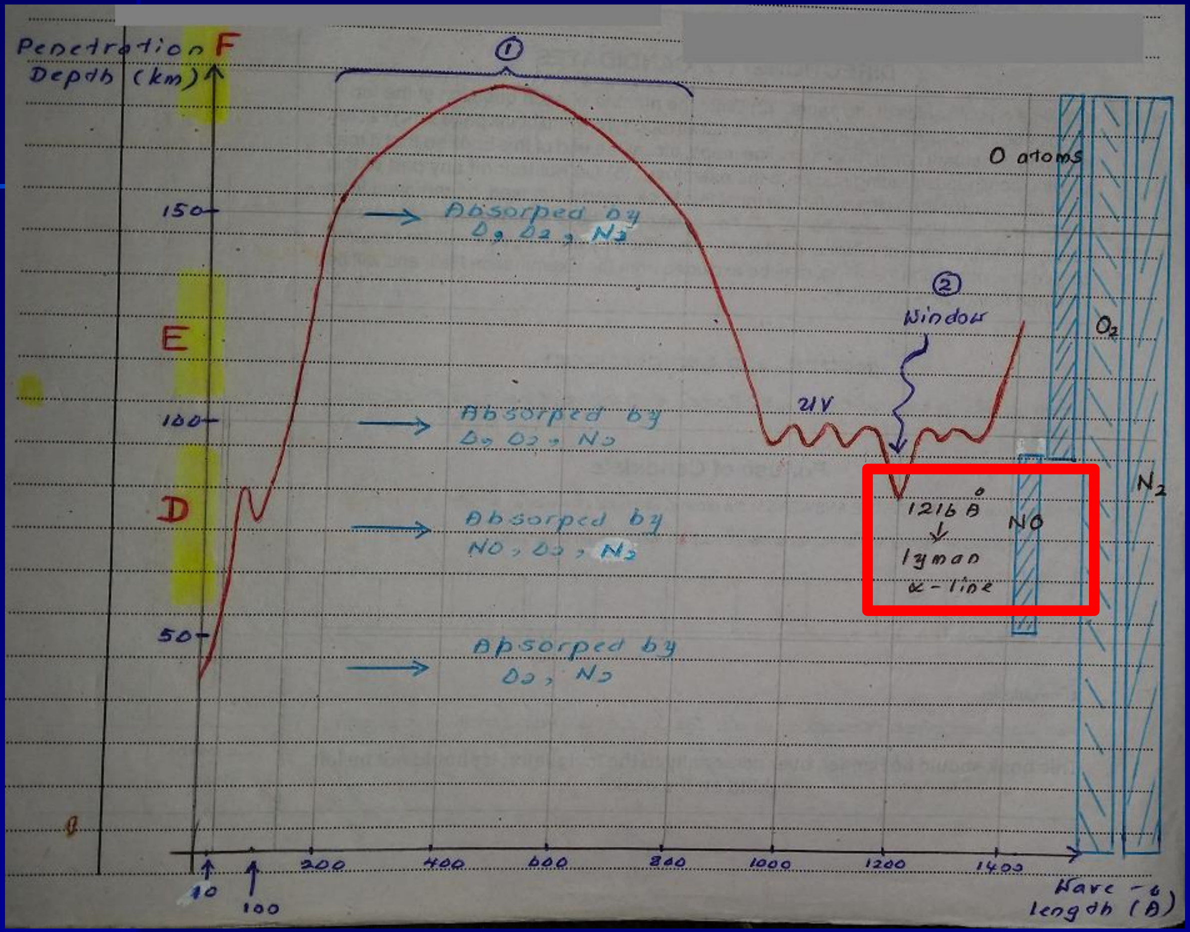
This phenomena has a ~11.2 years cycle !

Penetration Depth



- If a **Solar Flare is created** on the Sun, the **size of the Region-D is increasing** very fast with in several minutes (~8 min & 30 sec)

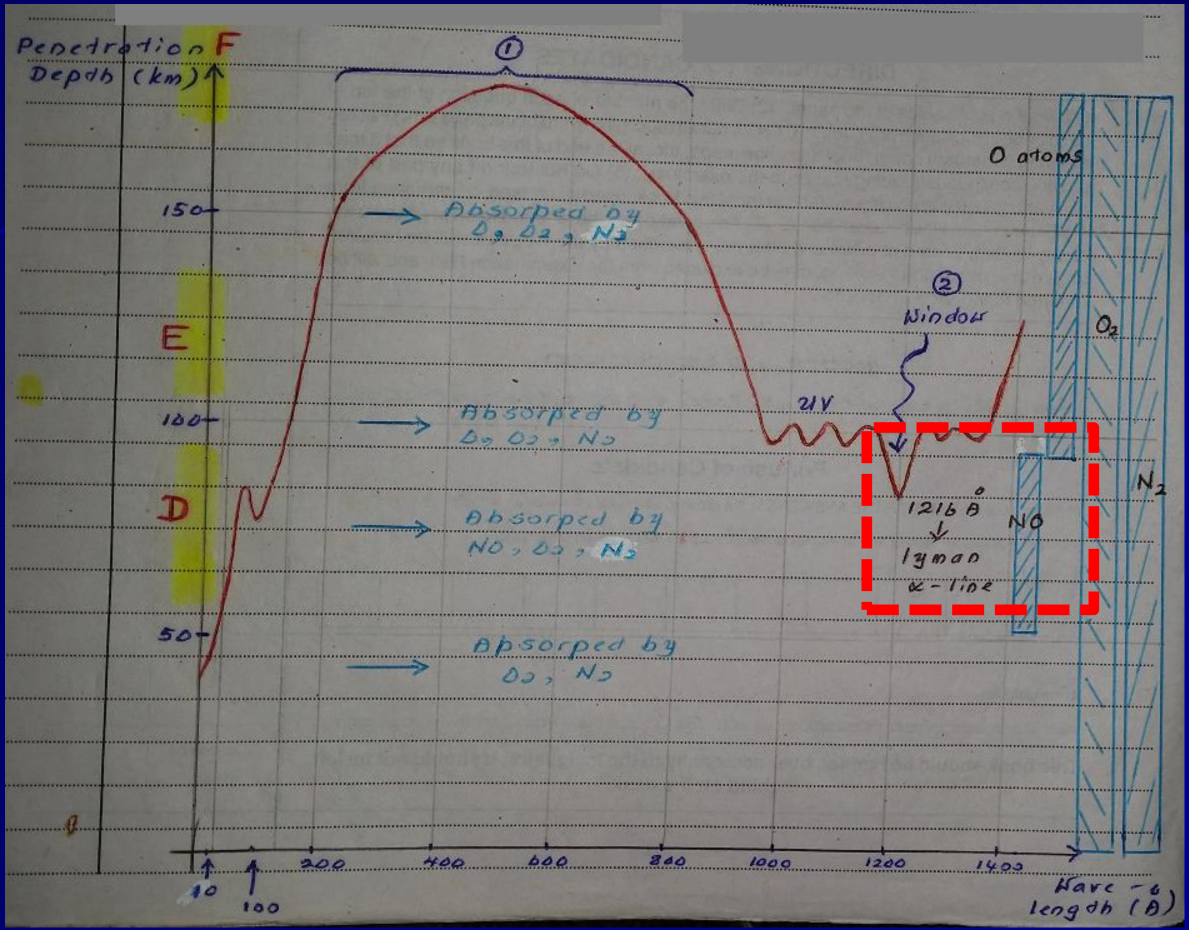
Penetration Depth



- Lyman alpha-radiation (1216 Å) absorbed by **NO** in the atmosphere.

Penetration Depth

- The Lyman alpha-ray (1216 Å) **going through the 100 km region** to lower region
- (< 100 km)



This phenomena is called "Window" of the **100 km region from the surface** of the Earth.!

Regular and Irregular Variations of the Ionosphere

The ionosphere we have described up to now and the numerical values we have given refer to an average, or typical as some people prefer to call it, **ionosphere**.
In practice these values vary by more than an order of magnitude with **time** and **location**.
some of these changes follow a known pattern, whereas others come and go on an irregular basis.

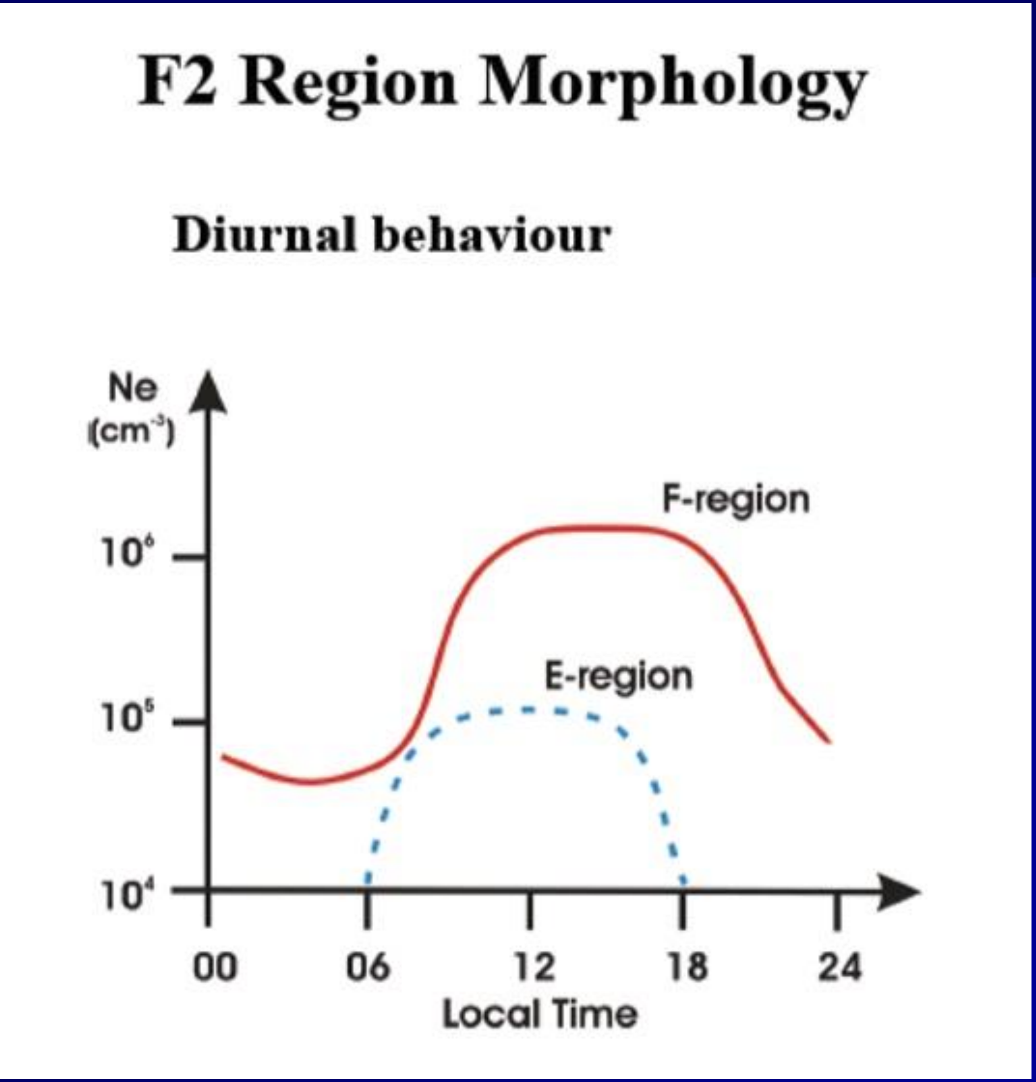
Regular Variations of the Ionosphere

- **The Latitudinal Dependence**

The latitudinal dependence of the ionospheric parameters, **mainly due to the change of the solar zenith angle with latitude**, but also **due to the change in the dip angle of the Earth's magnetic field**. There is also a **small longitudinal variation** because the **Earth's Magnetic Field various with longitude** along any given geographic latitude. The N_m (Molecular Number Density - electrons) can easily **vary by an order of magnitude from the polar to the equatorial regions**.

- **The Diurnal Variation**

The diurnal variation of the ionosphere which includes the peaking of the electron density usually in the early afternoon, the **sharp changes near sunrise and unset,** and the **disappearance of the lower layers during the night**. The N_m can again vary by an order of magnitude between night and day.



The Diurnal Behaviour of the E- Region and F-Region

Regular Variations of the Ionosphere

- **The Seasonal Variation**

The seasonal variation, which is also due to the change in the average zenith angle of the Sun as we move **between the summer and winter solstices** (සූර්ය නිවෘත්තිය).

- **The 27 Day Cycle**

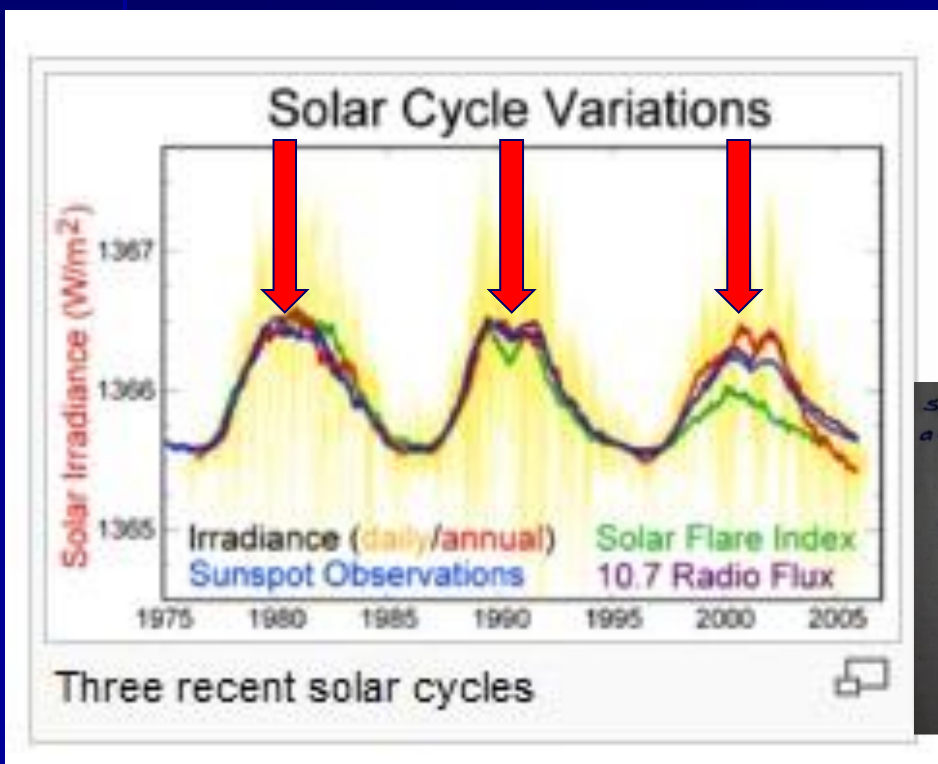
The 27 day cycle due to the intrinsic (true) rotation of the Sun. This cycle is especially noticeable during periods of **high solar activity when a very activity region** might last for more than one rotation of the Sun.

Active regions also have a tendency (willingness) to form in the same general area of other past active regions so that there is often a long lasting longitudinal asymmetry of activity on the Sun.

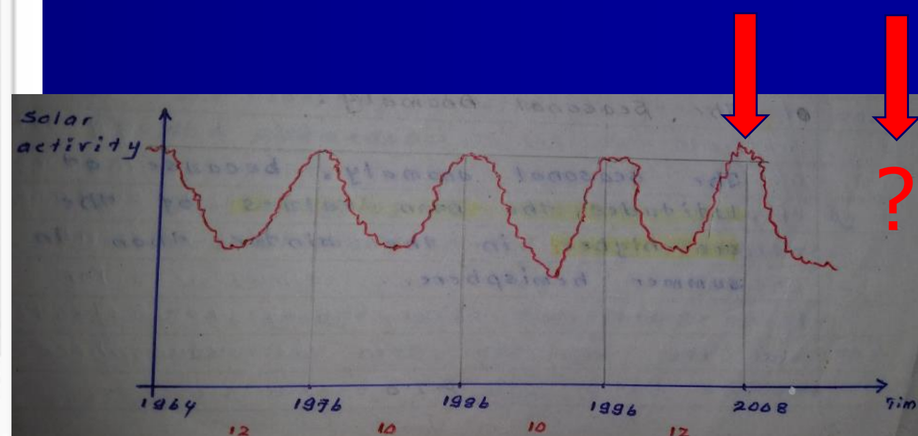
Regular Variations of the Ionosphere

- **The 11 year Solar Cycle**

The 11 year solar cycle, which represents the fairly regular increase and decrease of the solar activity and therefore of the ionizing radiation from the Sun with a period of approximately **11.1 years** (may be 11.2 years). The last solar maximum occurred in 2008 !



Three recent solar cycles



Solar Cycles						
Cycle	Started	Finished	Duration (years)	Maximum (monthly SSN (Smoothed Sunspot Number))[4]	Minimum (monthly SSN; end of cycle)[5][6]	Spotless Days (end of cycle)[7][8][9]
Solar cycle 1	March 1755	June 1766	11.3	86.5	11.2	
Solar cycle 2	June 1766	June 1775	9.0	115.8	7.2	
Solar cycle 3	June 1775	September 1784	9.3	158.5	9.5	
Solar cycle 4	September 1784	May 1798	13.7	141.1	3.2	
Solar cycle 5	May 1798	December 1810	12.6	49.2	0.0	
Solar cycle 6	December 1810	May 1823	12.4	48.7	0.1	
Solar cycle 7	May 1823	November 1833	10.5	71.5	7.3	
Solar cycle 8	November 1833	July 1843	9.8	146.9	10.6	
Solar cycle 9	July 1843	December 1855	12.4	131.9	3.2	~654
Solar cycle 10	December 1855	March 1867	11.3	97.3	5.2	~406
Solar cycle 11	March 1867	December 1878	11.8	140.3	2.2	~1028
Solar cycle 12	December 1878	March 1890	11.3	74.6	5.0	~736
Solar cycle 13	March 1890	February 1902	11.9	87.9 (Jan 1894)	2.7	~938
Solar cycle 14	February 1902	August 1913	11.5	64.2 (Feb 1906)	1.5	~1019
Solar cycle 15	August 1913	August 1923	10.0	105.4 (Aug 1917)	5.6	534
Solar cycle 16	August 1923	September 1933	10.1	78.1 (Apr 1928)	3.5	568
Solar cycle 17	September 1933	February 1944	10.4	119.2 (Apr 1937)	7.7	269
Solar cycle 18	February 1944	April 1954	10.2	151.8 (May 1947)	3.4	446
Solar cycle 19	April 1954	October 1964	10.5	201.3 (Mar 1958)	9.6	227
Solar cycle 20	October 1964	June 1976	11.7	110.6 (Nov 1968)	12.2	272
Solar cycle 21	June 1976	September 1986	10.3	164.5 (Dec 1979)	12.3	273
Solar cycle 22	September 1986	May 1996	9.7	158.5 (Jul 1989)	8.0	309
Solar cycle 23	May 1996	December 2008 [10]	12.6	120.8 (Mar 2000)	1.7	820 (through Jan 15, 2011) [11]
Solar cycle 24	December 2008 [10]					
Mean			11.1	114.1	5.8	

Regular Variations of the Ionosphere

- **The 11 year Solar Cycle**

The fact that all these variations follow a rather well-prescribed pattern does not necessarily mean that these patterns follow the predictions of the simple Chapman layer theory. According to the Chapman theory, for example, the highest F_0, F_2 and the lowest h_m must occur when the Sun reaches the smallest zenith angle, which naturally occurs at noon. The Chapman theory also predicts lower critical frequencies at higher latitudes and for the same latitude lower critical frequencies in the winder hemisphere.

All the variations of the ionosphere that do not follow the predictions of the Chapman Theory came to be known as **anomalies** and over the years many anomalies of this kind have been reported and diseased in the literature.

Thus we have:

- **The Equatorial or Geomagnetic Anomaly**
- **The Seasonal Anomaly**
- **The December Anomaly**
- **The Diurnal Anomaly**

Regular Variations of the Ionosphere

- **The 11 year Solar Cycle**

  - **The Equatorial or Geomagnetic Anomaly**

The equatorial or geomagnetic anomaly, because the $f_0 f_2$ varies with the geomagnetic rather than with the geographic latitude plus the fact that the noon values of the $F_0 F_2$ show a decrease along the geomagnetic equator at the equinoxes (clinic).

  - **The Seasonal Anomaly**

The seasonal anomaly, because at mid-latitudes the noon values of the $F_0 F_2$ are higher in the winter **than** in the summer hemisphere.

Regular Variations of the Ionosphere

- **The 11 year Solar Cycle**

  - **The December Anomaly**

The December anomaly, because on a worldwide basis the $F_0 F_2$ values of the ionosphere are in general higher around December.

  - **The Diurnal Anomaly**

The diurnal anomaly, because the diurnal variation of the $F_0 F_2$ is not always symmetric around the local noon.

This phenomenon is especially pronounced at mid-latitudes during the summer months when the evening and early night values of the $F_0 F_2$ approach and often exceed the corresponding noon value. The segment of high critical frequencies around noontime which is missing from the diurnal plot of the $F_0 F_2$ has been given the descriptive name **midday bite out**.

Regular Variations of the Ionosphere

- **The 11 year Solar Cycle**
  - **The Diurnal Anomaly**

People have tried to account for these so called anomalies by including effects that were neglected by the simple Chapman theory.

Some of the most important ones are:

1. Ambipolar diffusion in the presence of the Earth's magnetic field.
2. The coupling between the ionosphere and the plasmasphere.
3. The dragging of ionospheric plasma by neutral winds in the upper atmosphere.
4. The change with temperature of the **production rate** the **loss rate** and the **scale height** at any given attitude.

Irregular Variations of the Ionosphere

Besides the different anomalies which we have discussed above, the ionosphere shows also the following **structural irregularities**.

- **The Sporadic - E**

The sporadic-E, which is the frequent formation of a thin layer (1-5 km) of excess ionization at an attitude of about 110 km. The electron density of this layer can exceed by more than a factor of two the ambient electron density of the E-region.

The sporadic-E has been studied extensively both from the theoretical and the experimental point of view, but still there is no general agreement on the cause of this phenomenon. According to one of the more widely discussed theories, the appearance of the sporadic-E is due to **strong shear winds which often develop near the maximum of the E-layer.**

Irregular Variations of the Ionosphere

- **The Spread F**

  Ionograms occasionally show a large spread in the equivalent height from which the F-region echoes are returned. This time spread, which is much broader than the time width of the transmitted radio pulses, is produced either by a blobby structure of the F-region which causes in depth multiple scattering, or by a wavy structure of the F-region which permits the reflection of the radio waves by curved surface at different distance from the vertical. This phenomenon might last sometimes for several hours and is usually a good indication of disturbed conditions in the ionosphere.

- **The Ionospheric Irregularities**

  The ionospheric irregularities, which represent local perturbations (කැළඹීම) by a few percent in the electron density of the ionosphere. These irregularities are often elongated (long) along the lines of the Earth's Magnetic Field and their dimensions are of the order of 1 to 10 km.

Irregular Variations of the Ionosphere

- **Travelling Ionospheric Disturbances**

  These are large size perturbations of the electron density extending sometimes over 1000 km. They have been observed to travel with speeds of the order of 300 ms^{-1} over large distances and occasionally to make a full circle around the globe. The mechanism causing these large scale disturbances is not well understood. One possible suggestion is that they are produced by

  the sudden precipitation (running down) of a large number of energetic particles either in the polar regions or in the vicinity of a magnetic anomaly.

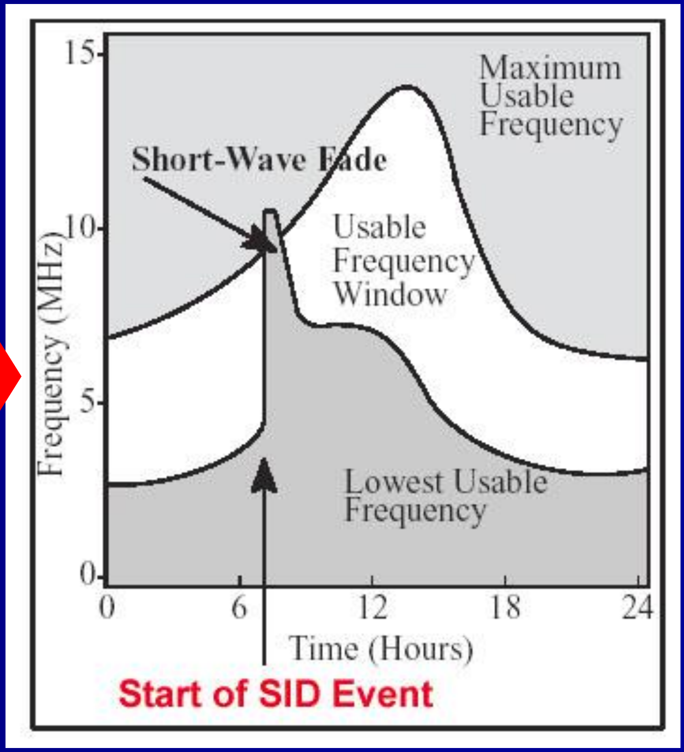
- **The Mid-Latitude Trough**

  This is a minimum in the electron densities of the ionosphere which develops primarily during the night time at a geomagnetic latitude (dip latitude) of approximately 60 degrees.

Irregular Variations of the Ionosphere

- **Sudden Ionospheric Disturbances (S I D)**

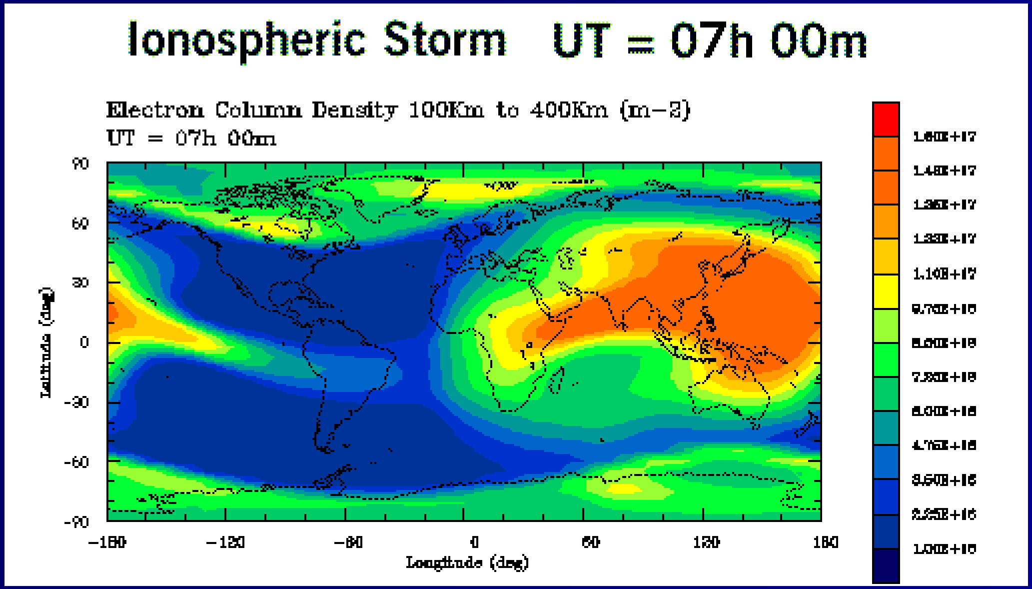
These are caused by the enhanced ultra-violet and X-ray radiation from the Sun during solar flare events. They occur only in the Sun-lit side of the Earth and they last, like the solar flares, from a few minutes to about one hour.



Irregular Variations of the Ionosphere

- **Ionospheric Storms**

These are closely associated with geomagnetic storms and can last from one to four days affecting the ionosphere over the entire globe. Observations of the unusual behavior of the ionosphere during these storms have been made and continue to be made by many groups around the world.



Many diurnal, seasonal and latitudinal storm effects have been discovered and serious efforts have been made for their theoretical interpretation.


Thank You !
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