PHYSICS OF IONOSPHERE

4.1 HISTORY

In 1899,.in a landmark experiment on December 12, 1901, Marconi, who is often called the "Father of Wireless," demonstrated transatlantic communication by receiving a signal in St. John's Newfoundland that had been sent from Cornwall, England. Because of his pioneering work in the use of electromagnetic radiation for radio communications, Marconi was awarded the Nobel Prize in physics in 1909.

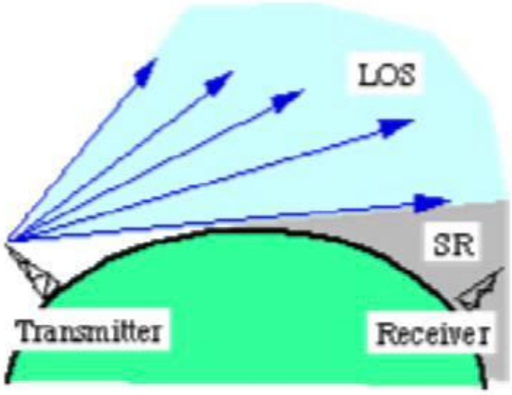

Figure 4.1 Areas in the light blue region are within the radio "Line of Sight" (LOS). The receiving antenna is in the shadow region (SR) and cannot receive a signal directly from the transmitter.

Marconi's famous experiment showed the way toward worldwide communication but also raised a serious scientific dilemma. Up to this point, it had been assumed that electromagnetic radiation traveled in straight lines in a manner similar to light waves. If this were true, the maximum possible communication distance would be determined by the geometry of the path as shown in Fig.4.1 to the left.

The radio signal would be heard up to the point where some intervening object blocked it. If there were no objects in the path, the maximum distance would be determined by the transmitter and receiver antenna heights and by the bulge (or curvature) of the earth. Drawing from light as an analogy, this distance is often called the *"Line-of-Sight" (LOS)* distance. In Marconi's transatlantic demonstration, something different was happening to cause the radio waves to apparently bend around the Earth's curvature so that the communication signals from England could be heard over such an unprecedented distance.

In 1902, Oliver Heaviside and Arthur Kennelly independently proposed that a conducting layer in the upper atmosphere would allow a transmitted EM signal to be reflected back toward the Earth. Up to this time, there was no direct evidence of such a region and little was known about the physical or electrical properties of the Earth's upper atmosphere. If such a conductive layer existed, it would permit a dramatic extension of the "line-of-Sight" limitation to radio communication as shown in Fig.4.2. to the left.

During the mid-1920s, the invention of the Ionosonde allowed direct observation of the ionosphere and permitted the first scientific study of its characteristics and variability and its effect on radio waves.

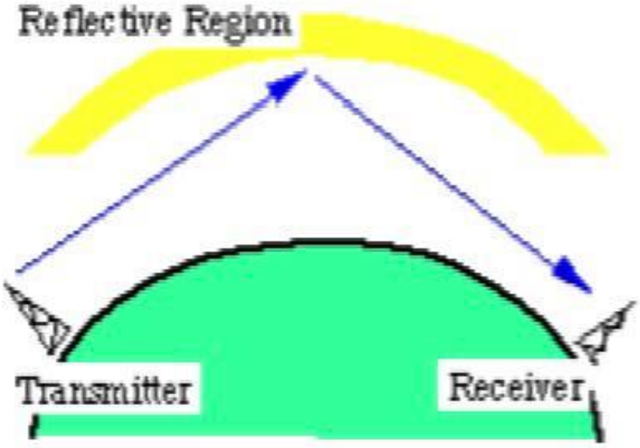

Figure 4.2 A conductive region at high altitude would "reflect" radio signals that reached it and return them to Earth.

4.2 REQUIREMENTS FOR AN IONOSPHERE

For a PLANETARY IONOSPHERE: The only requirements are a neutral atmosphere and a source of ionization for the gases in that atmosphere. Sources of ionization include photons and energetic particle "precipitation" The process involving the former is referred to as photoionization, and the later is often labeled impact ionization.

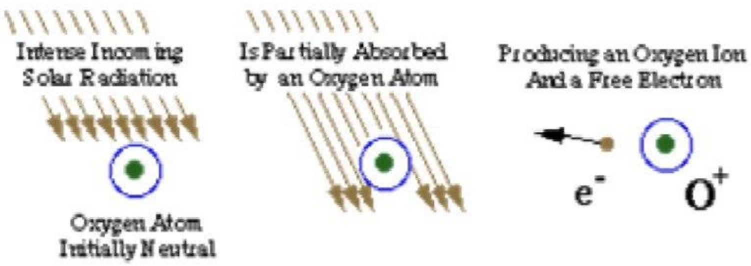

Figure 4.3 The conceptual drawing is a simplified explanation of the ionization process.

Solar photons in the extreme ultraviolet (EUV) and ultraviolet(UV) wavelength range of approximately 10nm to 100 nm typically produce at least the dayside ionosphere of the planets.

The photons come primarily from the Sun. Ionizing particles can come from the galaxy (cosmic rays), the Sun, the magnetosphere, and the ionosphere itself if a process for local ion or electron acceleration is operative. Precipitating energetic electrons produce additional ionizing photons within the atmosphere by a process known as bremsstrahlung or breaking radiation.

The only requirement on the ionizing photons and particles is that their energies, i.e., $h\nu$ in the case of photons, and kinetic energy in the case of particles exceed the ionization potential or binding of a neutral atmosphere atomic or molecular electron. In nature, atmospheric ionization usually is attributable to the maturity of these various sources, but often one dominates.

4.3 THE NEUTRAL ATMOSPHERE

The density n_i of a constituent of the upper neutral atmosphere obeys a hydrostatic equation:

$$n_i m_i g = -\frac{dP}{dh} = -\frac{d}{dh}\left(n_i k T_i\right) \tag{4.1}$$

which expresses a balance between the vertical gravitational force and the thermal-pressure-gradient force on the atmospheric gas.

Here,
mi: molecular or atomic mass,
g: the acceleration due to gravity,
h: altitude variable,
and
P: the thermal pressure, n_i k T_i
k: Boltzmann's constant,
Ti: temperature of the neutral gas under consideration

If T_i is assumed independent of h, this equation has the exponential solution

$$n_i = n_0 \exp\frac{-\left(h-h_0\right)}{H_i} \tag{4.2}$$

where $H_i = kT_i / m_i g$ defines the scale height of the gas, and n0 is the density at the reference altitude h0. Note that the scale-height dependence on particle mass is such that the lightest molecules and atoms have the largest scale height.
Most planetary atmospheres are dominated at high altitudes by hydrogen and helium. Of course, Ti may depend on h, so this simple exponential distribution will not always provide an accurate description.

4.4. ION PRODUCTION.

Some simplifying assumptions can be made that together will allow an analytical approach to ionosphere modeling known as *Chapman theory.*
In Chapman's theory, the goal is to describe ion production as a function of height for the simple case in which the details of photon absorption are hidden in a radiation-absorption cross-section σ and in which ion production is assumed to depend only on the amount of radiative energy absorbed.
We define the following variables:

n_i: density of neutrals (per cubic meter)
h: height
I: intensity of the radiation (energy flux, electron volts per square meter per second)
σ: photon-absorption cross-section (square meter).
Q: rate of ion production (photoionization rate, electrons per cubic meter per second)
s: line-of-sight path length
χ: zenith angle
C: number of electrons produced in the absorber per unit energy absorbed (electrons per electron volt).
We define the following variables:

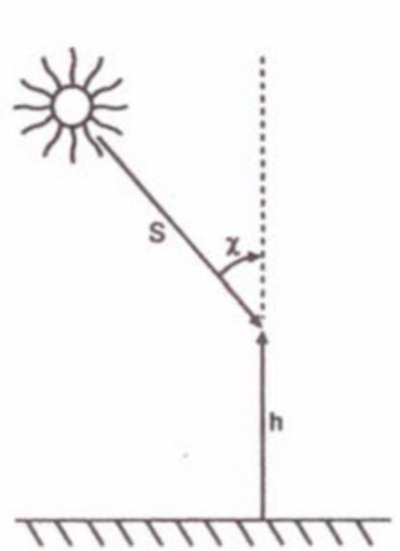

Figure 4.4: Illustration showing the line-of-sight path length s, the solar zenith angle χ, and The altitude h are illustrated.

The atmosphere is presumed to be exponential, planar, and horizontally stratified. Assumptions that are idealizations of the real world, where atmospheres are only approximately exponential and curved, and the scale height Hi depends on χ. As radiation is absorbed, its intensity decreases.

$$-\frac{dI}{ds} = \sigma n_i I \quad (4.3)$$

Because the rate of ion production should be proportional to the rate at which radiation is absorbed, we can write

$$Q = -C\frac{dI}{ds} = \sigma C n_i I \qquad (4.4)$$

where C is the constant of proportionality (approximately 1 ion pair per 35 eV in air).

For the peak or maximum of production(subscript m),

$$\frac{dQ}{ds} = 0$$

where s is related to h by ds=-dh secχ (Fig.4.4).

$$\sigma H_i n_m \sec\chi = 1 \qquad (4.5.a)$$

$$\sigma N_{im} = 1 \qquad (4.5.b)$$

where N_{im} is the integrated density $\int_{\infty}^{S_m} n_i ds$ along the line-of-sight up to the position of the peak S_m.

Useful term is ***optical depth*** τ, which describes the attenuation of the ionizating radiation. The optical dept arises naturally in the expansion for intensity at positions along the line-of-sight relative to the intesity at infinity.

Integrating, (4.3)

$$\ln\left(\frac{I(s)}{I(\infty)}\right) = -\sigma\int_{\infty}^{s} n_i ds = -\sigma N_{is}$$

or

$$I(s) = I(\infty)\exp(-\sigma N_{is}) = I(\infty)\exp(-\tau)$$

At the peak, $\sigma N_{is} = \sigma N_{im} = 1$; so the peak is the altitude where the optical depth is unity. We shall call $I(\infty)$ instead of I(0), because the former is standard nomeculter).

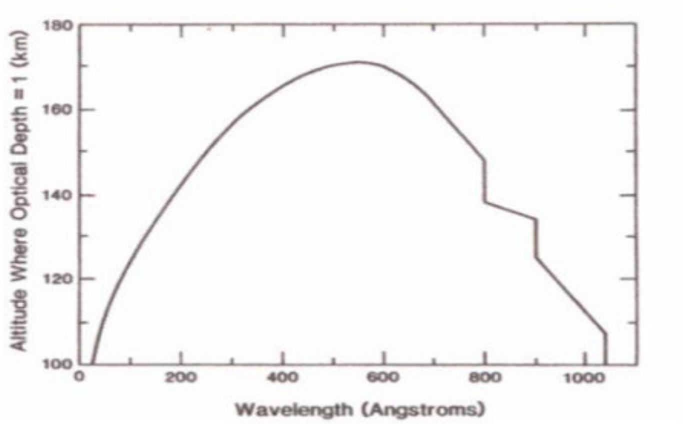

Figure 4.5: Photonwavelength versus the altitude in the Earth's atmosphere

The altitudes at which photons of varies wavelengths reach unit optical depth in the Earth's atmosphere are illustrate in Fig.4.5.

Now we return to the analysis of the radiation rate Q. The peak production rate is

$$Q_m = C\sigma n_m I_m = C\sigma\left(\sigma H_i \sec\chi\right)^{-1}\left(I(\infty)\exp(-1)\right) = \frac{CI(\infty)\cos\chi}{H_i}\exp(1) \quad \textbf{(4.6)}$$

Given the neutral-gas altitude profile $n_i = n_0 \exp\left(-(h-h_0)/H_i\right)$, we can, determine the height of the production peak h_m by writing

$$\sigma H_i n_m \sec\chi = 1 = \sigma H_i n_0 \exp\left(\frac{-(h_m - h_0)}{H_i}\right)\sec\chi \quad \textbf{(4.7)}$$

)

and solving for h_m.

Similarly, we can determine the dependence of the radiation intensity on h by using the earlier expression for I(s) and nothing that N_{is} is the integrated density along the line of sight:

$$I(h) = I(\infty)\exp\left[-\sigma n_0 H_i \sec\chi \exp\left(\frac{-(h-h_0)}{H_i}\right)\right] \quad \textbf{(4.8)}$$

The dependence of the production rate Q on h ,s then given by

$$Q = Q_m \exp\left[1 + \frac{(h_m - h_0)}{H_i} - \exp\left(\frac{(h_m - h_0)}{H_i}\right)\right] \quad \textbf{(4.9a)}$$

with $CI(\infty) = Q_m \exp(1) H / \cos \chi_i$.

This can be simplified by defining $y = (h - h_0)/H_i$, hence

$$Q = Q_m [1 - y - \exp(-y)] \quad \textbf{(4.9b)}$$

which is the ***Chapman production function***. Note that far above the peak (y≥2), a good approximation is

$$Q \propto \exp(-y) \quad \textbf{(4.9c)}$$

which says that because the radiation intensity is practically constant at high altitudes (not much absorption occurs), Q is proportional to neutral density. The rate Q is the rate of production of ions and photoelectrons, because these usually are produced in pairs most of ions are signly ionized in this process. It is notable that in the expansion for Q, the proton-absorption cross section does not explicitly appear. The properties of the absorber are contained in the constant C

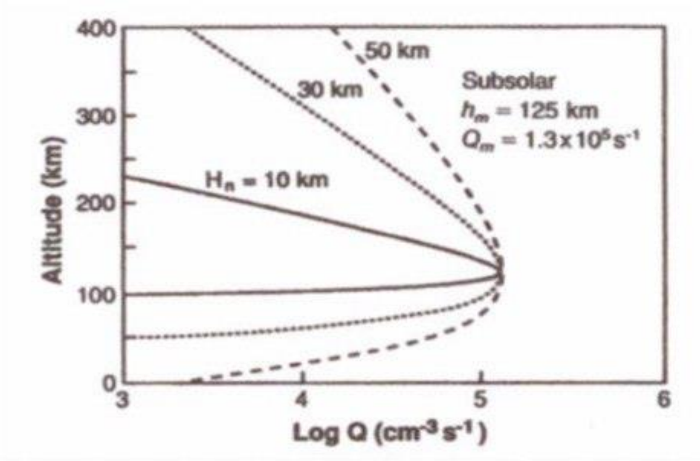

Figure 4.6: Chapman production function

The subsolar (χ=0) Chapman production function or ion production profile in atmospheres with several different scale heights is plotted in Fig.4.6.. Our derivation of the Chapman production function has assumed a flat earth in which the solar zenith angle has a fixed value.

4.5 ION LOSS

Once the ion production rate is known, the next critical quantity that must be specified for the ionospheric model is the ion or electron loss rate L. Ionospheric electrons disappear by virtue of three types of recombination:

1-Radiative recombination $e+X^+ \longrightarrow X+h\upsilon$

2-Dissociative recombination $e+XY^+ \longrightarrow X+Y$

3-Attachment $e+Z \longrightarrow Z^-$

The first of two of these are important throughout the bulk of the ionosphere. Radiative recombination is responsible for many types of observed airglows.In contrast, most of the emmision that one sees in an aurora occurs whatomic and molecular electrons are excited to high energy levels by Coulomb collisions with the passing precipitating particles and then undergo radiation re-excitation,

Recombination occurs at rates that depend on the local concentrations of the ions and electrons

$L= \alpha\ ne\ n_i$

where ne and ni are the electron and ion densities, and α is the recombination coefficient determined by empirical and theoretical models. For the more important atmospheric dissociative recombination reactions, such as

$O_2+e \rightarrow O+O$

And

$N_2^+ + e \rightarrow N+N$

It is notable that α is often assumed constant, although T_e generally depends on altitude.

4.6 DETERMINING IONOSPHERIC DENSITY FROM PRODUCTION AND LOSS RATE.

Once the ion production rates and loss rates are established, we can consider the problem of finding the altitude distribution of the ionospheric electron density ne. If the electrons and ions do not move very far from where they are produced (e.g., by virtue of a strong horizontal ambient magnetic field), we can say that ne (and thus n_i) obeys the equilibrium-continuity or particle-conservation equation

$$\frac{dn_e}{dt} = Q - L = 0$$

and if the loss rate is due to electron-ion collisions

$$Q = L = \alpha n_e^2$$

and hence

$$\boldsymbol{n_e = (Q/\alpha)^{0.5}} \qquad (4.10)$$

describes the spatial distribution of the electrons or ions. This particular distribution is called *photochemical equilibrium distribution* because it involves only local photochemistry. For example, the Chapman-layer models of the ionosphere include the Chapman production function and the assumption of photochemical equilibrium. However, in many cases, the electrons and ions wave significantly from their points of creation before they recombine, so we must consider a transport term in a more general continuity equation.